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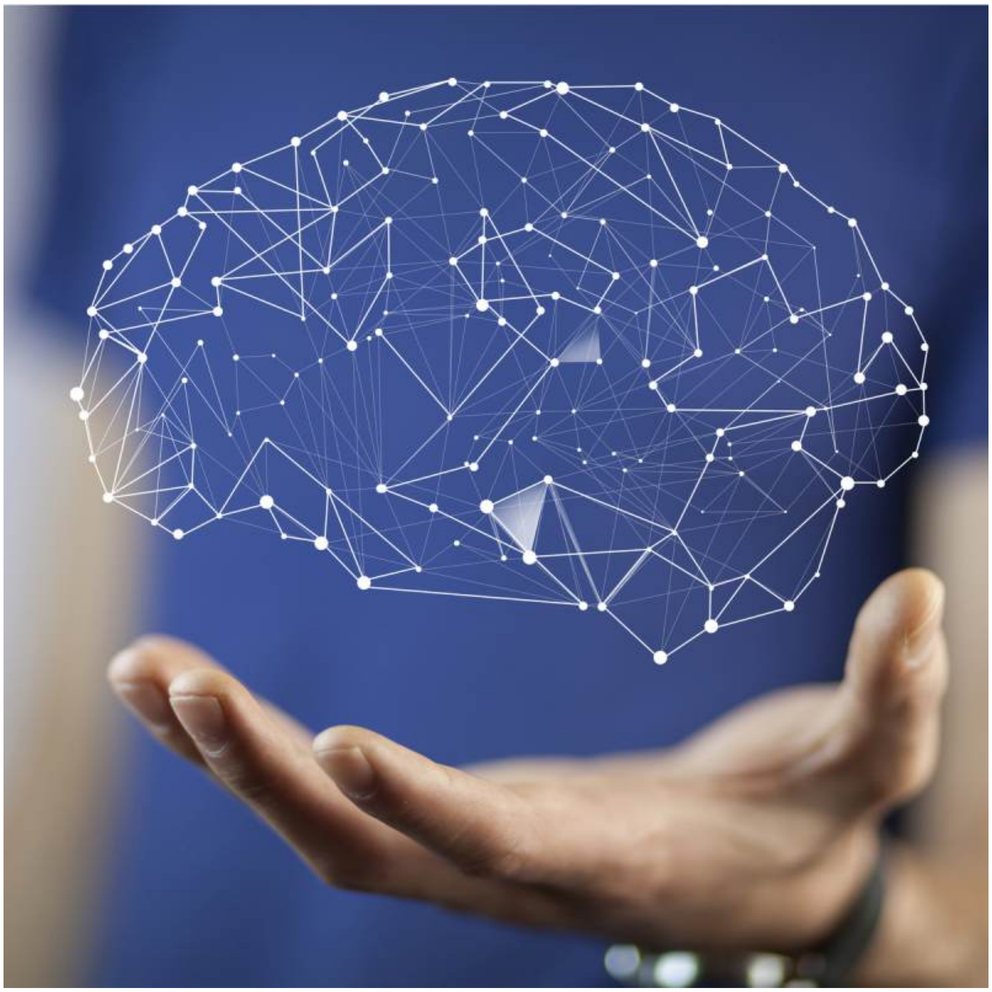

What Is Neuroscience?

Reviewed by Psychology Today Staff

Neuroscience examines the structure and function of the human brain and nervous system. Neuroscientists use cellular and molecular biology, anatomy and physiology, human behavior and cognition, and other disciplines, to map the brain at a mechanistic level.

Humans have an estimated hundred billion neurons, or brain cells, each with about a thousand connections to other cells. One of the great challenges of modern neuroscience is to map out all the networks of cell-to-cell communication—the brain circuits that process all thoughts, feelings, and behaviors. The resulting picture, emerging bit by bit, is known as "the connectome." The ability of the brain to elaborate new connections and neuronal circuits—neuroplasticity—underlies all learning.

Biology and psychology unite in the field of neuroscience, to tackle questions such as the brain's role in pain perception or the underlying cause of Parkinson's disease. Computer simulations, imaging, and other tools give researchers and medical experts new insight into the physical anatomy of the brain, its five million kilometers of wiring, and its relationship to the rest of the mind and body.

How Neuroscience Helps Us Understand the Mind and Brain

with neural connections. These connections link together its various lobes and also link sensory input and motor output with the brain's message centers, allowing information to come in and be sent back out.

One major aim of current neuroscience research, then, is to study how this wiring works and what happens when it's damaged. New developments in brain scanning allow researchers to see more detailed images and determine not only where there may be damage but also how that damage affects, for instance, motor skills and cognitive behavior in conditions like multiple sclerosis and dementia.

A rapidly expanding discipline, neuroscience findings have grown by leaps and bounds over the past half-century. More work, however, will always be needed to fully understand the neural roots of human behavior, consciousness, and memory.

Next: Areas of the Brain

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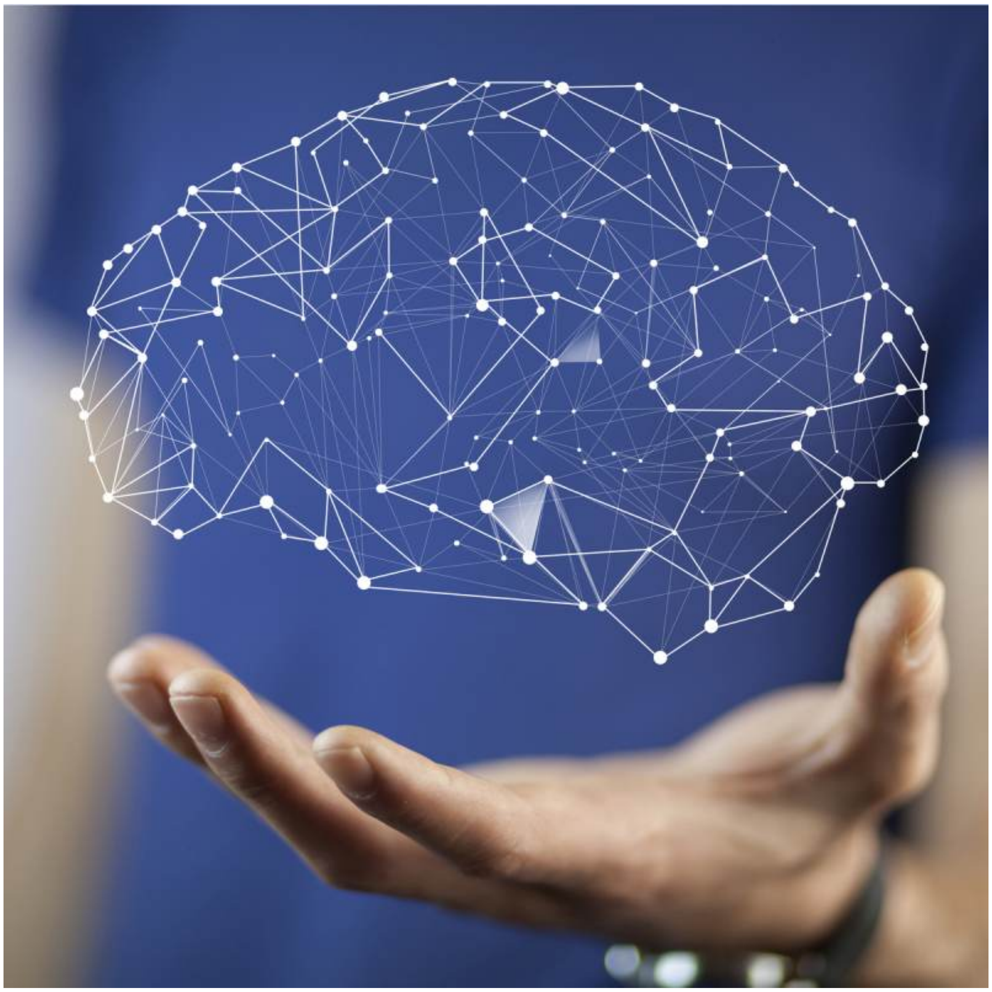

Areas of the Brain

Reviewed by Psychology Today Staff

The human brain, as the seat of mental life—from the most complicated intellectual processes down to routine and unconscious bodily control—is necessarily enormously complex.

The largest part of the brain is the highly-evolved cerebrum. The topmost portion is divided into two hemispheres, each with four lobes, within which are many other subdivisions. The cerebral cortex forms the outer layer of the cerebrum. Nested deeper within the brain are essential structures such as the basal ganglia, the amygdala, and the hippocampus. Toward the bottom of the brain are more primitive structures, including the cerebellum and brain stem. These also fulfill critical functions.

Running through parts of the brain are a dozen pairs of cranial nerves, which link the brain directly to muscles and sense organs in the head, neck, and upper body. The brain also contains four interconnected spaces called ventricles, which produce and are filled with cerebrospinal fluid. This fluid is distributed to the exterior of the brain and to the spinal cord, where it provides a cushion against physical impact and helps maintain normal function.

The brain and spinal cord together form the body's command structure: the central nervous system. The peripheral nervous

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Hemispheres of the Brain

The cerebrum is physically divided into two halves—the left hemisphere and right hemisphere—and the functions of which are specialized in certain ways. **Both hemispheres work closely together**, communicating via a bundle of nerve fibers, the corpus callosum, that forms a bridge between them.

The left hemisphere controls the movement of the opposite (right) side of the body. Among the tasks for which it is specialized are the ability to speak and aspects of language comprehension, though language ability involves both hemispheres. Broca’s area and Wernicke’s area, parts of the brain that are both linked to language, are typically located in the left hemisphere.

The right hemisphere controls the movement of the left side of the body. The right hemisphere is specialized relative to the left in some aspects of spatial processing, including that of three-dimensional relations between objects. It also

While each hemisphere has certain tasks to which it is especially tailored, broad mental activities and qualities such as perception, creativity, and reasoning are handled by both hemispheres together. (For more, see **Left Brain - Right Brain.**)

Lobes of the Brain

The cerebral hemispheres are commonly mapped out based on four large regions—the frontal lobe, the temporal lobe, the parietal lobe, and the occipital lobe—with one of each on either half of the brain.

- *The frontal lobes* form the front of the cerebrum, starting directly behind the forehead. Important for executive functioning, the frontal lobes are involved in decision-making, attention, producing voluntary movements (controlled by the motor area of the frontal lobe), and speech, along with various other voluntary and involuntary abilities.
- *The parietal lobes* are located behind the frontal lobes. The parietal lobes contain the primary sensory areas, which are involved in processing information about taste, touch, temperature, and movement. The parietal lobes also play a role in language processing, including reading.
- *The temporal lobes* sit on the sides of the brain. They contain the primary auditory cortices and process information from the ears; they also work with the occipital lobes to process visual information. The

structures including the hippocampus and amygdala.

- *The occipital lobes* form the back section of the cerebrum. They contain the primary visual cortices and are crucial for vision.

The Cortex

The cerebral cortex is the thin, outermost layer of the cerebrum, extending across all the brain's lobes. Just 1.5 to 5 millimeters in width, it is composed of the neurons that make up the brain's "gray matter" and handles much of the brain's work. (The gray matter of the cortex is interlinked with the rest of the brain by nerve fibers that make up the brain's "white matter.")

The cortex's distinctive, wrinkled appearance is due to its various ridges (gyri) and grooves (sulci). These provide for a larger total surface area within a condensed space—and hence more room for neurons—than would a totally smooth layer of brain cells.

Beneath the Cortex

Buried in the core of the brain are a collection of structures that serve a variety of important functions. Some of these essential components are:

- The *thalamus* is akin to a relay station, receiving signals going to and from the cerebrum and other parts of the nervous system. It is an integral part of the system of sensory processing, but is also involved in movement,

- The roughly pea-sized *hypothalamus*, below the thalamus, plays a role in bodily regulation, including the control of body temperature, sleep and wakefulness, hunger, and the release of the stress hormone cortisol and other hormones. The hypothalamus produces a number of hormones itself, including oxytocin, dopamine, vasopressin, and others. It is directly connected to and influences the functioning of the pituitary gland, which releases various hormones into the bloodstream.
- The *amygdala* is an almond-shaped structure that has a major role in producing emotional responses. It also helps to integrate emotional aspects of experience into memory and to produce fear-based memories and learning. There are a pair of amygdalae in the brain. The amygdala and its neighbor the hippocampus are two major components of the limbic system.
- The *hippocampus*, named for its resemblance of a seahorse's shape, is central to the creation and filing-away of memories. It is also involved in spatial processing and the ability to find one's way around. There are two hippocampi in the brain. Along with the amygdalae, they are major parts of the limbic system.
- The clusters of neurons called the *basal ganglia* are important for coordinating physical movements, including habitual behaviors.

Cerebellum

The cerebellum (Latin for "little brain") is packed with 50 percent of the neurons contained in the whole central nervous system. It is located at the rear and toward the hemispheres of its own, each containing an outer layer of grey matter and an inner area of white matter.

The cerebellum plays a central role in the control of the body's movements and in the learning of physical tasks. Based on signals from the inner ears and the muscles, the cerebellum enables the body to maintain balance and posture.

Brain Stem

The brain stem, situated at the bottom of the brain, is made up of three main parts: the midbrain, pons, and medulla oblongata.

- The *midbrain* is the highest part of the brain stem. Among other functions, it is responsible for certain reflexes, helps to process visual and auditory information, and contributes to the control of eye movement as well as other body movements.
- The *pons* (from the Latin for "bridge") is a base for connections between different parts of the brain, including between the cerebellum and the cerebral cortex as well as between the cerebellum and the medulla. It contains the endpoints of several cranial nerves that link the face region and the brain.
- The *medulla oblongata* (or medulla) is the lowest part of the brain stem. It is important for the control of basic, involuntary functions including breathing, digestion, heart rate, and certain reflexes (such as the gag reflex and sneezing). It is directly joined with the spinal cord and

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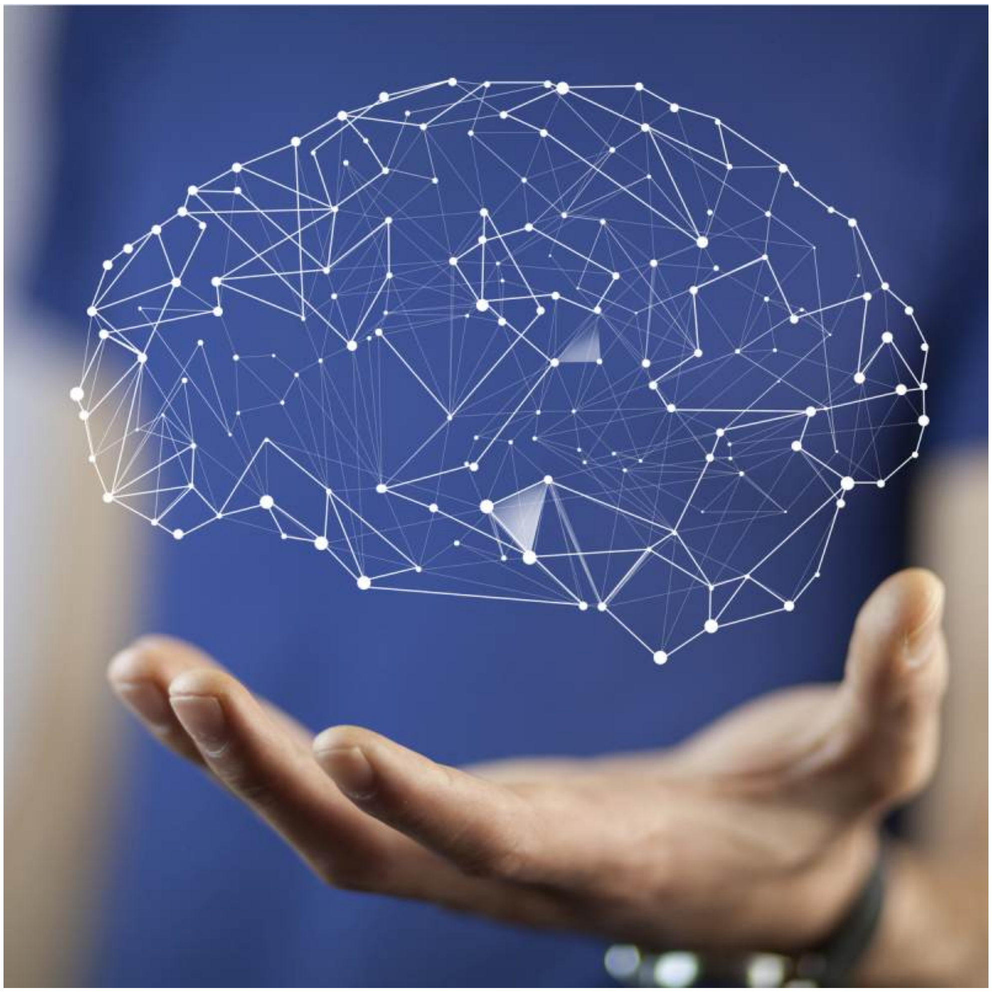

What Is Neuroscience?

Areas of the Brain

How Brain Cells Work

Fields of Study in Neuroscience

The Brain and Common Psychiatric Disorders

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Brain Disease and Injury

How Brain Cells Work

Reviewed by Psychology Today Staff

When a person thinks, speaks, eats, walks, or just sits comfortably with all bodily systems functioning normally, the billions of cells that make up the brain and the rest of the nervous system are hard at work.

The brain is an information-processing organ, and the brain cells that relay and handle all of this information are called neurons. With their special ability to produce and share electrical signals and a capacity to link up in complex webs, neurons are a basic component of the nervous system. The brain contains more than 100 billion of them.

It is through the development, activation, and modification of these neuronal networks that the brain is able to make sense of information about the world, to adapt and learn, and to direct behavior. But neurons are not alone in the brain or elsewhere in the nervous system: Brain cells called glia play various supporting roles to keep the system running smoothly.

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What Is a Neuron?

A neuron or nerve cell is the brain's fundamental building block for the transmission of information. The *cell body* (or soma) is a neuron's center, from which different types of extensions project outward toward other neurons. The branch-like *dendrites* of a neuron receive incoming signals from thousands of other neurons. Outgoing signals are then transmitted along a single extension called the *axon*, which can span long distances (as far as meters) to reach yet more neurons or other types of cell.

Between the axon of a transmitting neuron and the dendrite of a receiving neuron is a gap called the *synapse*—the site at which signals are passed between the brain cells.

The nervous system contains hundreds of different types of neurons that have physical forms specialized for their functions.

- *Sensory neurons* transmit signals from the sense organs about touch, sights, sounds, tastes, and smells.
- *Motor neurons* carry signals from the brain to the body's muscles in order to control movements.
- *Interneurons* convey signals between sensory and motor neurons and among themselves.

How Neurons Connect

Neurons communicate using electrical signals, or *action potentials*. In order for a neuron to transmit its own signal, it must first be sufficiently activated by incoming signals from other neurons via its dendrites. Then, an action potential is

To travel from the axon of one neuron to the dendrite of another neuron, a signal must cross the gap between neurons (the synapse), where it is translated from an electrical signal to a chemical signal. The action potential causes the release of molecules called *neurotransmitters*, which pass from one end of the synapse to the other. Once these molecules cross the synapse, the chemical signal is translated back to an electrical signal that continues toward the next neuron.

The ultimate effect of a signal from one neuron on the next neuron depends on the function of the synapse, which is based on the type of neurotransmitter released. *Excitatory synapses* send signals that encourage the creation of an action potential by the next neuron; *inhibitory synapses* work against it. Each neuron receives signals from both excitatory and inhibitory synapses.

The interconnections between neurons allow for the formation of highly complex information-processing networks. Over time, these connections can grow stronger or weaker depending on the neurons' patterns of activation. Changes in structure and function take place at the level of the synapses between neurons. This capacity for change is called *synaptic plasticity* and it is essential to the brain's ability to learn.

Neurotransmitters

Neurotransmitters, chemical molecules that pass between neurons, are a key part of the system that allows neurons to transmit information. Some types of molecules (excitatory

Key neurotransmitters include the following:

- *Acetylcholine* is important for the control of muscles and the secretion of hormones, as well as for cognitive function.
- *Norepinephrine (noradrenaline)* is key to the function of the sympathetic nervous system and to the “fight-or-flight” response.
- *Dopamine* helps to regulate reward behavior and mood, as well as in the control of body movements.
- *Serotonin* plays a role in the initiation of sleep and in appetite, mood, temperature control, and other functions.
- *Glutamate* is the most common excitatory neurotransmitter in the nervous system; it is involved in a wide variety of functions.
- *GABA (gamma-aminobutyric acid)* is the most widespread inhibitory neurotransmitter; it is also involved in a vast array of functions.

Some neurological and psychiatric disorders have been linked to problems with the activity of one or more neurotransmitters. For example, a loss of dopamine activity is a part of Parkinson’s disease, and Alzheimer’s disease is associated with dysfunction involving acetylcholine.

Many medications act to increase or reduce the activity of neurotransmitters. Selective serotonin reuptake inhibitors (SSRIs), commonly prescribed for depression and other psychiatric disorders, increase levels of serotonin. Anticonvulsants used to treat epilepsy work on GABA. And

Other Brain Cells (Glia)

Although neurons are considered the basic units of the brain and nervous system, they do not do all the work. *Glia* are a non-neuronal category of cells that do not transmit electrical signals but still form an important part of the nervous system. Glial cells provide structural and other kinds of support to neurons and help to ensure that neurons can function properly.

There are multiple types of glial cells with distinct purposes. Major kinds of glia include:

- *Microglia:* provide the central nervous system's immune defense against potential disease threats. They also dispose of leftovers from cell injury and death.
- *Astrocytes*: named for their star-like shape, support the function of neurons in part by helping to maintain an appropriate environment outside of the neurons. They can also directly affect neurotransmitter activity at the synapses between neurons.
- *Oligodendrocytes:* provide structural support to the axons of neurons through a process called *myelination*. They produce a substance called myelin, which makes up an insulating sheath around axons that allow them to carry electrical signals more efficiently.

Next: Fields of Study in Neuroscience

Essential Reads

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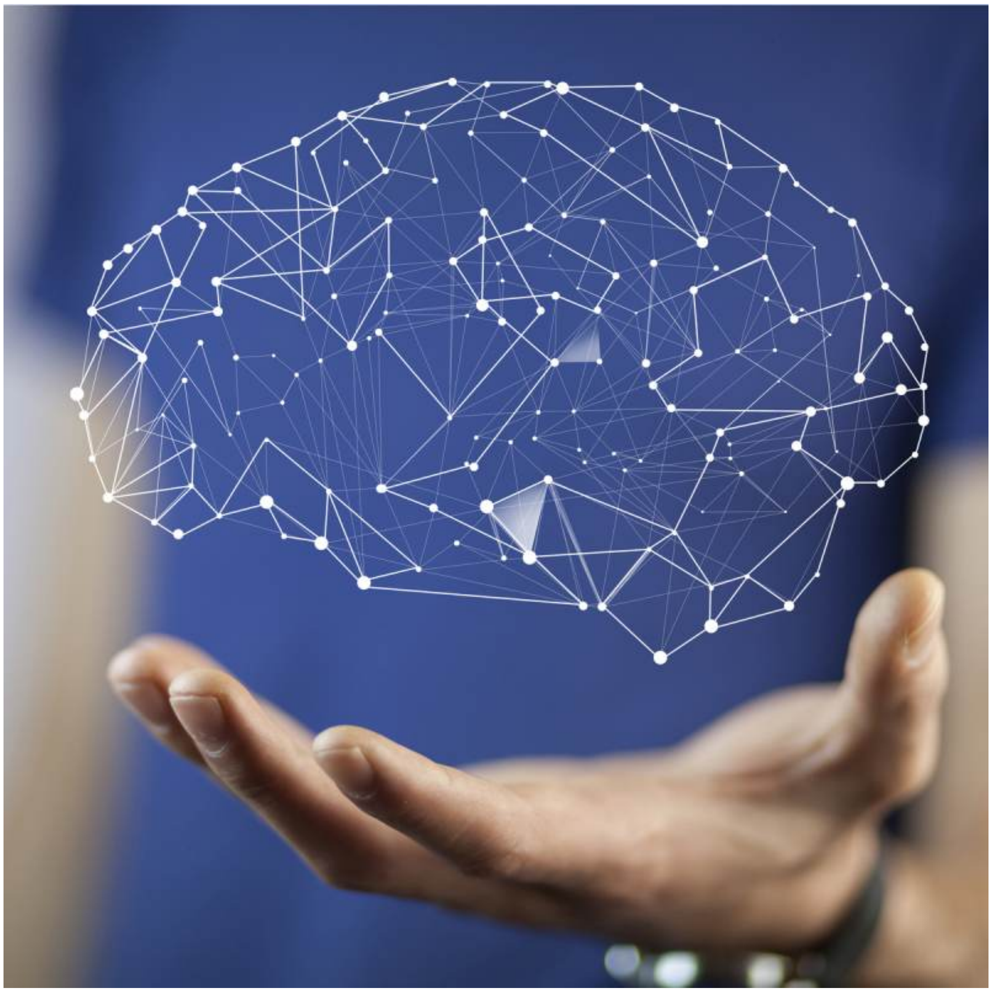

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Brain Disease and Injury

Fields of Study in Neuroscience

Reviewed by Psychology Today Staff

Neuroscience is a vast field of study containing a range of narrower subfields. Each involves a spotlight on the brain and other parts of the nervous system, connecting them to one or more zones of psychology and behavior—from thought processes to social interactions to mental illness.

Given how enmeshed the different aspects of mental life are, there is plenty of overlap between the different domains of neuroscience. Different branches can blend and feed into one another: Scientific research on cognition or emotions can be of value to neuroscientists who study psychiatric disorders, for instance.

Commonly recognized categories such as the ones below offer a sense of the breadth and diversity of neuroscience as an endeavor. Among the other fields of neuroscience are neuroanatomy, cellular and molecular neuroscience, and neurogenetics (the study of the nervous system's genetic basis). Neuroscientists in each field are typically researchers with a doctoral-level degree (such as a Ph.D. or MD).

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- Affective Neuroscience
- Behavioral Neuroscience
- Computational Neuroscience

Cognitive Neuroscience

Cognitive neuroscience investigates the neural mechanisms that underlie thinking and perception. It explores how information processing, which includes learning, remembering, deciding, and problem-solving, is made possible by the brain.

The scope of cognitive neuroscience includes how thought processes unfold at the cellular level—in specific neurons and the connections between them—as well as in the links between mental processes and larger brain regions and systems.

What do cognitive neuroscientists do?

Cognitive neuroscientists explore how the brain gives rise to mental processes and abilities. To do so, they analyze measures of cognition and aspects of individual brains—from structural variation and differences in the function of certain brain areas down to the activity of specific neurons (as they encode, for example, the location of an object in space). Such research provides insights into which parts of the brain, for example, are especially active when someone is

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What are some topics explored in cognitive neuroscience?

Examples of topics in cognitive neuroscience include **the formation of memories at the level of neurons,** how different brain areas collaborate to **produce language ability**, and how the brain's perception of the world **can be biased by factors such as motivation**. Cognitive neuroscientists also focus on areas such as attention, learning, decision-making, and consciousness.

Social Neuroscience

Social neuroscience examines the brain in the context of its connections to other people and the broader social world. It recognizes that humans are a highly social species and that the complexity of social interaction could help explain the evolution of the highly developed human brain.

Research in social neuroscience explores how a physical system gives rise to the kinds of relational processes that have long been observed in social psychology. It also seeks to describe the ways in which the brain and body themselves are affected by aspects of social life, such as social isolation or integration.

What do social neuroscientists do?

cognition and behavior. These include mental processes such as identifying someone as a member of a social group and trying to understand someone else's perspective. Researchers use measurements of biological activity (such as functional activation of particular brain areas) as well as measures of thinking and behavior to investigate the associations between them and how they influence each other.

What are some topics studied in social neuroscience?

Social neuroscience has highlighted the existence of **instantaneous brain activity related to social categorization and prejudice**; **loneliness-related differences** in how the brain represents the self and other people; and differences in **the amygdalae of altruists and psychopaths**. Other phenomena explored in social neuroscience include empathy, learning in social contexts, and group hierarchies.

Clinical Neuroscience

Clinical neuroscience is an area of study that focuses on mental and nervous system disorders. These include disorders studied in psychiatry and clinical psychology, such as depression and anxiety disorders, as well as neurodegenerative conditions such as Alzheimer's disease and multiple sclerosis. A major aim of neuroscientific

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What do clinical neuroscientists do?

Researchers in clinical neuroscience analyze data on brain activation and other aspects of nervous system function and how they relate to various forms of mental illness or dysfunction. This may involve comparing patterns of brain activation in subjects who have clinical levels of dysfunction with those of healthy subjects. A clinical neuroscientist conducts scientific research but does not necessarily treat patients, whereas **specialists in related clinical fields,** such as neurology and neuropsychology, are involved in assessment and treatment.

What are some topics studied in clinical neuroscience?

Neuroscientific methods such as brain imaging have been applied to better understand various psychiatric, neurodevelopmental, and neurological conditions. Neuroscientists have observed, for instance, differences in **how autistic children's brains respond to incoming social information** and in the activity of brain areas related to cognitive control **in people with mood and anxiety disorders.** Such findings could help inform theorizing about what causes symptoms in these conditions and how to target treatments.

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Developmental neuroscience seeks to describe how the brain and nervous system form and change. The study of how age-related changes in the brain correspond with the development of individuals' thinking and perception is called developmental cognitive neuroscience. Developmental neuroscientists explore both typical and atypical trajectories of nervous system development to better understand the bases of normal function and dysfunction.

What do developmental neuroscientists do?

Broadly speaking, developmental neuroscientists research how the anatomical form and functions of nervous systems develop within species, including both invertebrates and vertebrates. More specifically, developmental cognitive neuroscientists are interested in how cognitive processes that change as humans grow up—such as judgment and learning—correspond to aspects of the developing brain. They may, for example, present individuals of different ages, from young children to adults, with cognitive tasks and analyze how the results relate to differences in the activation of certain brain areas during the tasks.

What are some topics studied in developmental neuroscience?

Developmental neuroscientists have connected aspects of brain structure and function to various kinds of thinking and behavior over the lifespan. Neuroscientists have uncovered evidence that, for that less sleep in children is associated with lower volume in various brain areas; and that the brain's structure at age 6 is predictive of brain function and reasoning years later.

Affective Neuroscience

Affective neuroscience explores how the brain produces emotions. It identifies how particular structures, chemicals, and networks in the brain relate to affective states such as anger, fear, pleasure, and desire and how they give rise to complex emotional experiences. Affective neuroscientists use findings from humans as well as non-human animals with analogous emotional responses to better understand the nature of these responses.

What do affective neuroscientists do?

Affective neuroscience involves observing how the activation of certain areas and networks of structures in the brain (as well as differences in brain structure) correspond to various emotional states, which researchers may evoke in the lab. Based on their findings, affective neuroscientists not only identify what is happening in the brain when individuals have particular sorts of emotional experiences, but also theorize and debate about what an emotion actually is —whether, for instance, there are deeply rooted "basic emotion" categories or whether emotions are more complex and consciously constructed.

What are some topics studied in affective neuroscience?

Emotional experiences of all shades, and how the brain produces them, are the territory of affective neuroscientists. They have explored how specific brain chemicals and structures help produce emotional responses—such as **the neurotransmitter dopamine and desire** or **the amygdala and automatic responses to threats** (and less directly, feelings of fear). They have also illustrated that different parts of the brain work together to produce **any particular emotional state.**

Behavioral Neuroscience

Behavioral neuroscience, also called biological psychology, is the study of how the brain and the rest of the nervous system provide the foundation for behavior. It examines the neural basis of capacities such as thinking and perception, learning, emotion, and motivation. As such, behavioral neuroscience overlaps with a number of contemporary fields in neuroscience, such as cognitive neuroscience (focused on thinking and perception) and affective neuroscience (focused on emotions).

What do behavioral neuroscientists do?

Behavioral neuroscientists investigate the links between the body and behavior in humans as well as non-human animals. They use a wide array of

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rats. They also explore the role of factors that interact with the nervous system (such as hormones and drug consumption) in explaining behavior.

What are some topics studied in behavioral neuroscience?

Studies of the neural mechanisms underlying **craving and addiction,** the **formation of memories, fear conditioning** and behavioral responses to threats, and impairments in cognitive abilities are all examples of research that falls under the category of behavioral neuroscience. Many experiments in behavioral neuroscience use models of nonhuman animal behavior as a way to better understand the neural basis of human behavior.

Computational Neuroscience

Computational neuroscience is an area of brain research that makes use of the power of computer modeling and mathematical tools to unpack how the brain works in all of its complexity. The approaches of computational neuroscience, which enable researchers to grapple with vast quantities of data about the nervous system, help them to develop explanations for how events unfold from the levels of chemicals and individual neurons up through the levels of neuronal networks and ultimately behavior and cognition.

Computational neuroscientists develop mathematical models and theories of neural function—accounts of the brain's workings that can be tested based on data from studies of humans and nonhuman animals. Some use computer-based artificial neural networks, which use simplified representations of interconnected neurons, to help understand how information is handled by real networks in the brain. Computational neuroscientists also create models that directly incorporate real-world experimental data.

What are some topics studied in computational neuroscience?

Neuroscientists have used computational methods to explore the processes underlying memory, attention, object recognition, and decision-making, among other cognitive capacities. Models of brain activity have been employed to study, for example, how the prefrontal cortex learns about new situations and how damage to it might impair this ability.

Next: The Brain and Common Psychiatric Disorders

Essential Reads

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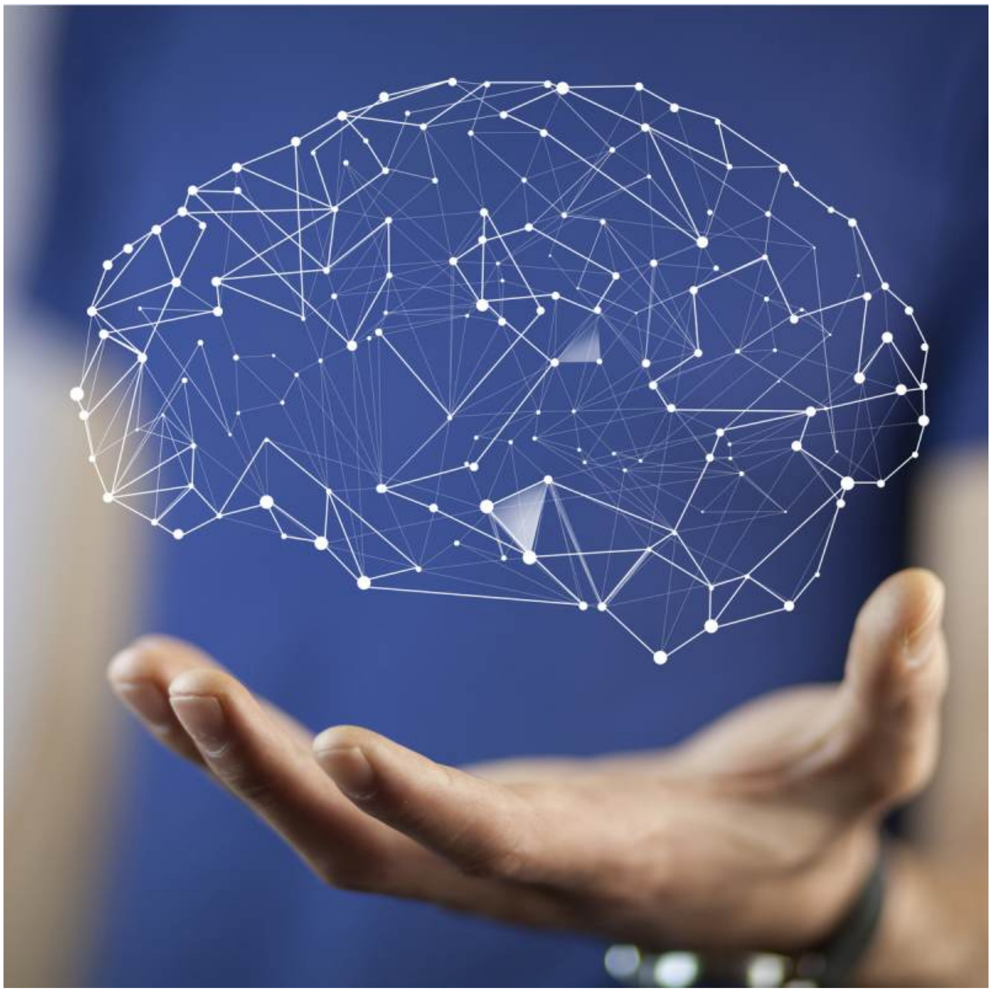

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Brain Disease and Injury

How Brain Activity Is Measured

Reviewed by Psychology Today Staff

How do scientists peer into the brain to better understand what is happening, where, and why? By taking advantage of the brain's electromagnetic properties or by sending radioactive markers into the body, neuroscientists use brain imaging technologies to create detailed pictures of neuronal activity and physiological processes. They can then analyze how the measurements of brain function vary across different situations—as people are prompted to behave, think, or feel in certain ways—or how they vary across individuals. In doing so, researchers gain clues about the brain's workings and their links to mental illness, cognition, perception, emotion, and the many other facets of mental life.

Major types of brain imaging techniques used today include functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and emission computed tomography. Each presents a different sort of neural portrait and each has strengths and limitations. So they are adopted depending on the particular needs of researchers, and sometimes used in combination.

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Functional Magnetic Resonance Imaging (fMRI)

When new findings about the brain are reported based on “brain scans” of human beings, they very frequently involve magnetic resonance imaging (MRI). MRI employs a magnetic field to collect information about the body—it can produce cross-sectional images of various body parts, including the brain. It is the most prominent method in neuroscience for studying the structure of the brain, including differences in the structural characteristics of different people’s brains.

Since the 1990s, scientists have widely used MRI to measure changes in the brain’s *function* as well—a technique called functional MRI (fMRI). This approach equips researchers to analyze the activity levels in specific brain areas from moment to moment, in 3-D, with a relatively high degree of detail.

How does fMRI work?

In MRI, a person lays within a magnetic field produced by a tube-shaped machine. An MRI system makes use of the magnetic properties of atoms within the body to generate detailed, three-dimensional images of the structure of body parts, including the brain. In the case of functional MRI (fMRI), the system produces images of the brain’s function, indicating whether the activity of neurons is increased or decreased in specific parts of the brain, and under what conditions.

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during cognitive tasks, or while perceiving certain kinds of objects, or when a person does nothing in particular. Moreover, different groups of people (such as those diagnosed with a mental disorder and those with no diagnosis) may show differences in how parts of their brains function under certain conditions. In research that uses fMRI, participants are commonly given tasks to do while their brains are scanned to see how particular kinds of mental activity correspond with the activity of neurons in the brain.

What is a BOLD signal?

In fMRI studies, BOLD stands for blood-oxygen-level-dependent. A BOLD signal is a brain imaging signal that is increased or decreased by the level of oxygen in the blood within any given part of the brain. This signal change is possible because the magnetic properties of blood hemoglobin that lacks oxygen differ from those of oxygenated hemoglobin. Since blood-oxygen levels and blood flow are related to the activity of neurons, a BOLD signal is a useful way to gauge changes in neuronal activity in specific brain areas.

What does it mean when part of the brain "lights up" in fMRI?

What are some examples of how fMRI is used

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Electroencephalography (EEG)

Unlike fMRI, which provides an indirect impression of brain cell activity based on blood flow, electroencephalography (EEG) **directly measures electrical activity in the brain.** EEG measurements are made non-invasively through the scalp, and they are relatively limited in terms of what they show about *where* in the brain activity has increased or decreased at any given moment. However, EEG captures electrical changes on the order of milliseconds, which makes it a valuable tool for analyzing brain dynamics over time.

How does EEG work?

In EEG, an array of flat metal electrodes are placed on a person's scalp. These electrodes measure electrical signals that result from the activity of neurons in the cerebral cortex. The readings can provide a picture of voltage change on the scalp over time, including at intervals shorter than one second. EEG measures can be used as indicators of mental processes (such as perception of an image) or states (such as alertness) and can help diagnose conditions such as epilepsy or a sleep disorder. The record of brain activity produced by EEG is called the electroencephalogram.

What is an event-related potential (ERP)?

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activity of the brain, recorded using EEG during a specific time interval, that occurs in response to an event of interest (such as seeing a word or image). The characteristics of event-related potentials observed under different conditions—when a person recognizes different kinds of words, for example—can provide information about the extent to which the brain processes involved are similar or distinct.

What are some examples of how EEG is used in neuroscience?

Emission Computed Tomography

Emission computed tomography takes its name from the emission of radioactive energy by tracers injected into the blood—a signature aspect of this approach to understanding the brain. Given that, emission computed tomography is more invasive than other commonly used forms of brain imaging. Like fMRI, it provides a close look at what is happening within different parts of the brain. And in addition to measuring blood flow in the brain, the method has been used to study the brain's metabolic processes—another way of assessing function.

Two major kinds of emission computed tomography are positron emission tomography (PET) and single-photon emission computed tomography (SPECT). Each uses different types of radioactive isotopes and they are monitored in the brain using different tools.

work?

In emission computed tomography, radioactive atoms are injected into a person's bloodstream and are circulated into the brain. The energy they emit is monitored by external devices, providing information about their concentration in the brain. Based on the type of radioactive tracer used, this process can be used to measure blood flow in the brain or physiological processes such as glucose metabolism or neurotransmitter production. A mathematical model allows the data on radiation to be translated into information about brain processes.

What are some examples of how emission computed tomography is used in neuroscience?

Positron emission tomography (PET) allows for the analysis of physiological processes in ways other forms of brain imaging do not. For example, PET has been used to measure the amount of a protein related to inflammation **in people with untreated depression.** It also enables researchers to detect the release of a neurotransmitter, such as dopamine, in a specific part of the brain (during activities like **listening to music**).

Next: How the Brain Develops

Essential Reads

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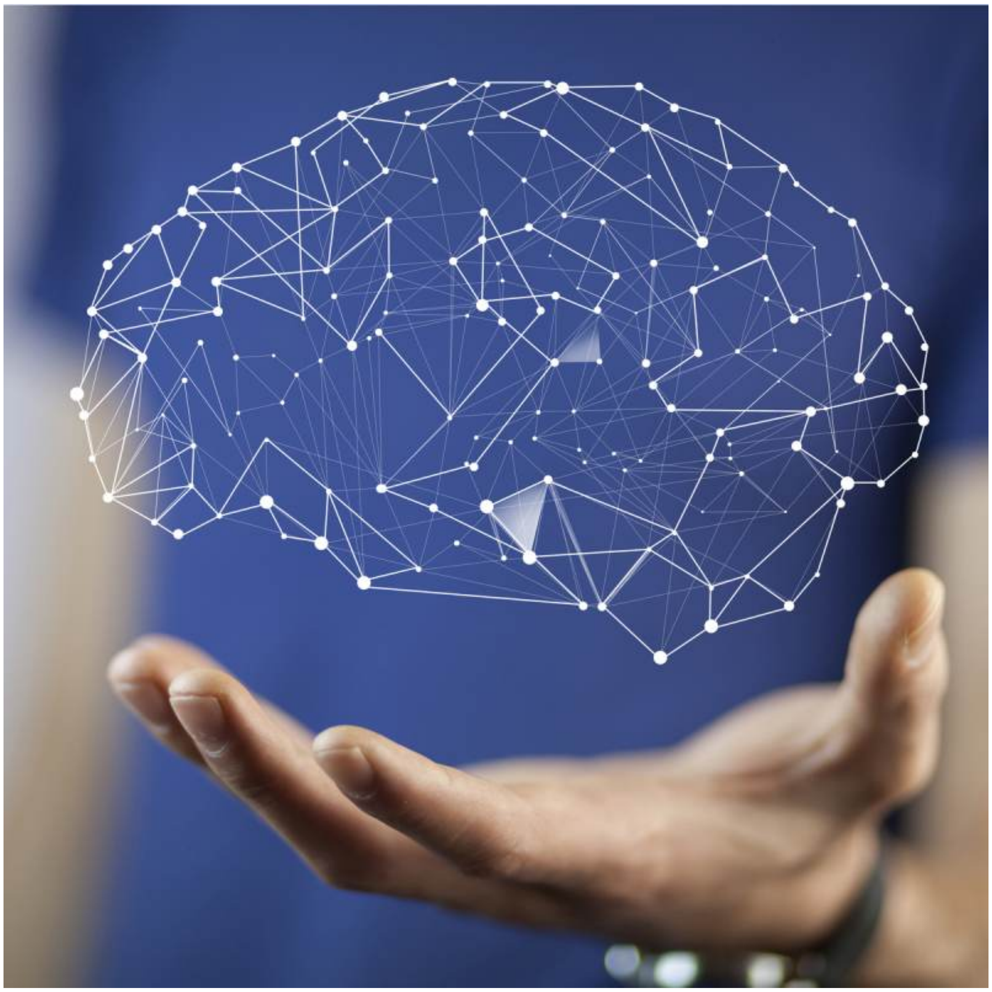

How the Brain Develops

Reviewed by Psychology Today Staff

Before a person is even born, the brain has undergone intense expansion and growth in its complexity. This dramatic development continues into the first years of childhood. After an early boom period, a process of refinement and reduction sets in: childrens' and adolescents' brains respond to their life experiences and the world around them, and the most-used connections between brain cells are strengthened while others are pruned.

While the brain typically reaches a mature state of development in early adulthood, the internal processes that make and remake the brain—the birth of new neurons and death of old ones, the creation and dissipation of neural connections, and more—persist across the lifespan. At most any age, the brain retains the capacity to change.

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Stages of Early Brain Development

happening at different rates in different parts of the brain. But there are some major trends in the construction and remodeling that take place:

- **Rapid growth in the womb:** By the last trimester of pregnancy, a fetus's brain undergoes major increases in size, folding of the brain's brain's outer layer (cortex), and the development of connections between neurons. The brain begins to develop its wrinkled outer surface. Major long-range signaling pathways made up of white matter begin to form several months into gestation and establish themselves by birth.
- **The first years:** Brain volume doubles in the first year of life as connections between neurons grow and other developmental processes unfold—including myelination, which boosts signaling speed between neurons. White matter pathways between spaced-apart regions of the cortex develop. Brain volume continues growing in the second year (an estimated 15 percent).
- **Developmental peaks in childhood:** The brain grows more gradually, with brain size peaking around age 10 for girls and age 14 for boys. The density of synapses in the brain reaches its height and begins to decrease. The areas of the cortex involved in movement and sensation reached maturity earlier than those involved in executive control, such as the prefrontal cortex, which will continue developing into adulthood. Brain areas beneath the cortex (such as those in the limbic system) exhibit relatively little change.
- **A transition period during adolescence:** In teen brains, gray matter in the cortex thins considerably. The number of synapses between neurons in the cortex is scaled

particular susceptibility to outside influence. Studies find that some structures beneath the cortex (such as the amygdala and hippocampus) increase in volume, while others (such as the striatum) are reduced.

- **Approaching maturity in early adulthood:** Grey matter volume in the cortex continues to decrease in early adulthood, leveling out in a person's 20s. White matter volume continues to increase. The prefrontal cortex, involved in planning and other executive functions, is still developing into early adulthood (with changes such as synaptic pruning), later than a number of other brain areas.

Does everyone's brain change in the same way during development?

No. While scientists have observed general trends, there is considerable variation between individuals in terms of when and to what extent aspects of the brain change. Individual differences in brain development can be related to psychological differences. For example, researchers have related measures of intelligence to patterns of cortical thickening and thinning in certain brain areas (including parts of the prefrontal cortex) during childhood and adolescence.

What are some major factors that influence the developing brain?

An individual's genes are a key factor affecting how the brain develops throughout early life. Genes contribute to normal individual variation in brain development,

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syndrome due to their impact on the brain. There are also many known environmental factors that can affect a brain's development. Starting in the womb, adequate nutrition can help ensure healthy brain development, while exposure to certain infections or toxins (such as alcohol) can lead to abnormalities in brain development. In childhood, a safe and nurturing environment facilitates proper growth, while trauma or other severe adverse experiences, as well as exposure to toxic substances such as lead, may negatively impact the brain's development.

How much does the brain grow during childhood?

Neurogenesis and Neuronal Development

Neurogenesis is the process by which new neurons are created. During neurogenesis, stem cells become non-specialized neural progenitor cells, which in turn produce specific kinds of neurons. The bulk of neurogenesis happens during the prenatal period of brain development, though new brain cells are made in certain areas of the brain throughout a person's life.

Following their creation, neurons must *migrate* to their designated areas of the brain, a process in which the structural and support cells called glia play an important role. There, they begin to form connections with other neurons.

and after birth but continues well into adulthood.

The interlinking of neurons during childhood results in many more synapses than remain in the adult brain. The reduction in synapses that happens as a person grows up is thought to be adaptive: Synapses that are activated frequently are strengthened, while those that are not used grow weaker and disappear in a process called *synaptic pruning*. With age, many of a brain's original neurons (possibly more than half) are themselves programmed to die as a normal part of development.

Another key process in neuronal development that begins before birth is *myelination,* in which proteins form layers called myelin sheaths around a neuron's outward extension (axon). Myelin sheaths serve in large part to increase the speed with which electrical signals can be transmitted along the axon and to other neurons.

Continued Change in Adulthood

After a period of substantial adjustment during adolescence and early adulthood, the brain reaches a period of relative stability. But changes in the brain's wiring and structure will continue to some degree throughout a person's life. Even after it has reached its mature state, the brain is plastic, reforming parts of itself in response to an individual's experience of the world.

What is neuroplasticity?

the brain to change in response to experience and the environment. It encompasses a range of changes in the brain's structure, from updates to neuronal networks that reflect learning and the formation of new memories to larger structural adaptations in response to brain injury that help to preserve function. The brain is especially plastic (or changeable) early in life, but plasticity remains an essential quality of the brain throughout adulthood.

Does the brain create new neurons in adulthood?

Yes. While most of the brain's neurons are present at birth, neurogenesis (the creation of new neurons) continues in certain areas of the brain during adulthood. One major brain structure in which neurogenesis occurs in adults is the hippocampus, which plays an important role in learning and memory.

Can you increase neurogenesis in adulthood?

Next: Promoting Brain Health

Essential Reads

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Find a Therapist (City or Zip)

Hormones

Reviewed by Psychology Today Staff

Hormones are a class of signaling molecules that exist in all multi-cell organisms and, in humans, include commonly-known examples like melatonin, testosterone, and cortisol. They influence the health and functioning of the body and brain in a wide variety of ways; on a psychological level, they affect mood, how we behave, who we're attracted to (or not), and more.

Contents

What Are Hormones?

Hormones are molecular substances produced by multicellular organisms that allow different parts of the body—including organs, tissue, and the brain—to signal to and communicate with one another. Broadly, via this signaling, hormones help to regulate much of the organism's physiology and behavior acids, proteins, fatty acids, or can be classified as steroids.

There are dozens of hormones currently known and studied. Those that play a key role in psychological and behavioral functions include:

- **Adrenaline:** A hormone and neurotransmitter secreted primarily by the adrenal glands (near the kidneys) and some neurons in the brain, typically during stressful, exciting, or highly emotional situations. Also known as *epinephrine*, adrenaline increases heart rate and blood flow to the brain and muscles, allowing the body to react quickly and, if necessary, engage in fight-or-flight.
- **Cortisol:** A hormone produced by the adrenal gland that regulates key physical functions such as balancing blood sugar and dampening inflammation; it also helps the body to cope with stress. Cortisol is released regularly throughout the day, peaking early in the morning and dipping overnight. When faced with a stressful situation, the body releases heightened amounts of cortisol to prevent inflammation and increase glucose reserves in the blood; over time, consistently high levels of cortisol can lead to negative physical and emotional effects, such as worsened immunity.
- **Dopamine:** A neurotransmitter and hormone released by the brain during rewarding activities such as eating, sex, and exercise. Known as a "feel-good" hormone, dopamine contributes to feelings of pleasure and motivates humans (and other animals) to seek out rewarding activities. It also plays key roles in learning, attention, and emotion.
- **Estrogen:** A sex hormone that, while present in both sexes, is largely responsible for female sexual

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functioning, and libido (in both sexes). It's also vital to brain health, playing a role in emotional regulation, mood disorders, and memory, particularly as age increases and, in women, menopause starts.

- **Ghrelin:** A hormone produced primarily by the gastrointestinal tract—most notably in the stomach—that helps to regulate appetite. When ghrelin is released, appetite increases. Once the body signals that it's full, ghrelin production slows down; this, along with the increase in the hormone leptin, motivates the person to stop eating. Ghrelin is typically regulated by the body's circadian rhythm, the timing of the last meal, and blood sugar levels; however, it can be disrupted by factors such as stress and poor sleep, which can lead to dysregulated appetite.
- **Growth Hormone:** A hormone that stimulates growth, cell reproduction, and cell repair. Also known as human growth hormone, or HGH, it is produced by the pituitary gland. Though production continues throughout the lifetime, it ramps up during puberty to increase height, boost muscle mass, and promote bone growth and strengthening. HGH also regulates immune functioning, rejuvenates tissues and organs, and is an essential component of collagen production, which boosts skin and hair health.
- **Insulin:** A hormone produced in the pancreas that regulates metabolism and blood sugar. Insulin is released as the body breaks down carbohydrates into glucose, allowing glucose to enter cells where it is used as energy, and carrying excess glucose to the liver. Those who make very little insulin—or who become resistant to its effects,

- **Leptin:** A hormone released by adipose tissue (also known as fat) that works in concert with ghrelin to regulate appetite. When ghrelin is released, hunger increases; leptin is released after food is consumed to signal fullness and discourage additional intake. The body becoming increasingly resistant to leptin's effects over time is a risk factor for obesity; a condition known as leptin receptor deficiency can also promote obesity (and psychological distress) by triggering **near-constant hunger.**

- **Melatonin:** A hormone released primarily by the brain's pineal gland that regulates the body's sleep-wake cycle. **Melatonin** levels rise and fall naturally throughout the day, peaking in the evening (to promote feelings of sleepiness before bedtime) and dipping to their lowest levels in the morning. While the melatonin cycle is strongly influenced by the 24-hour cycle of day and night, it can also be affected by food, physical activity, genetics, and travel.

- **Norepinephrine:** A hormone and neurotransmitter released by the brain and the adrenal glands. Among other functions, **norepinephrine** is critical for the fight-or-flight response. In the brain, it helps regulate attention, alertness, vigilance, and anxiety; in the body, increased levels of norepinephrine speed heart rate, breathing, and blood pressure. Like adrenaline, norepinephrine production increases during stressful or exciting situations.

- **Oxytocin:** A hormone and neurotransmitter produced by the hypothalamus and released by the pituitary gland. Known colloquially as the "love hormone," **oxytocin** plays a key role in socializing, romantic relationships, and parent-child bonding, as it is released during group aggression toward members of the "out-group."

- **Progesterone:** A sex hormone primarily implicated in the female reproductive cycle. Though it's also necessary for male sexual function (as it aids the production of testosterone), progesterone's main roles are to regulate the menstrual cycle, the development of female sex characteristics, such as breasts, and pregnancy. In women, progesterone is produced in the ovaries and works in concert with estrogen.
- **Testosterone:** A sex hormone that is the main driver of male sexual development and libido; it also plays a smaller role in female sexual functioning. Testosterone is often thought of as a driver of aggression, and though it does play a role in aggression to some degree, it also affects language skills, cognitive functioning, growth, and physical health. Testosterone is produced in the testicles of males and in the ovaries of females.
- **Vasopressin:** A hormone produced by the hypothalamus and released by the pituitary gland that has several physiological functions, including the regulation of blood pressure and circulatory function. Recent research (most notably in animals) suggests that vasopressin may also play a role in disorders like autism, as well as work in concert with oxytocin to promote social bonding.

What is the endocrine system?

The endocrine system is a network of glands and other structures throughout the body that synthesize and secrete hormones. Endocrine glands release hormones into the circulatory system, where they

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aspects of mental and physical health. Primary structures in the endocrine system include the adrenal gland, the pineal gland, the pituitary gland, the ovaries and testes, the pancreas, and the hypothalamus.

What are the main functions of hormones?

Hormones' main function is to communicate between organs and tissues throughout the body to regulate physiology and behavior. This can include regulating physical functions such as respiration, digestion, lactation, or growth; hormones also have a hand in behavioral activities such as sleep, mood, movement, and sexual function.

How many hormones are in the human body?

What's the difference between hormones and neurotransmitters?

Can something be both a hormone and a neurotransmitter?

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Hormones and Everyday Life

Hormones are silent drivers of behavior and personality, and their molecular fingerprints are on countless day-to-day activities and occurrences, ranging from attraction to appetite. Decades of biological and psychological research have found that certain hormones are associated with specific traits, emotions, and behaviors, but in reality, the human endocrine system is so complex that the same chemical may behave radically differently from person to person. Hormones affect people in different ways throughout their lives, and hormone levels can spike dramatically at physical or emotional transitions. New parents are slammed with a rush of hormones, for instance, as are rookie players on sports teams and tweens entering middle school.

How do hormones affect behavior?

Hormones affect behavior in myriad, complex ways that are often dependent on the situation. Testosterone, for example, has been linked to aggressive or antisocial behavior and competitiveness in situations that call for it. On the other hand, in non-competitive situations, **testosterone has been**

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Do hormones play a role in personality?

Hormones have a hand in aggression, dominance, risk-aversion, warmth, generosity, and other elements that determine how someone behaves, thinks, and feels. Hormones' connection to personality models such as the Big 5 is less clear, though some studies have found, for instance, that higher levels of testosterone and dopamine are both linked to greater extraversion.

What role do hormones play in mood?

How does cortisol affect sleep?

Can you lower cortisol naturally?

How does melatonin influence sleep?

How do hormones affect hunger?

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When laypeople think of hormones, the sex hormones—most notably testosterone and estrogen—are often the first ones that come to mind, for unsurprising reasons. The sex hormones are critical for sexual function, libido, and reproduction—areas of great interest to many adults—and they also have a hand in romantic bonds and long-term relationships. Despite their renown, however, the sex hormones are more complex than is widely understood. And while they certainly influence sexual behavior, they are not the sole driver of an individual's sexual and romantic satisfaction.

Do hormones change women's taste in men?

Past studies have found that during ovulation (when levels of hormones like estrogen increase), heterosexual women are more attracted to men with "masculine" faces (strong jaw, heavy brow, etc). However, newer and more rigorously-designed research finds little correlation between ovulation and women's mate preferences, suggesting that the role of hormones in women's sexual taste may be overstated.

Do hormones make women desire sex more?

Research has found that heterosexual women do appear to be more interested in sex during ovulation —both with a long-term partner and with men outside of the pair. The evolutionary reasons for this make

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Do hormones influence men's taste in women?

Can hormones affect romantic relationships?

Can hormones increase or decrease my desire for sex?

When Hormones Go Awry

Since hormones serve such a wide range of functions in the mind and body, they can trigger unpleasant physical or psychological symptoms—or even medical conditions—when they fall out of balance. Hormonal imbalances or endocrine disorders are not always easy to identify, and may require medical tests to properly diagnose. But while endocrine disorders may necessitate formal medical treatment, certain hormonal imbalances may be treated with lifestyle changes or by addressing symptoms directly. In some cases, however, supplemental hormones may be given to correct imbalances.

Ultimately, hormones—even the same hormone—can serve a wide range of functions, from slowing growth to stimulating it, and from activating the immune system to inhibiting it. There is little in the human body that hormones don't play a role in;

What is a hormonal imbalance?

A hormonal imbalance is said to occur when there is too much or too little of a particular hormone in the bloodstream. It may trigger negative physical or psychological symptoms, such as mood instability or depression, weight gain or weight loss, disrupted menstrual cycles, frequent fatigue, muscle pain, or a wide range of other symptoms.

How are hormonal imbalances managed and treated?

Individuals who suspect a hormonal imbalance should consult with a medical professional to measure hormone levels and test for other possible causes of negative symptoms. If a hormonal imbalance is identified, treatment may include hormonal supplement therapy or hormonal-blocking medications (such as anti-androgen medications). Lifestyle changes, such as losing weight or eating a healthier diet, may also help the body better regulate its hormones.

What are some common endocrine disorders?

How are hormones used in medical treatment?

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How are hormones used in mental health care?

How does excess cortisol affect physical health?

What is psychosocial short stature?

Why am I so hungry all the time?

Hormone Myths and Facts

Testosterone is what makes men so manly. Oxytocin is the "love hormone." And cortisol is responsible for crazy amounts of stress, right?

Not exactly. In fact, most of what the average person understands about the role of hormones is a heavily simplified version of how they actually function in the human body. In reality, testosterone is necessary for both males and females. Oxytocin can stimulate pleasant feelings and boost close bonds, but it has also been linked to feelings of social prejudice. And cortisol helps the body deal with stressful situations; it's only when there's too much of it present for too long that it starts to have negative effects.

Is oxytocin really the "love hormone"?

breastfeeding, and other activities that promote close bonds between romantic partners, parents and children, or tight social groups—hence it's reputation as a "love hormone." But it can also foster negative behavior. In human and animal studies, stimulating **oxytocin receptors in the brain was shown to trigger aggression**, an "us-versus-them" mentality, social avoidance, or dishonesty—all directed toward out-group members. Such behavior is likely to prioritize the well-being of the "in-group," thus further fostering a family or tribe's social bonds.

Do women need testosterone?

Yes. Despite testosterone's better-known association with male behavior and development, **testosterone is actually important for both sexes—particularly when it comes to sexuality**. Studies show that women with diminished testosterone (produced in the ovaries and the adrenal gland) show markedly decreased libido; in some cases, treating such women with testosterone may help overcome a low sex drive.

Is estrogen bad for men?

Does cortisol cause stress?

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Is “adrenal fatigue” real?

Can you be addicted to adrenaline?

Can adrenaline give you superhuman strength?

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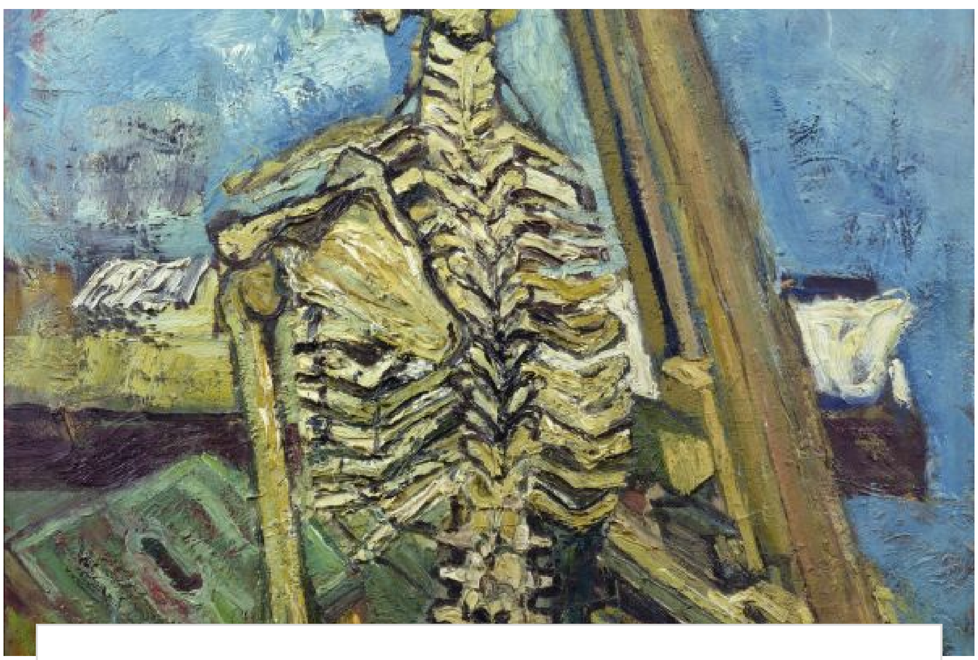
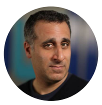


Melatonin and Osteoporosis

Osteoporosis is a potentially debilitating disease that affects millions worldwide. Current treatments leave much to be desired. Could the natural hormone melatonin have any role?

What Is a Supercomputer and How Does It Work?

What is a supercomputer? We go inside Argonne National Laboratory to find out.



Written by Mike Thomas

Image: Shutterstock

UPDATED BY
Rose Velazquez | Jul 08, 2022

WHAT IS A SUPERCOMPUTER?

Supercomputers divide problems or tasks into multiple parts that are worked on simultaneously by thousands of processors, making them dramatically faster than the everyday laptop or desktop computer.

The facility, located about 25 miles from Chicago, is home to supercomputing resources housed in a 25,000-square-foot data center with low ceilings and a white tile floor. With all of that equipment whirring away, it is not a quiet place. Nearest the computers, visitors must speak-shout in order to be heard above a constant loud hum.

With support from the U.S. Department of Energy, Argonne's work bolsters groundbreaking research.

This kind of state-of-the-art technology is the backbone of "changing the way scientists explore the evolution of our universe, biological systems, weather forecasting and even renewable energy."

Theta is one of two supercomputers at the Argonne National Laboratory. | Photo: Argonne National Laboratory

What Is a Supercomputer?

Supercomputers have for years employed a technique called "massively parallel processing," whereby problems are split into parts and worked on simultaneously by thousands of processors as opposed to the one-at-a-time "serial" method of, say, your regular old MacBook Air. Here's another good analogy, this one from Explainthatstuff.com:

> *It's like arriving at a checkout with a cart full of items, but then splitting your items up between several different friends. Each friend can go through a separate checkout with a few of the items and pay separately. Once you've all paid, you can get together again, load up the cart, and leave. The more items there are and the more friends you have, the faster it gets to do things by parallel processing — at least, in theory.*

"You have to use parallel computing to really take advantage of the power of the supercomputer," said Caitlin Joann Ross, who did a six-month residency at Argonne

"Debugging" issues, she told Built In in 2019, are the chief cause of that frustration. Calculations that might run smoothly using four processors, for instance, could break down if a fifth is added.

"If you've got everything running perfectly," Ross said, "then whatever it is that you're running is running a lot faster than it might on a computer with fewer processors or a single processor. There are certain computations that might take weeks or months to run on your laptop, but if you can parallelize it efficiently to run on a supercomputer, it might take a day."

Another area of Ross' work involved simulating supercomputers themselves — more specifically, the networks used on supercomputers. Data from applications that run on actual supercomputers is fed into a simulator, which allows various functions to be tested without taking the whole system offline. Something called "communications interference" is one of those functions.

"In real life, different users will submit jobs to the supercomputer, which will do some type of scheduling to determine when those jobs run," Ross said. "There will typically be multiple different jobs running on the supercomputer at the same time. They use different compute nodes, but they share the network resources. So the communication from someone else's job may slow down your job, based on the way data is routed through the network. With our simulations, we can explore these types of situations and test out things such as other routing protocols that could help improve the performance of the network.

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14 High Performance Computing Applications & Examples

A brain in a supercomputer | Henry Markram

Israeli neuroscientist Henry Markham talks about building a model of the human brain. | Video: TED

What Do Supercomputers Do?

Supercomputing's chief contribution to science has been its ever-improving ability to simulate reality. This capability helps humans make better performance predictions and design better products in fields from manufacturing and oil to pharmaceutical and military. Jack Dongarra, one of the world's foremost supercomputing experts, likened that ability to having a crystal ball.

"Say I want to understand what happens when two galaxies collide," Dongarra said. "I can't really do that experiment. I can't take two galaxies and collide them. So I have to build a model and run it on a computer. Or in the old days, when they designed a car, they would take that car and crash it into a wall to see how well it stood up to the impact. Well, that's pretty expensive and time consuming. Today, we don't do that very often; we build a computer model with all the physics [calculations] and crash it into a simulated wall to understand where the weak points are."

WHAT ARE SUPERCOMPUTERS USED FOR

Supercomputers are used to simulate various potential outcomes very quickly. These blazing-fast computers are used by government organizations and corporations for everything from finding new oil repositories to developing new life-saving medicines.

projected value of more than $50 billion by 2028.

“Industry gets it. They are investing in high performance computers to be more competitive and to gain an edge on their competition. And they feel that money is well spent. They are investing in these things to help drive their products and innovation, their bottom line, their productivity and their profitability,” Dongarra, who spent an early portion of his career at Argonne, said.

But it’s bigger than just ROI.

“Traditional commercial enterprise can see return on investment calculations of, ’It saved us this amount of physical testing costs,’ or, ’We were able to get to market quicker and therefore gain extra income,'" Andrew Jones, a UK-based high performance computing consultant, said. "But a basic ROI calculation for HPC is not necessarily where the value comes from. If you ask an oil company, it doesn’t come down to being able to find oil 30 percent cheaper. It comes down to being able to find oil or not."

Companies that use supercomputing to make big-picture improvements and increase efficiency have an edge on their competitors.

“And the same is true for a lot of the science," Jones added. "You’re not necessarily looking for a return on investment in a specific sense, you’re looking for general capability — whether our researchers are able to do science that is internationally competitive or not.”

things that go boom. Sophisticated simulations have eliminated the need for real-world testing: “They don’t develop something, go out into the desert, drill a hole and see if it works," Dongarra said of a practice that stopped decades ago. "They simulate that [weapon] design on a supercomputer.”

In a major upgrade, the Air Force Research Lab — one of five U.S. Department of Defense supercomputing centers — installed four sharable supercomputers on which the entire U.S. military can conduct classified research.

Supercomputers also impact artificial intelligence. They turbo-charge the machine learning processes to produce quicker results from more data (as in this climate science research).

“To be engaged in supercomputing is to believe in the power of the algorithm to distill valuable, meaningful information from the repeated implementation of procedural logic,” Scott Fulton III wrote for ZDNet. “At the foundation of supercomputing are two ideals: one that professes that today’s machine will eventually reach a new and extraordinarily valuable solution, followed by a second and more subtle notion that today’s machine is a prototype for tomorrow’s.”

While Dongarra thinks supercomputers will shape the future of AI, exactly *how* that will happen isn’t entirely foreseeable.

“To some extent, the computers that are being developed today will be used for applications that need artificial intelligence, deep learning and neuro-networking computations,” Dongarra said. “It’s going to be a tool that aids scientists in understanding and solving some of the most challenging problems we have.”

Source: Argonne National Laboratory's Flickr page

SUPERCOMPUTERS

An interactive chronology of major events in the evolution of supercomputing.

DEBUT OF FIRST SUPERCOMPUTER, THE CDC 6600

How Fast Is a Supercomputer?

Because faster computers allow researchers to more quickly gain greater insight into whatever they're working on, there's an ever-mounting need — or at least a strong desire — for speed. Dongarra called it "a never-ending quest," and sustained exascale capabilities are the pinnacle of that quest so far. Still, it is one of many.

The Department of Energy labeled exascale computing "the next milestone in the development of supercomputers" — speedier than the most powerful supercomputers to date.

Scores more supercomputers with sometimes epic-sounding names (Titan, Excalibur) operate in 31 other countries around the world. Manufactured by 36 different vendors, they're driven by 23 generations of processors and serve a variety of industries as well as government functions ranging from scientific research to national defense.

Those stats are from the website TOP500.org. Co-founded by Dongarra, it has kept tabs on all things supercomputing since 1993, and uses his LINPACK Benchmark (which estimates how fast a computer is likely to run one program or many) to measure performances.

10 FASTEST SUPERCOMPUTERS IN THE WORLD (SOURCE: TOP500)

6. Sunway TaihuLight (China)
7. Perlmutter (U.S.)
8. Selene (U.S.)
9. Tianhe-2A (China)
10. Adastra (France)

“The race between countries is partly real and partly artificial,” Jones said. “So, for example, if you are the director of a U.S. national lab and you’re trying to secure funding for your next HPC machine, it’s a very good argument to say that, ’Well, China’s got one that’s ten times bigger, so we need to catch up.’”

Government officials also enjoy a bit of supercomputing swagger, talking up their gargantuan processing power as the key to societal improvement — and, of course, evidence of their country’s total awesomeness.

“It’s basic economic competitiveness,” Jones said. “If you drop so far off that your nation is no longer economically competitive with other comparably sized nations, then that leads to a whole load of other political and security issues to deal with.”

The extremely powerful and fast Aurora supercomputer is expected to make its way to Argonne National Laboratory sometime in 2021. | Photo: Argonne National Laboratory

Understanding Exascale Computing Speed

The world's first exascale supercomputer, Frontier, made its debut at Tennessee's Oak Ridge National Laboratory — another U.S. Department of Energy partner — in May 2022. The speediest of all supercomputers, Frontier earned the distinction of "the first true exascale machine."

Frontier is among three exascale supercomputers receiving a chunk of a $1.8 billion investment from the U.S. Department of Energy. These supercomputers are capable of performing a billion billion (aka quintillion) calculations per second, putting them in a position to carry out minor computational miracles.

Installation of another of those three exascale supercomputers dubbed Aurora also began in May 2022 at Argonne. In preparation for its arrival, the computing facility undertook a major expansion.

Measured as 1018 FLOPS (which stands for floating point operations per second), an exascale system is six-billion-times faster than its long ago predecessor, the groundbreaking Cray-1 from 1964. Put in more tangible terms courtesy of Design News, space. “With Aurora, we can take those to the next level. Right now, we can do simulations of the evolution of the universe. But with Aurora, we’ll be able to do that in a more realistic manner, with more physics and more chemistry added to them. We’re starting to do things like try to understand how different drugs interact with each other and, say, some form of cancer. We can do that on a small scale now. We’ll be able to do that on an even larger scale with Aurora.”

At a March 2019 press conference announcing Aurora’s installation, Argonne associate laboratory director Rick Stevens explained that the system will handle high performance computing applications as well as analysis of streaming data that’s generated by accelerators, detectors, telescopes and other research equipment.

When the “father of supercomputing,” Seymour Cray, first began building his revolutionary machines in the 1960s, such a rippling display of computational muscle was incomprehensible. More than a half century later, it’s slowly becoming the norm — and will someday seem as quaint as an Atari 2600 does now.

FURTHER READING

Quantum Computing: Everything You Need to Know

The Future of Supercomputing

Your current smartphone is as fast as a supercomputer was in 1994 — one that had 1,000 processors and did nuclear simulations. (Is there an app for that?) It goes to reason, then, that the smartphone you have in a quarter-century could theoretically be on the level of Aurora. The point is, this stuff is speedy — and it’s only getting speedier.

“When I started in computing, we were doing megaflops — 106 operations. So things change. There are changes in architecture, changes in software and applications that

A TOP500.com story paints a picture of things to come in which simulations take a back seat.

"Machine learning, in particular, could come to dominate most computing domains, including HPC (and even data analytics) over the next decade-and-a-half," author Michael Feldman wrote. "While today it's mostly used as an auxiliary step in traditional scientific computing – for both pre-processing and post-processing simulations, in some cases, like drug discovery, it could conceivably replace simulations altogether."

Whatever form supercomputers take, Argonne's Papka said they'll become increasingly powerful and transformative, affecting everything from the pedestrian to the profound — from the design of more efficient electric car batteries to, just maybe, the eradication of long-battled diseases like cancer. Or so he hopes.

"The betterment of mankind," Papka said, "is a noble goal to have."

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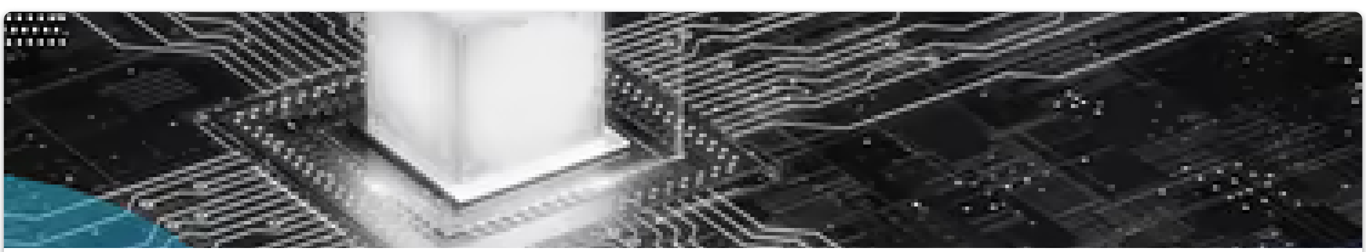

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Artificial Intelligence (AI)

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3 June 2020

Artificial intelligence

Artificial Intelligence (AI)

Artificial intelligence leverages computers and machines to mimic the problem-solving and decision-making capabilities of the human mind.

What is artificial intelligence?

KB) (link resides outside IBM)): "It is the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable."

However, decades before this definition, the artificial intelligence conversation began with Alan Turing's 1950 work "Computing Machinery and Intelligence" (PDF, 89.8 KB) (link resides outside of IBM). In this paper, Turing, often referred to as the "father of computer science", asks the following question: "Can machines think?" From there, he offers a test, now famously known as the "Turing Test", where a human interrogator would try to distinguish between a computer and human text response. While this test has undergone much scrutiny since its publication, it remains an important part of the history of AI.

One of the leading AI textbooks is Artificial Intelligence: A Modern Approach (link resides outside IBM, [PDF, 20.9 MB]), by Stuart Russell and Peter Norvig. In the book, they delve into four potential goals or definitions of AI, which differentiate computer systems as follows:

Human approach:

- Systems that think like humans
- Systems that act like humans

Ideal approach:

- Systems that think rationally
- Systems that act rationally

Alan Turing's definition would have fallen under the category of "systems that act like humans."

In its simplest form, artificial intelligence is a field that combines computer science and robust datasets to enable problem-solving. Expert systems, an early successful application of AI, aimed to copy a human's decision-making process. In the early days, it was time-consuming to extract and codify the human's knowledge.

comprised of AI algorithms that typically make predictions or classifications based on input data. Machine learning has improved the quality of some expert systems, and made it easier to create them.

Today, AI plays an often invisible role in everyday life, powering search engines, product recommendations, and speech recognition systems.

There is a lot of hype about AI development, which is to be expected of any emerging technology. As noted in Gartner's hype cycle (link resides outside IBM), product innovations like self-driving cars and personal assistants follow "a typical progression of innovation, from overenthusiasm through a period of disillusionment to an eventual understanding of the innovation's relevance and role in a market or domain." As Lex Fridman notes (01:08:15) (link resides outside IBM) in his 2019 MIT lecture, we are at the peak of inflated expectations, approaching the trough of disillusionment.

As conversations continue around AI ethics, we can see the initial glimpses of the trough of disillusionment. Read more about where IBM stands on AI ethics here.

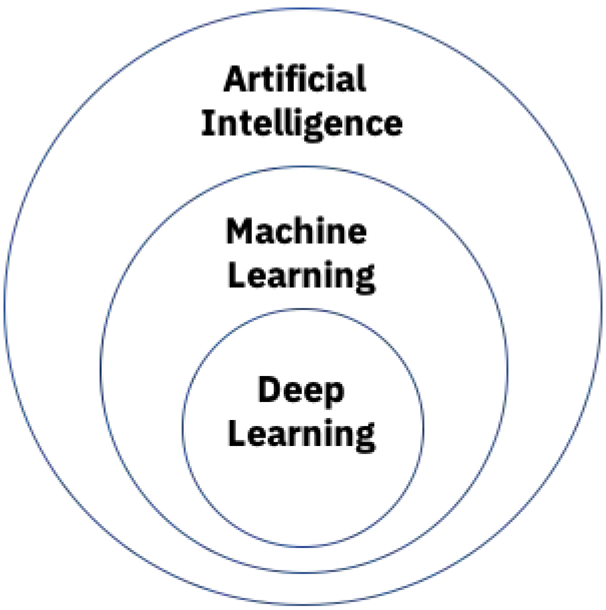
Types of artificial intelligence—weak AI vs. strong AI

Weak AI—also called Narrow AI or Artificial Narrow Intelligence (ANI)—is AI trained to perform specific tasks. Weak AI drives most of the AI that surrounds us today. 'Narrow' might be a more accurate descriptor for this type of AI as it is anything but weak; it enables some powerful applications, such as Apple's Siri, Amazon's Alexa, IBM Watson, and autonomous vehicles.

Strong AI is made up of Artificial General Intelligence (AGI) and Artificial Super Intelligence (ASI). Artificial General Intelligence (AGI), or general AI, is a theoretical form of AI where a machine would have an intelligence equal to humans; it would have a self-aware consciousness that has the ability to solve problems, learn, and plan for the future. Artificial Super Intelligence (ASI)—also known as superintelligence—would surpass the intelligence and ability of the human brain. While strong AI is still entirely theoretical with no practical examples in use today, , *2001: A Space Odyssey.*

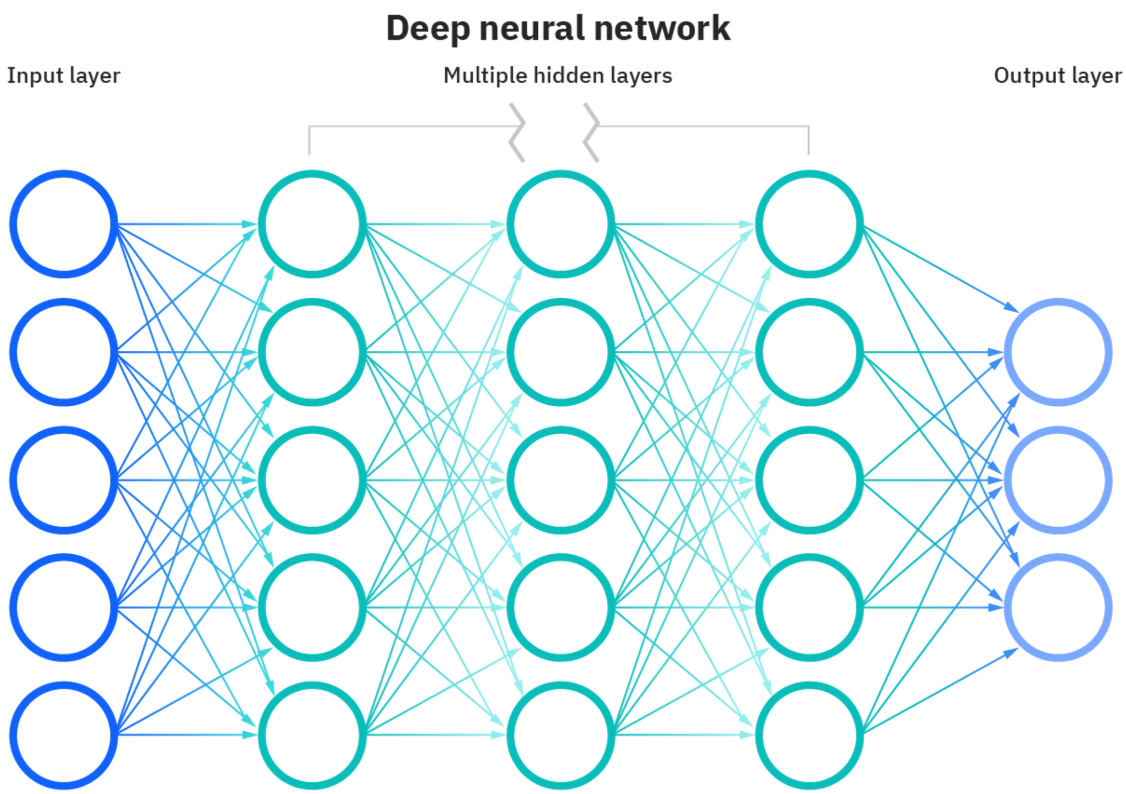
Deep learning vs. machine learning

Since deep learning and machine learning tend to be used interchangeably, it's worth noting the nuances between the two. As mentioned above, both deep learning and machine learning are sub-fields of artificial intelligence, and deep learning is actually a sub-field of machine learning.



The way in which deep learning and machine learning differ is in how each algorithm learns. "Deep" machine learning can use labeled datasets, also known as supervised learning, to inform its algorithm, but it doesn't necessarily require a labeled dataset. Deep learning can ingest unstructured data in its raw form (e.g. text, images), and it can automatically determine the set of features which distinguish different categories of data from one another. This eliminates some of the human intervention required and enables the use of larger data sets. You can think of deep learning as "scalable machine learning" as Lex Fridman notes in the same MIT lecture from above. Classical, or "non-deep", machine learning is more dependent on human intervention to learn. Human experts determine the set of features to understand the differences between data inputs, usually requiring more structured data to learn.

including the input and output layers. This is generally represented using the following diagram:



The rise of deep learning has been one of the most significant breakthroughs in AI in recent years, because it has reduced the manual effort involved in building AI systems. Deep learning was in part enabled by big data and cloud architectures, making it possible to access huge amounts of data and processing power for training AI solutions.

Artificial intelligence applications

There are numerous, real-world applications of AI systems today. Below are some of the most common examples:

- **Speech recognition:** It is also known as automatic speech recognition (ASR), computer speech recognition, or speech-to-text, and it is a capability which uses natural language processing (NLP) to translate human speech into a

- **Customer service:** Online chatbots are replacing human agents along the customer journey, changing the way we think about customer engagement across websites and social media platforms. Chatbots answer frequently asked questions (FAQs) about topics such as shipping, or provide personalized advice, cross-selling products or suggesting sizes for users. Examples include virtual agents on e-commerce sites; messaging bots, using Slack and Facebook Messenger; and tasks usually done by virtual assistants and voice assistants.

- **Computer vision:** This AI technology enables computers to derive meaningful information from digital images, videos, and other visual inputs, and then take the appropriate action. Powered by convolutional neural networks, computer vision has applications in photo tagging on social media, radiology imaging in healthcare, and self-driving cars within the automotive industry.

- **Recommendation engines:** Using past consumption behavior data, AI algorithms can help to discover data trends that can be used to develop more effective cross-selling strategies. This approach is used by online retailers to make relevant product recommendations to customers during the checkout process.

- **Automated stock trading:** Designed to optimize stock portfolios, AI-driven high-frequency trading platforms make thousands or even millions of trades per day without human intervention.

- **Fraud detection:** Banks and other financial institutions can use machine learning to spot suspicious transactions. Supervised learning can train a model using information about known fraudulent transactions. Anomaly detection can identify transactions that look atypical and deserve further investigation.

History of artificial intelligence: Key dates and names

Since the advent of electronic computing, some important events and milestones i the evolution of artificial intelligence include the following:

—proposes to answer the question 'can machines think?' and introduces the Turing Test to determine if a computer can demonstrate the same intelligence (or the results of the same intelligence) as a human. The value of the Turing Test has been debated ever since.

- **1956:** John McCarthy coins the term 'artificial intelligence' at the first-ever AI conference at Dartmouth College. (McCarthy would go on to invent the Lisp language.) Later that year, Allen Newell, J.C. Shaw, and Herbert Simon create the Logic Theorist, the first-ever running AI software program.

- **1967:** Frank Rosenblatt builds the Mark 1 Perceptron, the first computer based on a neural network that 'learned' though trial and error. Just a year later, Marvin Minsky and Seymour Papert publish a book titled *Perceptrons*, which becomes both the landmark work on neural networks and, at least for a while, an argument against future neural network research projects.

- **1973:** The PROLOG programming language is launched, based on a theorem-proving technique called resolution. PROLOG enables researchers to encapsulate and logically query knowledge, and becomes popular in the AI community.

- **1980s:** Neural networks, which use a backpropagation algorithm to train themselves, become widely used in AI applications.

- **1997:** IBM's Deep Blue beats then world champion Garry Kasparov in a chess match (and rematch).

- **2011:** IBM Watson beats champions Ken Jennings and Brad Rutter at *Jeopardy!*

- **2015:** Baidu's Minwa supercomputer uses a special kind of deep neural network called a convolutional neural network to identify and categorize images with a higher rate of accuracy than the average human.

- **2016:** DeepMind's AlphaGo program, powered by a deep neural network, beats Lee Sodol, the world champion Go player, in a five-game match. The victory is significant given the huge number of possible moves as the game progresses (over 14.5 trillion after just four moves!). Google bought DeepMind for a reported USD 400 million in 2014.

The future of AI

While Artificial General Intelligence remains a long way off, more and more businesses will adopt AI in the short term to solve specific challenges. Gartner predicts (link resides outside IBM) that 50% of enterprises will have platforms to operationalize AI by 2025 (a sharp increase from 10% in 2020).

Knowledge graphs are an emerging technology within AI. They can encapsulate associations between pieces of information and drive upsell strategies, recommendation engines, and personalized medicine. Natural language processing (NLP) applications are also expected to increase in sophistication, enabling more intuitive interactions between humans and machines.

Artificial intelligence and IBM Cloud

IBM has been a leader in advancing AI-driven technologies for enterprises and has pioneered the future of machine learning systems for multiple industries. Based on decades of AI research, years of experience working with organizations of all sizes, and on learnings from over 30,000 IBM Watson engagements, IBM has developed the AI Ladder for successful artificial intelligence deployments:

- **Collect:** Simplifying data collection and accessibility.
- **Organize:** Creating a business-ready analytics foundation.
- **Analyze:** Building scalable and trustworthy AI-driven systems.
- **Infuse:** Integrating and optimizing systems across an entire business framework.
- **Modernize:** Bringing your AI applications and systems to the cloud.

IBM Watson gives enterprises the AI tools they need to transform their business systems and workflows, while significantly improving automation and efficiency. Fc

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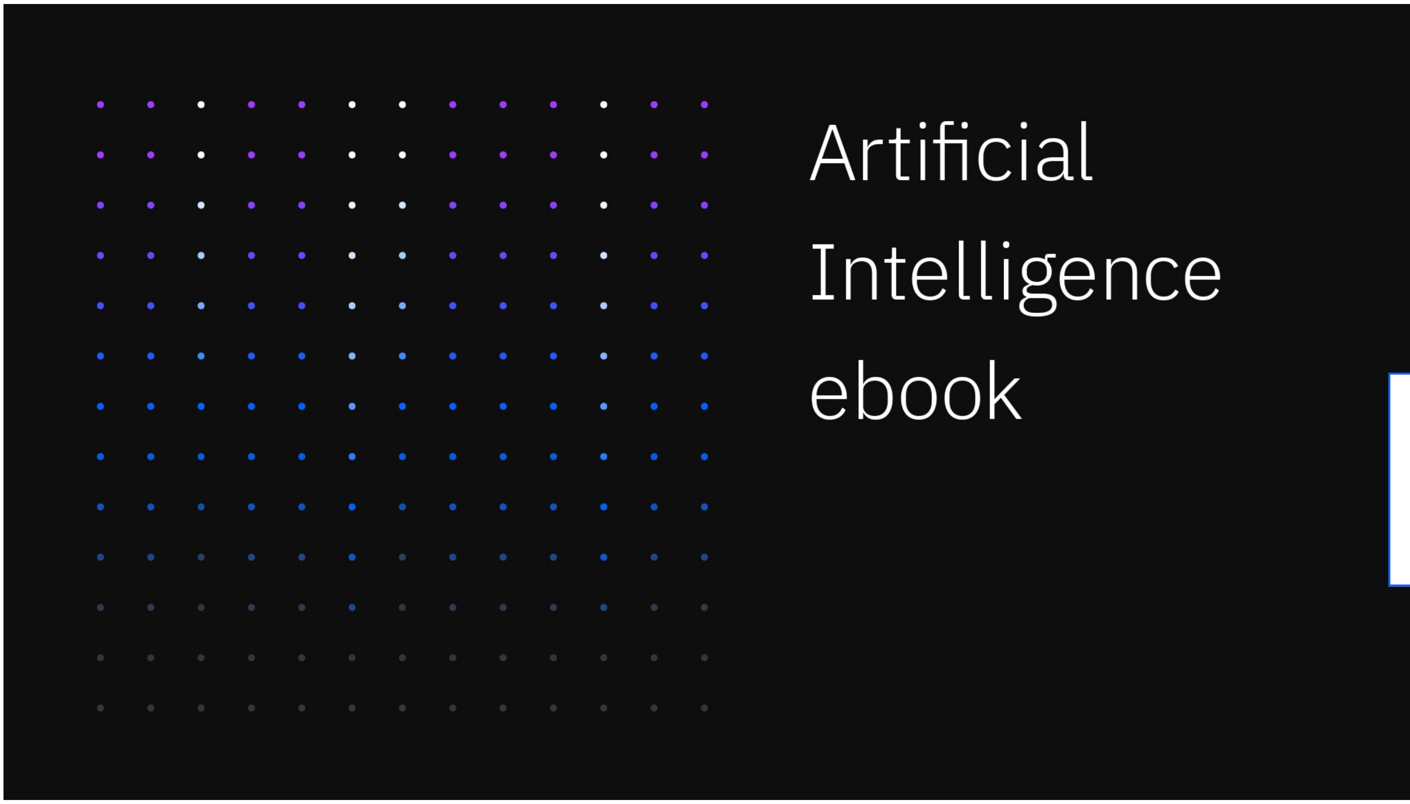

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Neural Networks

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By: **IBM Cloud Education**

17 August 2020

Artificial intelligence

What are neural networks?

Neural Networks

Neural networks reflect the behavic
human brain, allowing computer pr
recognize patterns and solve comm
in the fields of AI, machine learning,
learning.

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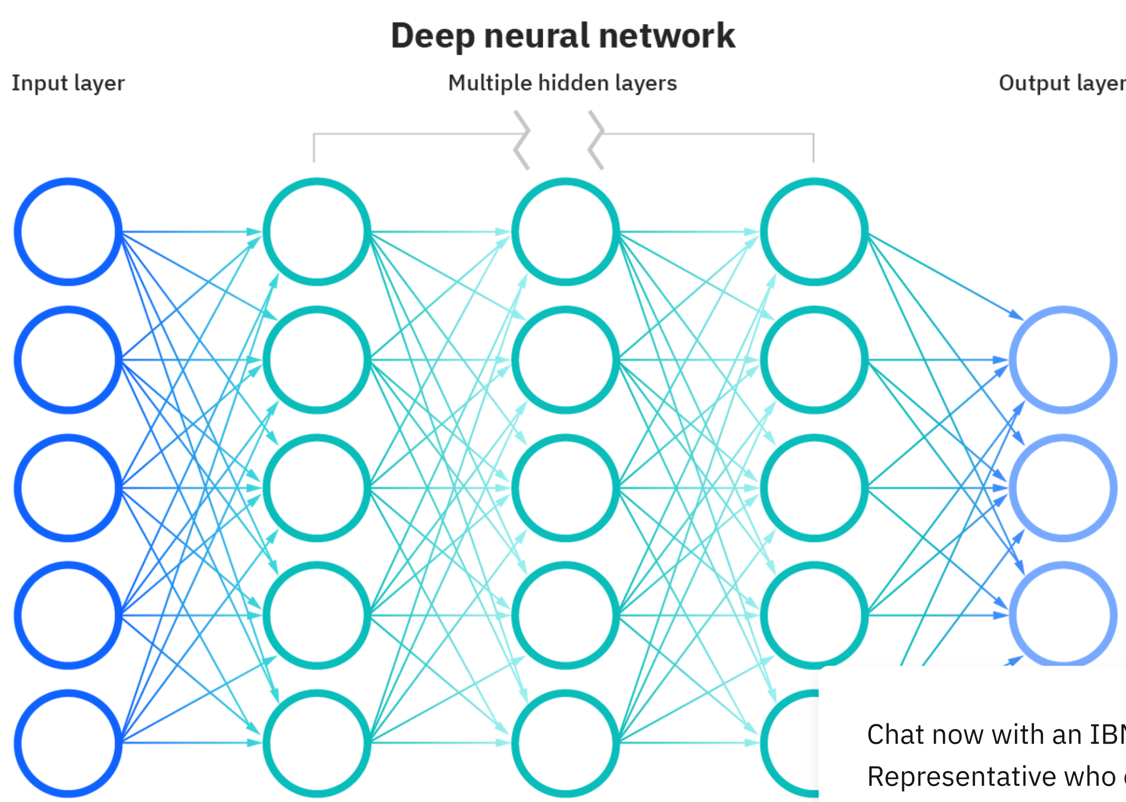
What are neural networks?

Neural networks, also known as artificial neural networks (ANNs) or simulated neural networks (SNNs), are a subset of machine learning and are at the heart of deep learning algorithms. Their name and structure are inspired by the human brain, mimicking the way that biological neurons signal to one another.

Artificial neural networks (ANNs) are comprised of a node layers, containing an input layer, one or more hidden layers, and an output layer. Each node, or artificial neuron, connects to another and has an associated weight and threshold. If the output of any individual node is above the specified threshold value, that node is activated, sending data to the next layer of the network. Otherwise, no data is passed along to the next layer of the network.



Neural networks rely on training data to learn and improve th
However, once these learning algorithms are fine-tuned for ac
powerful tools in computer science and artificial intelligence, allowing us to classify and cluster data at a high velocity. Tasks in speech recognition or image recognition

human experts. One of the most well-known neural networks is Google's search algorithm.

How do neural networks work?

Think of each individual node as its own linear regression model, composed of input data, weights, a bias (or threshold), and an output. The formula would look something like this:

$$\sum_{i=1}^{m} w_i x_i + bias = w_1 x_1 + w_2 x_2 + w_3 x_3 + bias$$

∑wixi + bias = w1x1 + w2x2 + w3x3 + bias

$$\text{output} = f(x) = \begin{cases} 1 \text{ if } \sum w_1 x_1 + b \geq 0 \\ 0 \text{ if } \sum w_1 x_1 + b < 0 \end{cases}$$

output = f(x) = 1 if ∑w1x1 + b>= 0; 0 if ∑w1x1 + b < 0

Once an input layer is determined, weights are assigned. These weights help determine the importance of any given variable, with larger ones contributing more significantly to the output compared to other inputs. All input their respective weights and then summed. Afterward, the ou an activation function, which determines the output. If that o threshold, it "fires" (or activates) the node, passing data to th network. This results in the output of one node becoming in t node. This process of passing data from one layer to the next network as a feedforward network.

Site feedback

(Yes: 1, No: 0). The decision to go or not to go is our predicted outcome, or y-hat. Let's assume that there are three factors influencing your decision-making:

1. Are the waves good? (Yes: 1, No: 0)
2. Is the line-up empty? (Yes: 1, No: 0)
3. Has there been a recent shark attack? (Yes: 0, No: 1)

Then, let's assume the following, giving us the following inputs:

- X1 = 1, since the waves are pumping
- X2 = 0, since the crowds are out
- X3 = 1, since there hasn't been a recent shark attack

Now, we need to assign some weights to determine importance. Larger weights signify that particular variables are of greater importance to the decision or outcome.

- W1 = 5, since large swells don't come around often
- W2 = 2, since you're used to the crowds
- W3 = 4, since you have a fear of sharks

Finally, we'll also assume a threshold value of 3, which would translate to a bias value of –3. With all the various inputs, we can start to plug in values into the formula to get the desired output.

Y-hat = (1*5) + (0*2) + (1*4) – 3 = 6

If we use the activation function from the beginning of this se that the output of this node would be 1, since 6 is greater tha you would go surfing; but if we adjust the weights or the thres different outcomes from the model. When we observe one de example, we can see how a neural network could make increa decisions depending on the output of previous decisions or la

In the example above, we used perceptrons to illustrate some of the mathematics having values between 0 and 1. Since neural networks behave similarly to decision trees, cascading data from one node to another, having x values between 0 and 1 will reduce the impact of any given change of a single variable on the output of any given node, and subsequently, the output of the neural network.

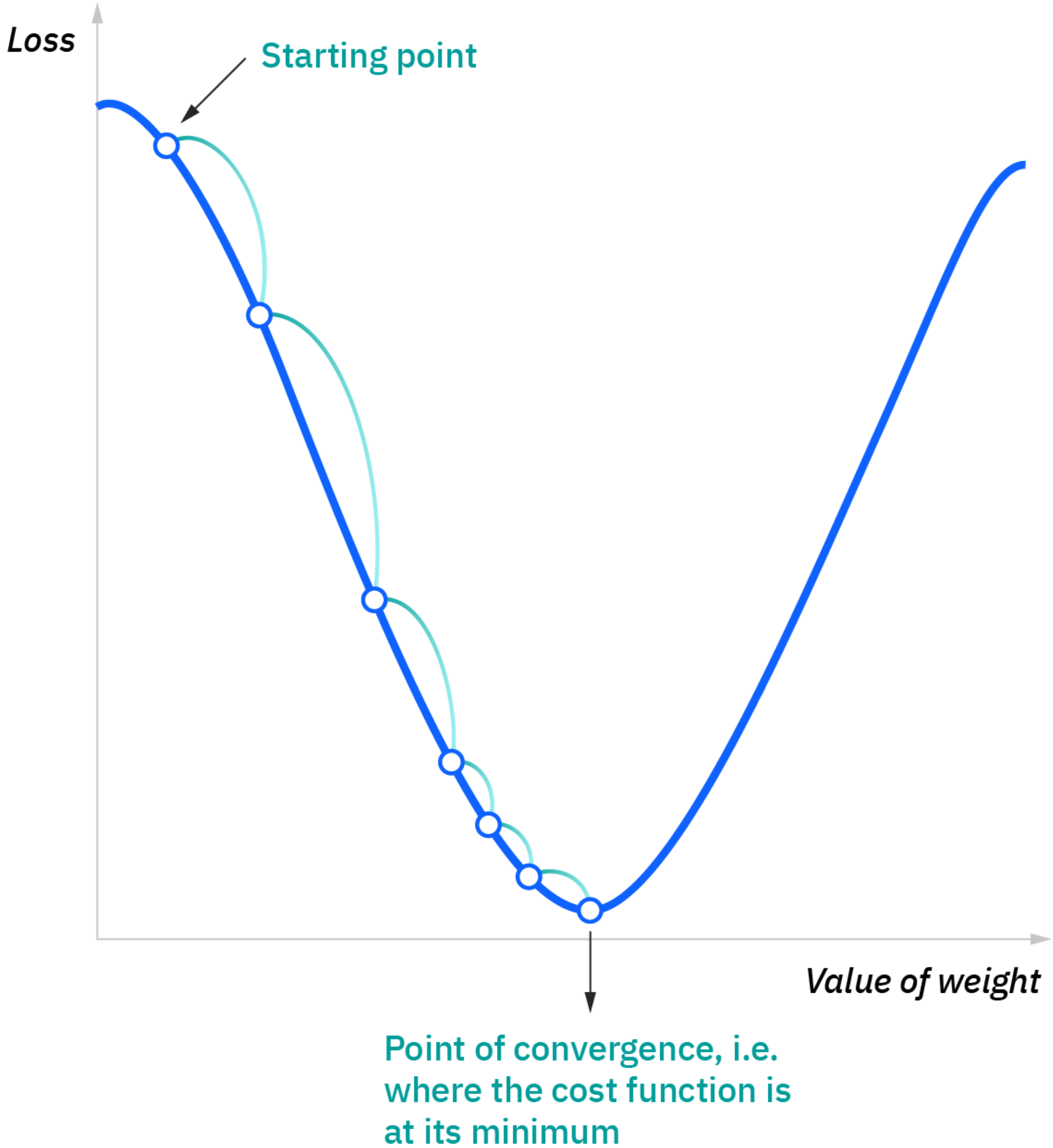
As we start to think about more practical use cases for neural networks, like image recognition or classification, we'll leverage supervised learning, or labeled datasets, to train the algorithm. As we train the model, we'll want to evaluate its accuracy using a cost (or loss) function. This is also commonly referred to as the mean squared error (MSE). In the equation below,

- *i* represents the index of the sample,
- y-hat is the predicted outcome,
- y is the actual value, and
- *m* is the number of samples.

$$Cost\ Function = MSE = \frac{1}{2m}\sum_{i=1}^{m}(\hat{y} - y)^2$$

Cost Function= *MSE*=1/2*m* ∑129_(*i*=1)^*m*▒(*y*̂^((*i*))−*y*^((*i*)))^2

Ultimately, the goal is to minimize our cost function to ensure correctness of fit for any given observation. As the model adjusts its weights and bias, it uses the cost function and reinforcement learning to reach the point of convergence, or the local minimum. The process in which the algorithm adjusts its weig descent, allowing the model to determine the direction to tak minimize the cost function). With each training example, the adjust to gradually converge at the minimum.



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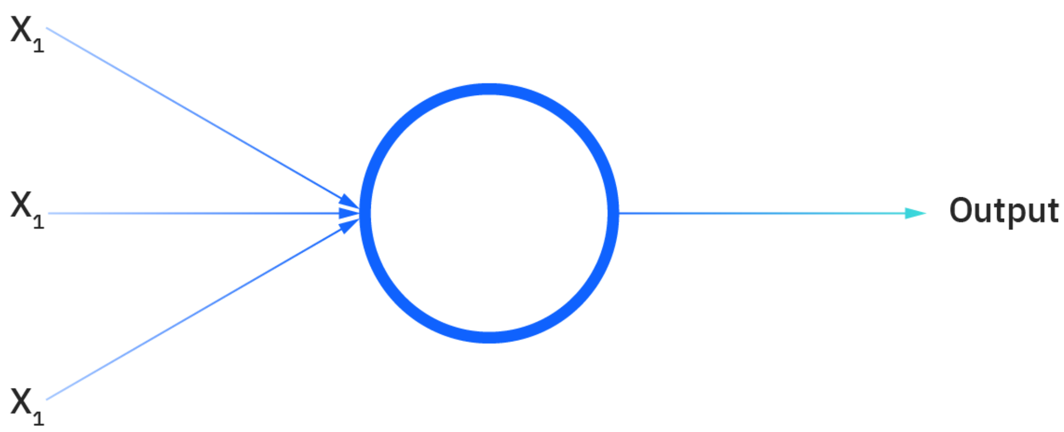
See this IBM Developer article for a deeper explanation of the quantitative concepts involved in neural networks.

Most deep neural networks are feedforward, meaning they flow in one direction only, from input to output. However, you can also train your model backpropagation; that is, move in the opposite direction from Backpropagation allows us to calculate and attribute the erro neuron, allowing us to adjust and fit the parameters of the mo

Types of neural networks

Neural networks can be classified into different types, which are used for different purposes. While this isn't a comprehensive list of types, the below would be representative of the most common types of neural networks that you'll come across for its common use cases:

The perceptron is the oldest neural network, created by Frank Rosenblatt in 1958. It has a single neuron and is the simplest form of a neural network:



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Feedforward neural networks, or multi-layer perceptrons (MLPs), are what we've primarily been focusing on within this article. They are comprised of an input layer, a hidden layer or layers, and an output layer. While these neural networks are also commonly referred to as MLPs, it's important to note that they are actually comprised of sigmoid neurons, not perceptrons, as most real-world problems are nonlinear. Data usually is fed into these models to train them, and they are the foundation for computer vision, natural language processing, and other neural networks.

Convolutional neural networks (CNNs) are similar to feedforward networks, but they're usually utilized for image recognition, pattern recognition, and/or computer vision. These networks harness principles from linear algebra multiplication, to identify patterns within an image.

Recurrent neural networks (RNNs) are identified by their feed learning algorithms are primarily leveraged when using time- predictions about future outcomes, such as stock market pre forecasting.

Neural networks vs. deep learning

Deep Learning and neural networks tend to be used interchangeably in conversation, which can be confusing. As a result, it's worth noting that the "deep" in deep learning is just referring to the depth of layers in a neural network. A neural network that consists of more than three layers—which would be inclusive of the inputs and the output—can be considered a deep learning algorithm. A neural network that only has two or three layers is just a basic neural network.

To learn more about the differences between neural networks and other forms of artificial intelligence, like machine learning, please read the blog post "AI vs. Machine Learning vs. Deep Learning vs. Neural Networks: What's the Difference?"

History of neural networks

The history of neural networks is longer than most people think. While the idea of "a machine that thinks" can be traced to the Ancient Greeks, we'll focus on the key events that led to the evolution of thinking around neural networks, which has ebbed and flowed in popularity over the years:

1943: Warren S. McCulloch and Walter Pitts published "A logical calculus of the ideas immanent in nervous activity (PDF, 1 MB) (link resides outside IBM)" This research sought to understand how the human brain could produce complex patterns through connected brain cells, or neurons. One of the main ideas that came out of this work was the comparison of neurons with a binary threshold to Boolean logic (i.e., 0/1 or true/false statements).

1958: Frank Rosenblatt is credited with the development of t
documented in his research, "The Perceptron: A Probabilistic
Storage and Organization in the Brain" (PDF, 1.6 MB) (link res
takes McCulloch and Pitt's work a step further by introducing
equation. Leveraging an IBM 704, Rosenblatt was able to get
how to distinguish cards marked on the left vs. cards marked on the right.

1974: While numerous researchers contributed to the idea of backpropagation, Paul Werbos was the first person in the US to note its application within neural networks within his PhD thesis (PDF, 8.1 MB) (link resides outside IBM).

1989: Yann LeCun published a paper (PDF, 5.7 MB) (link resides outside IBM) illustrating how the use of constraints in backpropagation and its integration into the neural network architecture can be used to train algorithms. This research successfully leveraged a neural network to recognize hand-written zip code digits provided by the U.S. Postal Service.

Neural networks and IBM Cloud

For decades now, IBM has been a pioneer in the development of AI technologies and neural networks, highlighted by the development and evolution of IBM Watson. Watson is now a trusted solution for enterprises looking to apply advanced natural language processing and deep learning techniques to their systems using a proven tiered approach to AI adoption and implementation.

Watson uses the Apache Unstructured Information Management Architecture (UIMA) framework and IBM's DeepQA software to make powerful deep learning capabilities available to applications. Utilizing tools like IBM Watson Studio, your enterprise can seamlessly bring open source AI projects into production while deploying and running models on any cloud.

For more information on how to get started with deep learning technology, explore IBM Watson Studio and the Deep Learning service.

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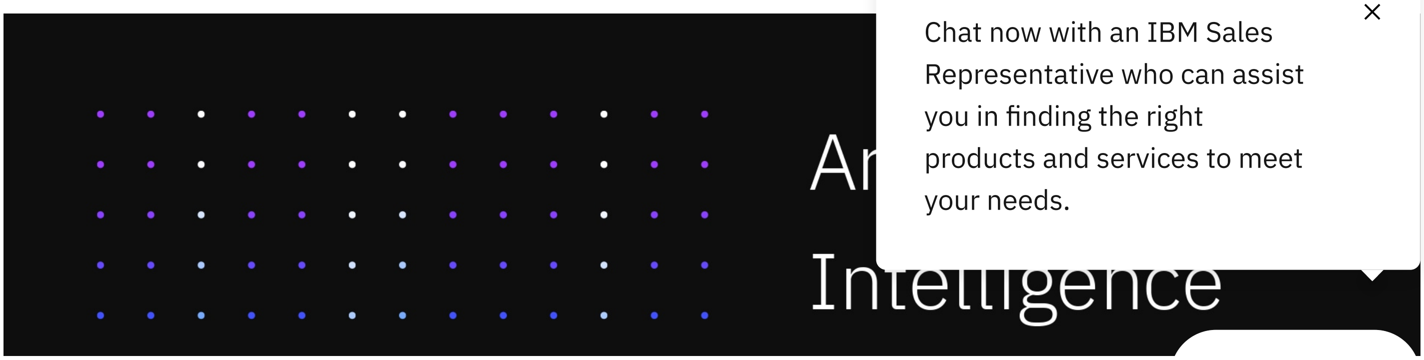

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Global Positioning System

The **Global Positioning System** (**GPS**), originally **Navstar GPS**,[2] is a satellite-based radionavigation system owned by the United States government and operated by the United States Space Force.[3] It is one of the global navigation satellite systems (GNSS) that provides geolocation and time information to a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites.[4] It does not require the user to transmit any data, and operates independently of any telephonic or Internet reception, though these technologies can enhance the usefulness of the GPS positioning information. It provides critical positioning capabilities to military, civil, and commercial users around the world. Although the United States government created, controls and maintains the GPS system, it is freely accessible to anyone with a GPS receiver.[5]

The GPS project was started by the U.S. Department of Defense in 1973. The first prototype spacecraft was launched in 1978 and the full constellation of 24 satellites became operational in 1993. Originally limited to use by the United States military, civilian use was allowed from the 1980s following an executive order from President Ronald Reagan after the Korean Air Lines Flight 007 incident.[6] Advances in technology and new demands on the existing system have now led to efforts to modernize the GPS and implement the next generation of GPS Block IIIA satellites and Next Generation Operational Control System (OCX).[7] Announcements from Vice President Al Gore and the Clinton Administration in 1998 initiated these changes, which were authorized by the U.S. Congress in 2000.

From the early 1990s, GPS positional accuracy was degraded by the United States government by a program called Selective Availability, which could selectively degrade or deny access to the system at any time,[8] as happened to the Indian military in 1999 during the Kargil War. However, this practice was discontinued on May 1, 2000, in accordance with a bill signed into law by President Bill Clinton.[9] As a result, several countries have developed or are in the process of setting up other global or regional satellite navigation systems.

Global Positioning System (GPS)

Global Positioning System logo

Country/ies of origin	United States
Operator(s)	US Space Force
Type	Military, civilian
Status	Operational
Coverage	Global
Accuracy	500–30 cm (16–0.98 ft)
Constellation size	
Total satellites	77
Satellites in orbit	32 (operational 31)
First launch	February 22, 1978
Total launches	75
Orbital characteristics	
Regime(s)	6 MEO planes
Orbital height	20,180 km (12,540 mi)
Other details	
Cost	$12 billion[1] (initial constellation)

	$750 million per year[1] (operating cost)
Website	gps.gov (https://www.gps.gov)

The Russian Global Navigation Satellite System (GLONASS) was developed contemporaneously with GPS, but suffered from incomplete coverage of the globe until the mid-2000s.[10] GLONASS reception in addition to GPS can be combined in a receiver thereby allowing for additional satellites available to enable faster position fixes and improved accuracy, to within two meters (6.6 ft).[11][12]

Artist's impression of GPS Block IIR satellite in Earth orbit

Civilian GPS receivers ("GPS navigation device") in a marine application

China's BeiDou Navigation Satellite System began global services in 2018, and finished its full deployment in 2020.[13] There are also the European Union Galileo navigation satellite system, and India's NavIC. Japan's Quasi-Zenith Satellite System (QZSS) is a GPS satellite-based augmentation system to enhance GPS's accuracy in Asia-Oceania, with satellite navigation independent of GPS scheduled for 2023.[14]

Automotive navigation system in a taxicab

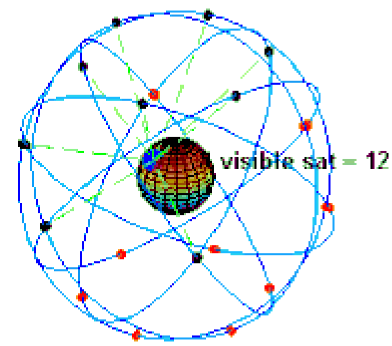
An Air Force Space Command Senior Airman runs through a checklist during Global Positioning System satellite operations.

When selective availability was lifted in 2000, GPS had about a five-meter (16 ft) accuracy. GPS receivers that use the L5 band have much higher accuracy, pinpointing to within 30 centimeters (11.8 in), while high-end users (typically engineering and land surveying applications) are able to have accuracy on several of the bandwidth signals to within two centimeters, and even sub-millimeter accuracy for long-term measurements.[9][15][16] Consumer devices, like smartphones, can be as accurate as to within 4.9 m (or better with assistive services like Wi-Fi positioning also enabled).[17] As of May 2021, 16 GPS satellites are broadcasting L5 signals, and the signals are considered pre-operational, scheduled to reach 24 satellites by approximately 2027.

Contents

History

The GPS project was launched in the United States in 1973 to overcome the limitations of previous navigation systems,[18] combining ideas from several predecessors, including classified engineering design studies from the 1960s. The U.S. Department of Defense developed the system, which originally used 24 satellites, for use by the United States military, and became fully operational in 1995. Civilian use was allowed from the 1980s. Roger L. Easton of the Naval Research Laboratory, Ivan A. Getting of The Aerospace Corporation, and Bradford Parkinson of the Applied Physics Laboratory are credited with inventing it.[19] The work of Gladys West is credited as instrumental in the development of computational techniques for detecting satellite positions with the precision needed for GPS.[20]



GPS constellation system animation

The design of GPS is based partly on similar ground-based radio-navigation systems, such as LORAN and the Decca Navigator, developed in the early 1940s.

In 1955, Friedwardt Winterberg proposed a test of general relativity—detecting time slowing in a strong gravitational field using accurate atomic clocks placed in orbit inside artificial satellites. Special and general relativity predicted that the clocks on GPS satellites, as observed by those on Earth, run 38 microseconds faster per day than those on the Earth. The design of GPS corrects for this difference; because without doing so, GPS calculated positions would accumulate errors of up to 10 kilometers per day (6 mi/d).[21]

Predecessors

In 1955, Dutch Naval officer Wijnand Langeraar submitted a patent application for a radio-based Long-Range Navigation System, with the US Patent office on February 16, 1955, and was granted Patent US2980907A [22] on April 18, 1961.

When the Soviet Union launched the first artificial satellite (Sputnik 1) in 1957, two American physicists, William Guier and George Weiffenbach, at Johns Hopkins University's Applied Physics Laboratory (APL) decided to monitor its radio transmissions.[23] Within hours they realized that, because of the Doppler effect, they could pinpoint where the satellite was along its orbit. The Director of the APL gave them access to their UNIVAC to do the heavy calculations required.

Early the next year, Frank McClure, the deputy director of the APL, asked Guier and Weiffenbach to investigate the inverse problem: pinpointing the user's location, given the satellite's. (At the time, the Navy was developing the submarine-launched Polaris missile, which required them to know the submarine's location.) This led them and APL to develop the TRANSIT system.[24] In 1959, ARPA (renamed DARPA in 1972) also played a role in TRANSIT.[25][26][27]

TRANSIT was first successfully tested in 1960.[28] It used a constellation of five satellites and could provide a navigational fix approximately once per hour.

In 1967, the U.S. Navy developed the Timation satellite, which proved the feasibility of placing accurate clocks in space, a technology required for GPS.

In the 1970s, the ground-based OMEGA navigation system, based on phase comparison of signal transmission from pairs of stations,[29] became the first worldwide radio navigation system. Limitations of these systems drove the need for a more universal navigation solution with greater accuracy.

Although there were wide needs for accurate navigation in military and civilian sectors, almost none of those was seen as justification for the billions of dollars it would cost in research, development, deployment, and operation of a constellation of navigation satellites. During the Cold War arms race, the nuclear threat to the existence of the United States was the one need that did justify this cost in the view of the United States Congress. This deterrent effect is why GPS was funded. It is also the reason for the ultra-secrecy at that time. The nuclear triad consisted of the United States Navy's submarine-launched ballistic missiles (SLBMs) along with United States Air Force (USAF) strategic bombers and intercontinental ballistic missiles (ICBMs). Considered vital to the nuclear deterrence posture, accurate determination of the SLBM launch position was a force multiplier.

Precise navigation would enable United States ballistic missile submarines to get an accurate fix of their positions before they launched their SLBMs.[30] The USAF, with two thirds of the nuclear triad, also had requirements for a more accurate and reliable navigation system. The U.S. Navy and U.S. Air Force were developing their own technologies in parallel to solve what was essentially the same problem.

To increase the survivability of ICBMs, there was a proposal to use mobile launch platforms (comparable to the Soviet SS-24 and SS-25) and so the need to fix the launch position had similarity to the SLBM situation.

In 1960, the Air Force proposed a radio-navigation system called MOSAIC (MObile System for Accurate ICBM Control) that was essentially a 3-D LORAN. A follow-on study, Project 57, was performed in 1963 and it was "in this study that the GPS concept was born." That same year, the concept was pursued as Project 621B, which had "many of the attributes that you now see in GPS"[31] and promised increased accuracy for Air Force bombers as well as ICBMs.

Updates from the Navy TRANSIT system were too slow for the high speeds of Air Force operation. The Naval Research Laboratory (NRL) continued making advances with their Timation (Time Navigation) satellites, first launched in 1967, second launched in 1969, with the third in 1974 carrying the first atomic clock into orbit and the fourth launched in 1977.[32]

Another important predecessor to GPS came from a different branch of the United States military. In 1964, the United States Army orbited its first Sequential Collation of Range (SECOR) satellite used for geodetic surveying.[33] The SECOR system included three ground-based transmitters at known locations that would send signals to the satellite transponder in orbit. A fourth ground-based station, at an undetermined position, could then use those signals to fix its location precisely. The last SECOR satellite was launched in 1969.[34]

Development

With these parallel developments in the 1960s, it was realized that a superior system could be developed by synthesizing the best technologies from 621B, Transit, Timation, and SECOR in a multi-service program. Satellite orbital position errors, induced by variations in the gravity field and radar refraction among others, had to be resolved. A team led by Harold L Jury of Pan Am Aerospace Division in Florida from 1970 to 1973, used real-time data assimilation and recursive estimation to do so, reducing systematic and residual errors to a manageable level to permit accurate navigation.[35]

During Labor Day weekend in 1973, a meeting of about twelve military officers at the Pentagon discussed the creation of a *Defense Navigation Satellite System (DNSS)*. It was at this meeting that the real synthesis that became GPS was created. Later that year, the DNSS program was named

Navstar.[36] Navstar is often erroneously considered an acronym for "NAVigation System Using Timing and Ranging" but was never considered as such by the GPS Joint Program Office (TRW may have once advocated for a different navigational system that used that acronym).[37] With the individual satellites being associated with the name Navstar (as with the predecessors Transit and Timation), a more fully encompassing name was used to identify the constellation of Navstar satellites, *Navstar-GPS*.[38] Ten "Block I" prototype satellites were launched between 1978 and 1985 (an additional unit was destroyed in a launch failure).[39]

The effect of the ionosphere on radio transmission was investigated in a geophysics laboratory of Air Force Cambridge Research Laboratory, renamed to Air Force Geophysical Research Lab (AFGRL) in 1974. AFGRL developed the Klobuchar model for computing ionospheric corrections to GPS location.[40] Of note is work done by Australian space scientist Elizabeth Essex-Cohen at AFGRL in 1974. She was concerned with the curving of the paths of radio waves (atmospheric refraction) traversing the ionosphere from NavSTAR satellites.[41]

After Korean Air Lines Flight 007, a Boeing 747 carrying 269 people, was shot down in 1983 after straying into the USSR's prohibited airspace,[42] in the vicinity of Sakhalin and Moneron Islands, President Ronald Reagan issued a directive making GPS freely available for civilian use, once it was sufficiently developed, as a common good.[43] The first Block II satellite was launched on February 14, 1989,[44] and the 24th satellite was launched in 1994. The GPS program cost at this point, not including the cost of the user equipment but including the costs of the satellite launches, has been estimated at US$5 billion (equivalent to $9 billion in 2021).[45]

Initially, the highest-quality signal was reserved for military use, and the signal available for civilian use was intentionally degraded, in a policy known as Selective Availability. This changed with President Bill Clinton signing on May 1, 2000, a policy directive to turn off Selective Availability to provide the same accuracy to civilians that was afforded to the military. The directive was proposed by the U.S. Secretary of Defense, William Perry, in view of the widespread growth of differential GPS services by private industry to improve civilian accuracy. Moreover, the U.S. military was developing technologies to deny GPS service to potential adversaries on a regional basis.[46]

Since its deployment, the U.S. has implemented several improvements to the GPS service, including new signals for civil use and increased accuracy and integrity for all users, all the while maintaining compatibility with existing GPS equipment. Modernization of the satellite system has been an ongoing initiative by the U.S. Department of Defense through a series of satellite acquisitions to meet the growing needs of the military, civilians, and the commercial market.

As of early 2015, high-quality, FAA grade, Standard Positioning Service (SPS) GPS receivers provided horizontal accuracy of better than 3.5 meters (11 ft),[47] although many factors such as receiver and antenna quality and atmospheric issues can affect this accuracy.

GPS is owned and operated by the United States government as a national resource. The Department of Defense is the steward of GPS. The *Interagency GPS Executive Board (IGEB)* oversaw GPS policy matters from 1996 to 2004. After that, the National Space-Based Positioning, Navigation and Timing Executive Committee was established by presidential directive in 2004 to advise and coordinate federal departments and agencies on matters concerning the GPS and related systems.[48] The executive committee is chaired jointly by the Deputy Secretaries of Defense and Transportation. Its membership includes equivalent-level officials from the Departments of State, Commerce, and Homeland Security, the Joint Chiefs of Staff and NASA. Components of the executive office of the president participate as observers to the executive committee, and the FCC chairman participates as a liaison.

The U.S. Department of Defense is required by law to "maintain a Standard Positioning Service (as defined in the federal radio navigation plan and the standard positioning service signal specification) that will be available on a continuous, worldwide basis," and "develop measures to prevent hostile use of GPS and its augmentations without unduly disrupting or degrading civilian uses."

Timeline and modernization

Summary of satellites[49][50][51]

Block	Launch period	Satellite launches				Currently in orbit and healthy
		Suc-cess	Fail-ure	In prep-aration	Plan-ned	
I	1978–1985	10	1	0	0	0
II	1989–1990	9	0	0	0	0
IIA	1990–1997	19	0	0	0	0
IIR	1997–2004	12	1	0	0	7
IIR-M	2005–2009	8	0	0	0	7
IIF	2010–2016	12	0	0	0	12
IIIA	2018–	5	0	5	0	5
IIIF	—	0	0	0	22	0
Total		75	2	5	22	31

(Last update: July 8, 2021)

USA-203 from Block IIR-M is unhealthy [52] For a more complete list, see *List of GPS satellites*

- In 1972, the USAF Central Inertial Guidance Test Facility (Holloman AFB) conducted developmental flight tests of four prototype GPS receivers in a Y configuration over White Sands Missile Range, using ground-based pseudo-satellites.[53]
- In 1978, the first experimental Block-I GPS satellite was launched.[39]
- In 1983, after Soviet interceptor aircraft shot down the civilian airliner KAL 007 that strayed into prohibited airspace because of navigational errors, killing all 269 people on board, U.S. President Ronald Reagan announced that GPS would be made available for civilian uses once it was completed,[54][55] although it had been previously published in Navigation magazine, and that the CA code (Coarse/Acquisition code) would be available to civilian users.
- By 1985, ten more experimental Block-I satellites had been launched to validate the concept.
- Beginning in 1988, command and control of these satellites was moved from Onizuka AFS, California to the 2nd Satellite Control Squadron (2SCS) located at Falcon Air Force Station in Colorado Springs, Colorado.[56][57]
- On February 14, 1989, the first modern Block-II satellite was launched.
- The Gulf War from 1990 to 1991 was the first conflict in which the military widely used GPS.[58]
- In 1991, a project to create a miniature GPS receiver successfully ended, replacing the previous 16 kg (35 lb) military receivers with a 1.25 kg (2.8 lb) handheld receiver.[26]
- In 1992, the 2nd Space Wing, which originally managed the system, was inactivated and replaced by the 50th Space Wing.
- By December 1993, GPS achieved initial operational capability (IOC), with a full constellation (24 satellites) available and providing the Standard Positioning Service (SPS).[59]
- Full Operational Capability (FOC) was declared by Air Force Space Command (AFSPC) in April 1995, signifying full availability of the military's secure Precise Positioning Service (PPS).[59]
- In 1996, recognizing the importance of GPS to civilian users as well as military users, U.S. President Bill Clinton issued a policy directive[60] declaring GPS a dual-use system and establishing an Interagency GPS Executive Board to manage it as a national asset.

- In 1998, United States Vice President Al Gore announced plans to upgrade GPS with two new civilian signals for enhanced user accuracy and reliability, particularly with respect to aviation safety, and in 2000 the United States Congress authorized the effort, referring to it as *GPS III*.
- On May 2, 2000 "Selective Availability" was discontinued as a result of the 1996 executive order, allowing civilian users to receive a non-degraded signal globally.
- In 2004, the United States government signed an agreement with the European Community establishing cooperation related to GPS and Europe's Galileo system.
- In 2004, United States President George W. Bush updated the national policy and replaced the executive board with the National Executive Committee for Space-Based Positioning, Navigation, and Timing.[61]

Emblem of the 50th Space Wing

- November 2004, Qualcomm announced successful tests of assisted GPS for mobile phones.[62]
- In 2005, the first modernized GPS satellite was launched and began transmitting a second civilian signal (L2C) for enhanced user performance.[63]
- On September 14, 2007, the aging mainframe-based Ground Segment Control System was transferred to the new Architecture Evolution Plan.[64]
- On May 19, 2009, the United States Government Accountability Office issued a report warning that some GPS satellites could fail as soon as 2010.[65]
- On May 21, 2009, the Air Force Space Command allayed fears of GPS failure, saying "There's only a small risk we will not continue to exceed our performance standard."[66]
- On January 11, 2010, an update of ground control systems caused a software incompatibility with 8,000 to 10,000 military receivers manufactured by a division of Trimble Navigation Limited of Sunnyvale, Calif.[67]
- On February 25, 2010,[68] the U.S. Air Force awarded the contract to develop the GPS Next Generation Operational Control System (OCX) to improve accuracy and availability of GPS navigation signals, and serve as a critical part of GPS modernization.

Awards

On February 10, 1993, the National Aeronautic Association selected the GPS Team as winners of the 1992 Robert J. Collier Trophy, the US's most prestigious aviation award. This team combines researchers from the Naval Research Laboratory, the USAF, the Aerospace Corporation, Rockwell International Corporation, and IBM Federal Systems Company. The citation honors them "for the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago."


AFSPC Vice Commander Lt. Gen. DT Thompson presents Dr. Gladys West with an award as she is inducted into the Air Force Space and Missile Pioneers Hall of Fame.

Two GPS developers received the National Academy of Engineering Charles Stark Draper Prize for 2003:

- Ivan Getting, emeritus president of The Aerospace Corporation and an engineer at MIT, established the basis for GPS, improving on the World War II land-based radio system called LORAN (*Lo*ng-range *R*adio *A*id to *N*avigation).
- Bradford Parkinson, professor of aeronautics and astronautics at Stanford University, conceived the present satellite-based system in the early 1960s and developed it in conjunction with the U.S. Air Force. Parkinson served twenty-one years in the Air Force, from 1957 to 1978, and retired with the rank of colonel.

GPS developer Roger L. Easton received the National Medal of Technology on February 13, 2006.[69]

Francis X. Kane (Col. USAF, ret.) was inducted into the U.S. Air Force Space and Missile Pioneers Hall of Fame at Lackland A.F.B., San Antonio, Texas, March 2, 2010, for his role in space technology development and the engineering design concept of GPS conducted as part of Project 621B.

In 1998, GPS technology was inducted into the Space Foundation Space Technology Hall of Fame.[70]

On October 4, 2011, the International Astronautical Federation (IAF) awarded the Global Positioning System (GPS) its 60th Anniversary Award, nominated by IAF member, the American Institute for Aeronautics and Astronautics (AIAA). The IAF Honors and Awards Committee recognized the uniqueness of the GPS program and the exemplary role it has played in building international collaboration for the benefit of humanity.[71]

On December 6, 2018, Gladys West was inducted into the Air Force Space and Missile Pioneers Hall of Fame in recognition of her work on an extremely accurate geodetic Earth model, which was ultimately used to determine the orbit of the GPS constellation.[72]

On February 12, 2019, four founding members of the project were awarded the Queen Elizabeth Prize for Engineering with the chair of the awarding board stating "Engineering is the foundation of civilisation; there is no other foundation; it makes things happen. And that's exactly what today's Laureates have done - they've made things happen. They've re-written, in a major way, the infrastructure of our world."[73]

Principles

The GPS receiver calculates its own four-dimensional position in spacetime based on data received from multiple GPS satellites. Each satellite carries an accurate record of its position and time, and transmits that data to the receiver.

The satellites carry very stable atomic clocks that are synchronized with one another and with ground clocks. Any drift from time maintained on the ground is corrected daily. In the same manner, the satellite locations are known with great precision. GPS receivers have clocks as well, but they are less stable and less precise.

Since the speed of radio waves is constant and independent of the satellite speed, the time delay between when the satellite transmits a signal and the receiver receives it is proportional to the distance from the satellite to the receiver. At a minimum, four satellites must be in view of the receiver for it to compute four unknown quantities (three position coordinates and the deviation of its own clock from satellite time).

More detailed description

Each GPS satellite continually broadcasts a signal (carrier wave with modulation) that includes:

- A pseudorandom code (sequence of ones and zeros) that is known to the receiver. By time-aligning a receiver-generated version and the receiver-measured version of the code, the time of arrival (TOA) of a defined point in the code sequence, called an epoch, can be found in the receiver clock time scale
- A message that includes the time of transmission (TOT) of the code epoch (in GPS time scale) and the satellite position at that time

Conceptually, the receiver measures the TOAs (according to its own clock) of four satellite signals. From the TOAs and the TOTs, the receiver forms four time of flight (TOF) values, which are (given the speed of light) approximately equivalent to receiver-satellite ranges plus time difference between the receiver and GPS satellites multiplied by speed of light, which are called pseudo-ranges. The receiver then computes its three-dimensional position and clock deviation from the four TOFs.

In practice the receiver position (in three dimensional Cartesian coordinates with origin at the Earth's center) and the offset of the receiver clock relative to the GPS time are computed simultaneously, using the navigation equations to process the TOFs.

The receiver's Earth-centered solution location is usually converted to latitude, longitude and height relative to an ellipsoidal Earth model. The height may then be further converted to height relative to the geoid, which is essentially mean sea level. These coordinates may be displayed, such as on a moving map display, or recorded or used by some other system, such as a vehicle guidance system.

User-satellite geometry

Although usually not formed explicitly in the receiver processing, the conceptual time differences of arrival (TDOAs) define the measurement geometry. Each TDOA corresponds to a hyperboloid of revolution (see Multilateration). The line connecting the two satellites involved (and its extensions) forms the axis of the hyperboloid. The receiver is located at the point where three hyperboloids intersect.[74][75]

It is sometimes incorrectly said that the user location is at the intersection of three spheres. While simpler to visualize, this is the case only if the receiver has a clock synchronized with the satellite clocks (i.e., the receiver measures true ranges to the satellites rather than range differences). There are marked performance benefits to the user carrying a clock synchronized with the satellites. Foremost is that only three satellites are needed to compute a position solution. If it were an essential part of the GPS concept that all users needed to carry a synchronized clock, a smaller number of satellites could be deployed, but the cost and complexity of the user equipment would increase.

Receiver in continuous operation

The description above is representative of a receiver start-up situation. Most receivers have a track algorithm, sometimes called a *tracker*, that combines sets of satellite measurements collected at different times—in effect, taking advantage of the fact that successive receiver positions are usually close to each other. After a set of measurements are processed, the tracker predicts the receiver location corresponding to the next set of satellite measurements. When the new measurements are collected, the receiver uses a weighting scheme to combine the new measurements with the tracker prediction. In general, a tracker can (a) improve receiver position and time accuracy, (b) reject bad measurements, and (c) estimate receiver speed and direction.

The disadvantage of a tracker is that changes in speed or direction can be computed only with a delay, and that derived direction becomes inaccurate when the distance traveled between two position measurements drops below or near the random error of position measurement. GPS units can use measurements of the Doppler shift of the signals received to compute velocity accurately.[76] More advanced navigation systems use additional sensors like a compass or an inertial navigation system to complement GPS.

Non-navigation applications

GPS requires four or more satellites to be visible for accurate navigation. The solution of the navigation equations gives the position of the receiver along with the difference between the time kept by the receiver's on-board clock and the true time-of-day, thereby eliminating the need for a more precise and possibly impractical receiver based clock. Applications for GPS such as time transfer, traffic signal timing, and synchronization of cell phone base stations, make use of this cheap and highly accurate timing. Some GPS applications use this time for display, or, other than for the basic position calculations, do not use it at all.

Although four satellites are required for normal operation, fewer apply in special cases. If one variable is already known, a receiver can determine its position using only three satellites. For example, a ship on the open ocean usually has a known elevation close to 0m, and the elevation of an aircraft may be known.[a] Some GPS receivers may use additional clues or assumptions such as reusing the last known altitude, dead reckoning, inertial navigation, or including information from the vehicle computer, to give a (possibly degraded) position when fewer than four satellites are visible.[77][78][79]

Structure

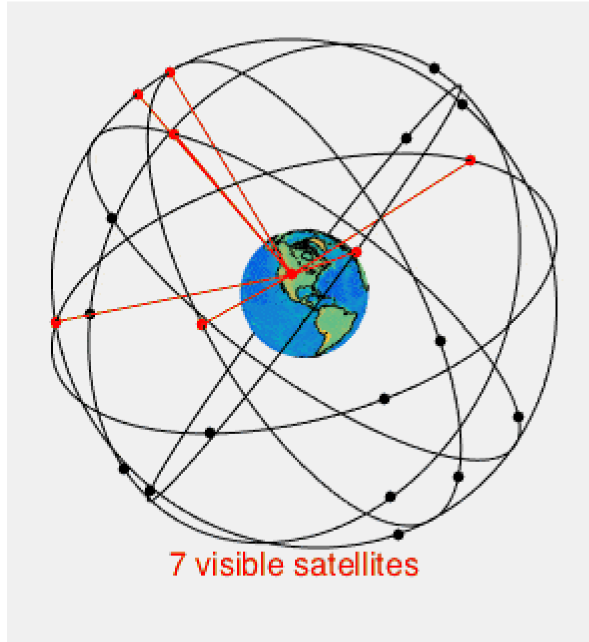
The current GPS consists of three major segments. These are the space segment, a control segment, and a user segment.[80] The U.S. Space Force develops, maintains, and operates the space and control segments. GPS satellites broadcast signals from space, and each GPS receiver uses these signals to calculate its three-dimensional location (latitude, longitude, and altitude) and the current time.[81]

Space segment

Unlaunched GPS block II-A satellite on display at the San Diego Air & Space Museum

The space segment (SS) is composed of 24 to 32 satellites, or Space Vehicles (SV), in medium Earth orbit, and also includes the payload adapters to the boosters required to launch them into orbit. The GPS design originally called for 24 SVs, eight each in three approximately circular orbits,[82] but this was modified to six orbital planes with four satellites each.[83] The six orbit planes have approximately 55° inclination (tilt relative to the Earth's equator) and are separated by 60° right ascension of the ascending node (angle along the equator from a reference point to the orbit's intersection).[84] The orbital period is one-half a sidereal day, i.e., 11 hours and 58 minutes so that the satellites pass over the same locations[85] or almost the same locations[86] every day. The orbits are arranged so that at least six satellites are always within line of sight from everywhere on the Earth's surface (see animation at right).[87] The result of this objective is that the four satellites are not evenly spaced (90°) apart within each orbit. In general terms, the angular difference between satellites in each orbit is 30°, 105°, 120°, and 105° apart, which sum to 360°.[88]

Orbiting at an altitude of approximately 20,200 km (12,600 mi); orbital radius of approximately 26,600 km (16,500 mi),[89] each SV makes two complete orbits each sidereal day, repeating the same ground track each day.[90] This was very helpful during development because even with only four satellites, correct alignment means all four are visible from one spot for a few hours each day. For military operations, the ground track repeat can be used to ensure good coverage in combat zones.



A visual example of a 24-satellite GPS constellation in motion with the Earth rotating. Notice how the number of *satellites in view* from a given point on the Earth's surface changes with time. The point in this example is in Golden, Colorado, USA (39.7469°N 105.2108°W).

As of February 2019,[91] there are 31 satellites in the GPS constellation, 27 of which are in use at a given time with the rest allocated as stand-bys. A 32nd was launched in 2018, but as of July 2019 is still in evaluation. More decommissioned satellites are in orbit and available as spares. The additional satellites improve the precision of GPS receiver calculations by providing redundant measurements. With the increased number of satellites, the constellation was changed to a nonuniform arrangement. Such an arrangement was shown to improve accuracy but also improves reliability and availability of the system, relative to a uniform system, when multiple satellites fail.[92] With the expanded constellation, nine satellites are usually visible at any time from any point on the Earth with a clear horizon, ensuring considerable redundancy over the minimum four satellites needed for a position.

Control segment

The control segment (CS) is composed of:

1. a master control station (MCS),
2. an alternative master control station,
3. four dedicated ground antennas, and
4. six dedicated monitor stations.

Ground monitor station used from 1984 to 2007, on display at the Air Force Space and Missile Museum.

The MCS can also access Satellite Control Network (SCN) ground antennas (for additional command and control capability) and NGA (National Geospatial-Intelligence Agency) monitor stations. The flight paths of the satellites are tracked by dedicated U.S. Space Force monitoring stations in Hawaii, Kwajalein Atoll, Ascension Island, Diego Garcia, Colorado Springs, Colorado and Cape Canaveral, along with shared NGA monitor stations operated in England, Argentina, Ecuador, Bahrain, Australia and Washington DC.[93] The tracking information is sent to the MCS at Schriever Space Force Base 25 km (16 mi) ESE of Colorado Springs, which is operated by the 2nd Space Operations Squadron (2 SOPS) of the U.S. Space Force. Then 2 SOPS contacts each GPS satellite regularly with a navigational update using dedicated or shared (AFSCN) ground antennas (GPS dedicated ground antennas are located at Kwajalein, Ascension Island, Diego Garcia, and Cape Canaveral). These updates synchronize the atomic clocks on board the satellites to within a few nanoseconds of each other, and adjust the ephemeris of each satellite's internal orbital model. The updates are created by a Kalman filter that uses inputs from the ground monitoring stations, space weather information, and various other inputs.[94]

Satellite maneuvers are not precise by GPS standards—so to change a satellite's orbit, the satellite must be marked *unhealthy*, so receivers don't use it. After the satellite maneuver, engineers track the new orbit from the ground, upload the new ephemeris, and mark the satellite healthy again.

The operation control segment (OCS) currently serves as the control segment of record. It provides the operational capability that supports GPS users and keeps the GPS operational and performing within specification.

OCS successfully replaced the legacy 1970s-era mainframe computer at Schriever Air Force Base in September 2007. After installation, the system helped enable upgrades and provide a foundation for a new security architecture that supported U.S. armed forces.

OCS will continue to be the ground control system of record until the new segment, Next Generation GPS Operation Control System[7] (OCX), is fully developed and functional. The new capabilities provided by OCX will be the cornerstone for revolutionizing GPS's mission capabilities, enabling[95] U.S. Space Force to greatly enhance GPS operational services to U.S. combat forces, civil partners and myriad domestic and international users. The GPS OCX program also will reduce cost, schedule and technical risk. It is designed to provide 50%[96] sustainment cost savings through efficient software architecture and Performance-Based Logistics. In addition, GPS OCX is expected to cost millions less than the cost to upgrade OCS while providing four times the capability.

The GPS OCX program represents a critical part of GPS modernization and provides significant information assurance improvements over the current GPS OCS program.

- OCX will have the ability to control and manage GPS legacy satellites as well as the next generation of GPS III satellites, while enabling the full array of military signals.
- Built on a flexible architecture that can rapidly adapt to the changing needs of today's and future GPS users allowing immediate access to GPS data and constellation status through secure, accurate and reliable information.
- Provides the warfighter with more secure, actionable and predictive information to enhance situational awareness.
- Enables new modernized signals (L1C, L2C, and L5) and has M-code capability, which the legacy system is unable to do.
- Provides significant information assurance improvements over the current program including detecting and preventing cyber attacks, while isolating, containing and operating during such attacks.
- Supports higher volume near real-time command and control capabilities and abilities.

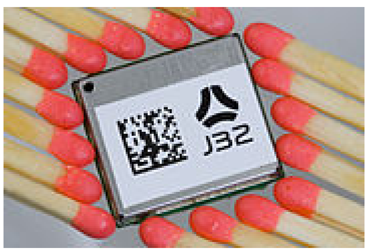
On September 14, 2011,[97] the U.S. Air Force announced the completion of GPS OCX Preliminary Design Review and confirmed that the OCX program is ready for the next phase of development.

The GPS OCX program has missed major milestones and is pushing its launch into 2021, 5 years past the original deadline. According to the Government Accounting Office, even this new deadline looks shaky.[98]

User segment

The user segment (US) is composed of hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service, and tens of millions of civil, commercial and scientific users of the Standard Positioning Service. In general, GPS receivers are composed of an antenna, tuned to the frequencies transmitted by the satellites, receiver-processors, and a highly stable clock (often a crystal oscillator). They may also include a display for providing location and speed information to the user. A receiver is often described by its number of channels: this signifies how many satellites it can monitor simultaneously. Originally limited to four or five, this has progressively increased over the years so that, as of 2007, receivers typically have between 12 and 20 channels. Though there are many receiver manufacturers, they almost all use one of the chipsets produced for this purpose.

GPS receivers come in a variety of formats, from devices integrated into cars, phones, and watches, to dedicated devices such as these.

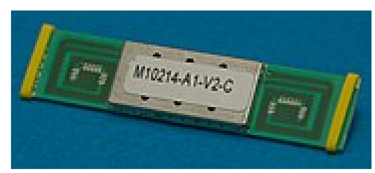


A typical OEM GPS receiver module measuring 15 mm × 17 mm (0.6 in × 0.7 in)

GPS receivers may include an input for differential corrections, using the RTCM SC-104 format. This is typically in the form of an RS-232 port at 4,800 bit/s speed. Data is actually sent at a much lower rate, which limits the accuracy of the signal sent using RTCM. Receivers with internal DGPS receivers can outperform those using external RTCM data. As of 2006, even low-cost units commonly include Wide Area Augmentation System (WAAS) receivers.

The first portable GPS unit, a Leica WM 101, displayed at the Irish National Science Museum at Maynooth.

Many GPS receivers can relay position data to a PC or other device using the NMEA 0183 protocol. Although this protocol is officially defined by the National Marine Electronics Association (NMEA),[99] references to this protocol have been compiled from public records, allowing open source tools like gpsd to read the protocol without violating intellectual property laws. Other proprietary protocols exist as well, such as the SiRF and MTK protocols. Receivers can interface with other devices using methods including a serial connection, USB, or Bluetooth.



A typical GPS receiver with integrated antenna.

Applications

While originally a military project, GPS is considered a dual-use technology, meaning it has significant civilian applications as well.

GPS has become a widely deployed and useful tool for commerce, scientific uses, tracking, and surveillance. GPS's accurate time facilitates everyday activities such as banking, mobile phone operations, and even the control of power grids by allowing well synchronized hand-off switching.[81]

Civilian

Many civilian applications use one or more of GPS's three basic components: absolute location, relative movement, and time transfer.

This antenna is mounted on the roof of a hut containing a scientific experiment needing precise timing.

- Amateur radio: clock synchronization required for several digital modes such as FT8, FT4 and JS8; also used with APRS for position reporting; is often critical during emergency and disaster communications support.
- Atmosphere: studying the troposphere delays (recovery of the water vapor content) and ionosphere delays (recovery of the number of free electrons).[100] Recovery of Earth surface displacements due to the atmospheric pressure loading.[101]
- Astronomy: both positional and clock synchronization data is used in astrometry and celestial mechanics and precise orbit determination.[102] GPS is also used in both amateur astronomy with small telescopes as well as by professional observatories for finding extrasolar planets.
- Automated vehicle: applying location and routes for cars and trucks to function without a human driver.
- Cartography: both civilian and military cartographers use GPS extensively.
- Cellular telephony: clock synchronization enables time transfer, which is critical for synchronizing its spreading codes with other base stations to facilitate inter-cell handoff and support hybrid GPS/cellular position detection for mobile emergency calls and other applications. The first handsets with integrated GPS launched in the late 1990s. The U.S. Federal Communications Commission (FCC) mandated the feature in either the handset or in the towers (for use in triangulation) in 2002 so emergency services could locate 911 callers. Third-party software developers later gained access to GPS APIs from Nextel upon launch, followed by Sprint in 2006, and Verizon soon thereafter.
- Clock synchronization: the accuracy of GPS time signals (±10 ns)[103] is second only to the atomic clocks they are based on, and is used in applications such as GPS disciplined oscillators.
- Disaster relief/emergency services: many emergency services depend upon GPS for location and timing capabilities.
- GPS-equipped radiosondes and dropsondes: measure and calculate the atmospheric pressure, wind speed and direction up to 27 km (89,000 ft) from the Earth's surface.
- Radio occultation for weather and atmospheric science applications.[104]
- Fleet tracking: used to identify, locate and maintain contact reports with one or more fleet vehicles in real-time.
- Geodesy: determination of Earth orientation parameters including the daily and sub-daily polar motion,[105] and length-of-day variabilities,[106] Earth's center-of-mass - geocenter motion,[107] and low-degree gravity field parameters.[108]
- Geofencing: vehicle tracking systems, person tracking systems, and pet tracking systems use GPS to locate devices that are attached to or carried by a person, vehicle, or pet. The application can provide continuous tracking and send notifications if the target leaves a designated (or "fenced-in") area.[109]
- Geotagging: applies location coordinates to digital objects such as photographs (in Exif data) and other documents for purposes such as creating map overlays with devices like Nikon GP-1
- GPS aircraft tracking
- GPS for mining: the use of RTK GPS has significantly improved several mining operations such as drilling, shoveling, vehicle tracking, and surveying. RTK GPS provides centimeter-level positioning accuracy.

- GPS data mining: It is possible to aggregate GPS data from multiple users to understand movement patterns, common trajectories and interesting locations.[110]
- GPS tours: location determines what content to display; for instance, information about an approaching point of interest.
- Mental health: tracking mental health functioning and sociability.[111]
- Navigation: navigators value digitally precise velocity and orientation measurements, as well as precise positions in real-time with a support of orbit and clock corrections.[112]
- Orbit determination of low-orbiting satellites with GPS receiver installed on board, such as GOCE,[113] GRACE, Jason-1, Jason-2, TerraSAR-X, TanDEM-X, CHAMP, Sentinel-3,[114] and some cubesats, e.g., CubETH.
- Phasor measurements: GPS enables highly accurate timestamping of power system measurements, making it possible to compute phasors.
- Recreation: for example, Geocaching, Geodashing, GPS drawing, waymarking, and other kinds of location based mobile games such as Pokémon Go.
- Reference frames: realization and densification of the terrestrial reference frames[115] in the framework of Global Geodetic Observing System. Co-location in space between Satellite laser ranging[116] and microwave observations[117] for deriving global geodetic parameters.[118][119]
- Robotics: self-navigating, autonomous robots using GPS sensors,[120] which calculate latitude, longitude, time, speed, and heading.
- Sport: used in football and rugby for the control and analysis of the training load.[121]
- Surveying: surveyors use absolute locations to make maps and determine property boundaries.
- Tectonics: GPS enables direct fault motion measurement of earthquakes. Between earthquakes GPS can be used to measure crustal motion and deformation[122] to estimate seismic strain buildup for creating seismic hazard maps.
- Telematics: GPS technology integrated with computers and mobile communications technology in automotive navigation systems.

Restrictions on civilian use

The U.S. government controls the export of some civilian receivers. All GPS receivers capable of functioning above 60,000 ft (18 km) above sea level and 1,000 kn (500 m/s; 2,000 km/h; 1,000 mph), or designed or modified for use with unmanned missiles and aircraft, are classified as munitions (weapons)—which means they require State Department export licenses.[123] This rule applies even to otherwise purely civilian units that only receive the L1 frequency and the C/A (Coarse/Acquisition) code.

Disabling operation above these limits exempts the receiver from classification as a munition. Vendor interpretations differ. The rule refers to operation at both the target altitude and speed, but some receivers stop operating even when stationary. This has caused problems with some amateur radio balloon launches that regularly reach 30 km (100,000 feet).

These limits only apply to units or components exported from the United States. A growing trade in various components exists, including GPS units from other countries. These are expressly sold as ITAR-free.

Military

As of 2009, military GPS applications include:

- Navigation: Soldiers use GPS to find objectives, even in the dark or in unfamiliar territory, and to coordinate troop and supply movement. In the United States armed forces, commanders use the *Commander's Digital Assistant* and lower ranks use the *Soldier Digital Assistant*.[124]
- Target tracking: Various military weapons systems use GPS to track potential ground and air targets before flagging them as hostile. These weapon systems pass target coordinates to precision-guided munitions to allow them to engage targets accurately. Military aircraft, particularly in air-to-ground roles, use GPS to find targets.
- Missile and projectile guidance: GPS allows accurate targeting of various military weapons including ICBMs, cruise missiles, precision-guided munitions and artillery shells. Embedded GPS receivers able to withstand accelerations of 12,000 *g* or about 118 km/s^2 (260,000 mph/s) have been developed for use in 155-millimeter (6.1 in) howitzer shells.[125]
- Search and rescue.
- Reconnaissance: Patrol movement can be managed more closely.
- GPS satellites carry a set of nuclear detonation detectors consisting of an optical sensor called a bhangmeter, an X-ray sensor, a dosimeter, and an electromagnetic pulse (EMP) sensor (W-sensor), that form a major portion of the United States Nuclear Detonation Detection System.[126][127] General William Shelton has stated that future satellites may drop this feature to save money.[128]

Attaching a GPS guidance kit to a dumb bomb, March 2003.

M982 Excalibur GPS-guided artillery shell.

GPS type navigation was first used in war in the 1991 Persian Gulf War, before GPS was fully developed in 1995, to assist Coalition Forces to navigate and perform maneuvers in the war. The war also demonstrated the vulnerability of GPS to being jammed, when Iraqi forces installed jamming devices on likely targets that emitted radio noise, disrupting reception of the weak GPS signal.[129]

GPS's vulnerability to jamming is a threat that continues to grow as jamming equipment and experience grows.[130][131] GPS signals have been reported to have been jammed many times over the years for military purposes. Russia seems to have several objectives for this behavior, such as intimidating neighbors while undermining confidence in their reliance on American systems, promoting their GLONASS alternative, disrupting Western military exercises, and protecting assets from drones.[132] China uses jamming to discourage US surveillance aircraft near the contested Spratly Islands.[133] North Korea has mounted several major jamming operations near its border with South Korea and offshore, disrupting flights, shipping and fishing operations.[134] Iranian Armed Forces disrupted the civilian airliner plane Flight PS752's GPS when it shot down the aircraft.[135][136]

Timekeeping

Leap seconds

While most clocks derive their time from Coordinated Universal Time (UTC), the atomic clocks on the satellites are set to "GPS time". The difference is that GPS time is not corrected to match the rotation of the Earth, so it does not contain leap seconds or other corrections that are periodically added to

UTC. GPS time was set to match UTC in 1980, but has since diverged. The lack of corrections means that GPS time remains at a constant offset with International Atomic Time (TAI) (TAI - GPS = 19 seconds). Periodic corrections are performed to the on-board clocks to keep them synchronized with ground clocks.[137]

The GPS navigation message includes the difference between GPS time and UTC. As of January 2017, GPS time is 18 seconds ahead of UTC because of the leap second added to UTC on December 31, 2016.[138] Receivers subtract this offset from GPS time to calculate UTC and specific time zone values. New GPS units may not show the correct UTC time until after receiving the UTC offset message. The GPS-UTC offset field can accommodate 255 leap seconds (eight bits).

Accuracy

GPS time is theoretically accurate to about 14 nanoseconds, due to the clock drift relative to International Atomic Time that the atomic clocks in GPS transmitters experience[139] Most receivers lose some accuracy in their interpretation of the signals and are only accurate to about 100 nanoseconds.[140][141]

Format

As opposed to the year, month, and day format of the Gregorian calendar, the GPS date is expressed as a week number and a seconds-into-week number. The week number is transmitted as a ten-bit field in the C/A and P(Y) navigation messages, and so it becomes zero again every 1,024 weeks (19.6 years). GPS week zero started at 00:00:00 UTC (00:00:19 TAI) on January 6, 1980, and the week number became zero again for the first time at 23:59:47 UTC on August 21, 1999 (00:00:19 TAI on August 22, 1999). It happened the second time at 23:59:42 UTC on April 6, 2019. To determine the current Gregorian date, a GPS receiver must be provided with the approximate date (to within 3,584 days) to correctly translate the GPS date signal. To address this concern in the future the modernized GPS civil navigation (CNAV) message will use a 13-bit field that only repeats every 8,192 weeks (157 years), thus lasting until 2137 (157 years after GPS week zero).

Communication

The navigational signals transmitted by GPS satellites encode a variety of information including satellite positions, the state of the internal clocks, and the health of the network. These signals are transmitted on two separate carrier frequencies that are common to all satellites in the network. Two different encodings are used: a public encoding that enables lower resolution navigation, and an encrypted encoding used by the U.S. military.

Message format

Each GPS satellite continuously broadcasts a *navigation message* on L1 (C/A and P/Y) and L2 (P/Y) frequencies at a rate of 50 bits per second (see bitrate). Each complete message takes 750 seconds ($12\frac{1}{2}$ minutes) to complete. The message structure has a basic format of a 1500-bit-long frame made up of five subframes, each subframe being 300 bits (6 seconds) long. Subframes 4 and 5 are subcommutated 25 times each, so that a complete data message requires the transmission of 25 full frames. Each subframe consists of ten words, each 30 bits long. Thus, with 300 bits in a subframe times 5 subframes in a frame times 25 frames in a message, each message is 37,500 bits long. At a transmission rate of 50-bit/s, this gives 750 seconds to transmit an entire almanac message (GPS). Each 30-second frame begins precisely on the minute or half-minute as indicated by the atomic clock on each satellite.[142]

GPS message format

Subframes	Description
1	Satellite clock, GPS time relationship
2–3	Ephemeris (precise satellite orbit)
4–5	Almanac component (satellite network synopsis, error correction)

The first subframe of each frame encodes the week number and the time within the week,[143] as well as the data about the health of the satellite. The second and the third subframes contain the *ephemeris* – the precise orbit for the satellite. The fourth and fifth subframes contain the *almanac*, which contains coarse orbit and status information for up to 32 satellites in the constellation as well as data related to error correction. Thus, to obtain an accurate satellite location from this transmitted message, the receiver must demodulate the message from each satellite it includes in its solution for 18 to 30 seconds. To collect all transmitted almanacs, the receiver must demodulate the message for 732 to 750 seconds or 12½ minutes.[144]

All satellites broadcast at the same frequencies, encoding signals using unique code-division multiple access (CDMA) so receivers can distinguish individual satellites from each other. The system uses two distinct CDMA encoding types: the coarse/acquisition (C/A) code, which is accessible by the general public, and the precise (P(Y)) code, which is encrypted so that only the U.S. military and other NATO nations who have been given access to the encryption code can access it.[145]

The ephemeris is updated every 2 hours and is sufficiently stable for 4 hours, with provisions for updates every 6 hours or longer in non-nominal conditions. The almanac is updated typically every 24 hours. Additionally, data for a few weeks following is uploaded in case of transmission updates that delay data upload.

Satellite frequencies

All satellites broadcast at the same two frequencies, 1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal). The satellite network uses a CDMA spread-spectrum technique[146]:607 where the low-bitrate message data is encoded with a high-rate pseudo-random (PRN) sequence that is different for each satellite. The receiver must be aware of the PRN codes for each satellite to reconstruct the actual message data. The C/A code, for civilian use, transmits data at 1.023 million chips per second, whereas the P code, for U.S. military use, transmits at 10.23 million chips per second. The actual internal reference of the satellites is 10.22999999543 MHz to compensate for relativistic effects[147][148] that make observers on the Earth perceive a different time reference with respect to the transmitters in orbit. The L1 carrier is modulated by both the C/A and P codes, while the L2 carrier is only modulated by

GPS frequency overview[146]:607

Band	Frequency	Description
L1	1575.42 MHz	Coarse-acquisition (C/A) and encrypted precision (P(Y)) codes, plus the L1 civilian (L1C) and military (M) codes on Block III and newer satellites.
L2	1227.60 MHz	P(Y) code, plus the L2C and military codes on the Block IIR-M and newer satellites.
L3	1381.05 MHz	Used for nuclear detonation (NUDET) detection.
L4	1379.913 MHz	Being studied for additional ionospheric correction.
L5	1176.45 MHz	Used as a civilian safety-of-life (SoL) signal on Block IIF and newer satellites.

the P code.[88] The P code can be encrypted as a so-called P(Y) code that is only available to military equipment with a proper decryption key. Both the C/A and P(Y) codes impart the precise time-of-day to the user.

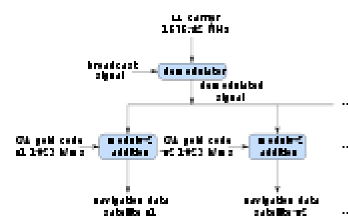
The L3 signal at a frequency of 1.38105 GHz is used to transmit data from the satellites to ground stations. This data is used by the United States Nuclear Detonation (NUDET) Detection System (USNDS) to detect, locate, and report nuclear detonations (NUDETs) in the Earth's atmosphere and near space.[149] One usage is the enforcement of nuclear test ban treaties.

The L4 band at 1.379913 GHz is being studied for additional ionospheric correction.[146]:607

The L5 frequency band at 1.17645 GHz was added in the process of GPS modernization. This frequency falls into an internationally protected range for aeronautical navigation, promising little or no interference under all circumstances. The first Block IIF satellite that provides this signal was launched in May 2010.[150] On February 5, 2016, the 12th and final Block IIF satellite was launched.[151] The L5 consists of two carrier components that are in phase quadrature with each other. Each carrier component is bi-phase shift key (BPSK) modulated by a separate bit train. "L5, the third civil GPS signal, will eventually support safety-of-life applications for aviation and provide improved availability and accuracy."[152]

In 2011, a conditional waiver was granted to LightSquared to operate a terrestrial broadband service near the L1 band. Although LightSquared had applied for a license to operate in the 1525 to 1559 band as early as 2003 and it was put out for public comment, the FCC asked LightSquared to form a study group with the GPS community to test GPS receivers and identify issue that might arise due to the larger signal power from the LightSquared terrestrial network. The GPS community had not objected to the LightSquared (formerly MSV and SkyTerra) applications until November 2010, when LightSquared applied for a modification to its Ancillary Terrestrial Component (ATC) authorization. This filing (SAT-MOD-20101118-00239) amounted to a request to run several orders of magnitude more power in the same frequency band for terrestrial base stations, essentially repurposing what was supposed to be a "quiet neighborhood" for signals from space as the equivalent of a cellular network. Testing in the first half of 2011 has demonstrated that the impact of the lower 10 MHz of spectrum is minimal to GPS devices (less than 1% of the total GPS devices are affected). The upper 10 MHz intended for use by LightSquared may have some impact on GPS devices. There is some concern that this may seriously degrade the GPS signal for many consumer uses.[153][154] *Aviation Week* magazine reports that the latest testing (June 2011) confirms "significant jamming" of GPS by LightSquared's system.[155]

Demodulation and decoding



Demodulating and Decoding GPS Satellite Signals using the Coarse/Acquisition Gold code.

Because all of the satellite signals are modulated onto the same L1 carrier frequency, the signals must be separated after demodulation. This is done by assigning each satellite a unique binary sequence known as a Gold code. The signals are decoded after demodulation using addition of the Gold codes corresponding to the satellites monitored by the receiver.[156][157]

If the almanac information has previously been acquired, the receiver picks the satellites to listen for by their PRNs, unique numbers in the range 1 through 32. If the almanac information is not in memory, the receiver enters a search mode until a lock is obtained on one of the satellites. To obtain a lock, it is necessary that there be an unobstructed line of sight from the receiver to the satellite. The receiver can then acquire the almanac and determine the satellites it should listen for. As it detects each satellite's signal, it identifies it by its distinct C/A code pattern. There can be a delay of up to 30 seconds before the first estimate of position because of the need to read the ephemeris data.

Processing of the navigation message enables the determination of the time of transmission and the satellite position at this time. For more information see Demodulation and Decoding, Advanced.

Navigation equations

Problem statement

The receiver uses messages received from satellites to determine the satellite positions and time sent. The *x, y,* and *z* components of satellite position and the time sent (*s*) are designated as [x_i, y_i, z_i, s_i] where the subscript *i* denotes the satellite and has the value 1, 2, ..., *n*, where $n \geq 4$. When the time of message reception indicated by the on-board receiver clock is $\tilde{t}_i$, the true reception time is $t_i = \tilde{t}_i - b$, where *b* is the receiver's clock bias from the much more accurate GPS clocks employed by the satellites. The receiver clock bias is the same for all received satellite signals (assuming the satellite clocks are all perfectly synchronized). The message's transit time is $\tilde{t}_i - b - s_i$, where s_i is the satellite time. Assuming the message traveled at the speed of light, *c*, the distance traveled is $(\tilde{t}_i - b - s_i)\,c$.

For n satellites, the equations to satisfy are:

$$d_i = \left(\tilde{t}_i - b - s_i\right) c,\ i = 1, 2, \dots, n$$

where d_i is the geometric distance or range between receiver and satellite *i* (the values without subscripts are the *x, y,* and *z* components of receiver position):

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}$$

Defining *pseudoranges* as $p_i = \left(\tilde{t}_i - s_i\right) c$, we see they are biased versions of the true range:

$$p_i = d_i + bc,\ i = 1, 2, \dots, n\ .$$[158][159]

Since the equations have four unknowns [*x, y, z, b*]—the three components of GPS receiver position and the clock bias—signals from at least four satellites are necessary to attempt solving these equations. They can be solved by algebraic or numerical methods. Existence and uniqueness of GPS solutions are discussed by Abell and Chaffee.[74] When *n* is greater than four, this system is overdetermined and a fitting method must be used.

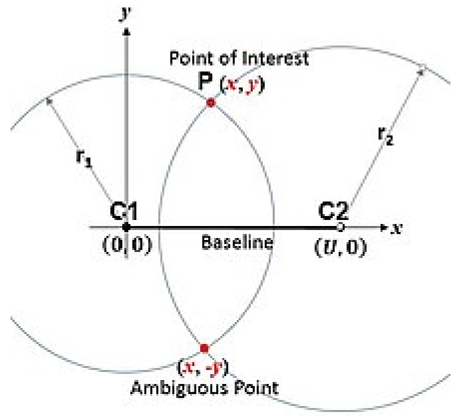
The amount of error in the results varies with the received satellites' locations in the sky, since certain configurations (when the received satellites are close together in the sky) cause larger errors. Receivers usually calculate a running estimate of the error in the calculated position. This is done by multiplying the basic resolution of the receiver by quantities called the geometric dilution of position (GDOP) factors, calculated from the relative sky directions of the satellites used.[160] The receiver location is expressed in a specific coordinate system, such as latitude and longitude using the WGS 84 geodetic datum or a country-specific system.[161]

Geometric interpretation

The GPS equations can be solved by numerical and analytical methods. Geometrical interpretations can enhance the understanding of these solution methods.

Spheres

The measured ranges, called pseudoranges, contain clock errors. In a simplified idealization in which the ranges are synchronized, these true ranges represent the radii of spheres, each centered on one of the transmitting satellites. The solution for the position of the receiver is then at the intersection of the surfaces of these spheres; see trilateration (more generally, true-range multilateration). Signals from at minimum three satellites are required, and their three spheres would typically intersect at two points.[162] One of the points is the location of the receiver, and the other moves rapidly in successive measurements and would not usually be on Earth's surface.



2-D Cartesian true-range multilateration (trilateration) scenario.

In practice, there are many sources of inaccuracy besides clock bias, including random errors as well as the potential for precision loss from subtracting numbers close to each other if the centers of the spheres are relatively close together. This means that the position calculated from three satellites alone is unlikely to be accurate enough. Data from more satellites can help because of the tendency for random errors to cancel out and also by giving a larger spread between the sphere centers. But at the same time, more spheres will not generally intersect at one point. Therefore, a near intersection gets computed, typically via least squares. The more signals available, the better the approximation is likely to be.

Hyperboloids

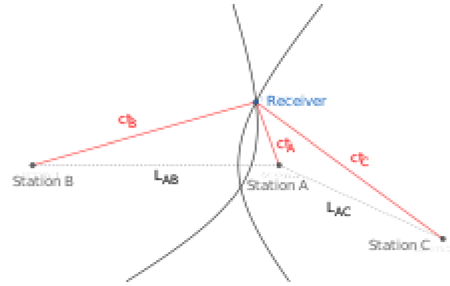
If the pseudorange between the receiver and satellite i and the pseudorange between the receiver and satellite j are subtracted, $p_i - p_j$, the common receiver clock bias (b) cancels out, resulting in a difference of distances $d_i - d_j$. The locus of points having a constant difference in distance to two points (here, two satellites) is a hyperbola on a plane and a hyperboloid of revolution (more specifically, a two-sheeted hyperboloid) in 3D space (see Multilateration). Thus, from four pseudorange measurements, the receiver can be placed at the intersection of the surfaces of three hyperboloids each with foci at a pair of satellites. With additional satellites, the multiple intersections are not necessarily unique, and a best-fitting solution is sought instead.[74][75][163][164][165][166]

Inscribed sphere

The receiver position can be interpreted as the center of an inscribed sphere (insphere) of radius bc, given by the receiver clock bias b (scaled by the speed of light c). The insphere location is such that it touches other spheres. The circumscribing spheres are centered at the GPS satellites, whose radii equal the measured pseudoranges p_i. This configuration is distinct from the one described above, in which the spheres' radii were the unbiased or geometric ranges d_i.[165]:36–37[167]

Hypercones

The clock in the receiver is usually not of the same quality as the ones in the satellites and will not be accurately synchronized to them. This produces pseudoranges with large differences compared to the true distances to the satellites. Therefore, in practice, the time difference between the receiver clock and the satellite time is defined as an unknown clock bias b. The equations are then solved simultaneously for the receiver position and the clock bias. The solution space $[x, y, z, b]$ can be seen as a four-dimensional spacetime, and signals from at minimum four satellites are needed. In that case each of the equations describes a hypercone (or spherical cone),[168] with the cusp located at the satellite, and the base a sphere around the satellite. The receiver is at the intersection of four or more of such hypercones.



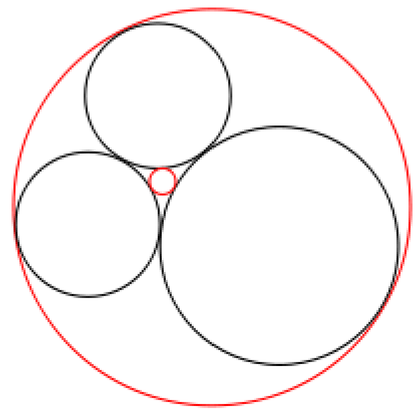
Three satellites (labeled as "stations" A, B, C) have known locations. The true times it takes for a radio signal to travel from each satellite to the receiver are unknown, but the true time differences are known. Then, each time difference locates the receiver on a branch of a hyperbola focused on the satellites. The receiver is then located at one of the two intersections.

Solution methods

Least squares

When more than four satellites are available, the calculation can use the four best, or more than four simultaneously (up to all visible satellites), depending on the number of receiver channels, processing capability, and geometric dilution of precision (GDOP).

Using more than four involves an over-determined system of equations with no unique solution; such a system can be solved by a least-squares or weighted least squares method.[158]



A smaller circle (**red**) inscribed and tangent to other circles (**black**), that need not necessarily be mutually tangent.

$$\left(\hat{x},\hat{y},\hat{z},\hat{b}\right)=\underset{(x,y,z,b)}{\arg\min}\sum_i\left(\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}+bc-p_i\right)^2$$

Iterative

Both the equations for four satellites, or the least squares equations for more than four, are non-linear and need special solution methods. A common approach is by iteration on a linearized form of the equations, such as the Gauss–Newton algorithm.

The GPS was initially developed assuming use of a numerical least-squares solution method—i.e., before closed-form solutions were found.

Closed-form

One closed-form solution to the above set of equations was developed by S. Bancroft.[159][169] Its properties are well known;[74][75][170] in particular, proponents claim it is superior in low-GDOP situations, compared to iterative least squares methods.[169]

Bancroft's method is algebraic, as opposed to numerical, and can be used for four or more satellites. When four satellites are used, the key steps are inversion of a 4x4 matrix and solution of a single-variable quadratic equation. Bancroft's method provides one or two solutions for the unknown quantities. When there are two (usually the case), only one is a near-Earth sensible solution.[159]

When a receiver uses more than four satellites for a solution, Bancroft uses the generalized inverse (i.e., the pseudoinverse) to find a solution. A case has been made that iterative methods, such as the Gauss–Newton algorithm approach for solving over-determined non-linear least squares problems, generally provide more accurate solutions.[171]

Leick et al. (2015) states that "Bancroft's (1985) solution is a very early, if not the first, closed-form solution."[172] Other closed-form solutions were published afterwards,[173][174] although their adoption in practice is unclear.

Error sources and analysis

GPS error analysis examines error sources in GPS results and the expected size of those errors. GPS makes corrections for receiver clock errors and other effects, but some residual errors remain uncorrected. Error sources include signal arrival time measurements, numerical calculations, atmospheric effects (ionospheric/tropospheric delays), ephemeris and clock data, multipath signals, and natural and artificial interference. Magnitude of residual errors from these sources depends on geometric dilution of precision. Artificial errors may result from jamming devices and threaten ships and aircraft[175] or from intentional signal degradation through selective availability, which limited accuracy to ≈ 6–12 m (20–40 ft), but has been switched off since May 1, 2000.[176][177]

Accuracy enhancement and surveying

GNSS enhancement refers to techniques used to improve the accuracy of positioning information provided by the Global Positioning System or other global navigation satellite systems in general, a network of satellites used for navigation.

Enhancement methods of improving accuracy rely on external information being integrated into the calculation process. There are many such systems in place and they are generally named or described based on how the GPS sensor receives the information. Some systems transmit additional information about sources of error (such as clock drift, ephemeris, or ionospheric delay), others provide direct measurements of how much the signal was off in the past, while a third group provide additional navigational or vehicle information to be integrated in the calculation process.

Regulatory spectrum issues concerning GPS receivers

In the United States, GPS receivers are regulated under the Federal Communications Commission's (FCC) Part 15 rules. As indicated in the manuals of GPS-enabled devices sold in the United States, as a Part 15 device, it "must accept any interference received, including interference that may cause undesired operation."[178] With respect to GPS devices in particular, the FCC states that GPS receiver manufacturers, "must use receivers that reasonably discriminate against reception of signals outside their allocated spectrum."[179] For the last 30 years, GPS receivers have operated next to the Mobile Satellite Service band, and have discriminated against reception of mobile satellite services, such as Inmarsat, without any issue.

The spectrum allocated for GPS L1 use by the FCC is 1559 to 1610 MHz, while the spectrum allocated for satellite-to-ground use owned by Lightsquared is the Mobile Satellite Service band.[180] Since 1996, the FCC has authorized licensed use of the spectrum neighboring the GPS band of 1525 to 1559 MHz to the Virginia company LightSquared. On March 1, 2001, the FCC received an application from LightSquared's predecessor, Motient Services, to use their allocated frequencies for an integrated satellite-terrestrial service.[181] In 2002, the U.S. GPS Industry Council came to an out-of-band-emissions (OOBE) agreement with LightSquared to prevent transmissions from LightSquared's ground-based stations from emitting transmissions into the neighboring GPS band of 1559 to 1610 MHz.[182] In 2004, the FCC adopted the OOBE agreement in its authorization for LightSquared to deploy a ground-based network ancillary to their satellite system – known as the Ancillary Tower Components (ATCs) – "We will authorize MSS ATC subject to conditions that ensure that the added terrestrial component remains ancillary to the principal MSS offering. We do not intend, nor will we permit, the terrestrial component to become a stand-alone service."[183] This authorization was reviewed and approved by the U.S. Interdepartment Radio Advisory Committee, which includes the U.S. Department of Agriculture, U.S. Space Force, U.S. Army, U.S. Coast Guard, Federal Aviation Administration, National Aeronautics and Space Administration (NASA), U.S. Department of the Interior, and U.S. Department of Transportation.[184]

In January 2011, the FCC conditionally authorized LightSquared's wholesale customers—such as Best Buy, Sharp, and C Spire—to only purchase an integrated satellite-ground-based service from LightSquared and re-sell that integrated service on devices that are equipped to only use the ground-based signal using LightSquared's allocated frequencies of 1525 to 1559 MHz.[185] In December 2010, GPS receiver manufacturers expressed concerns to the FCC that LightSquared's signal would interfere with GPS receiver devices[186] although the FCC's policy considerations leading up to the January 2011 order did not pertain to any proposed changes to the maximum number of ground-based LightSquared stations or the maximum power at which these stations could operate. The January 2011 order makes final authorization contingent upon studies of GPS interference issues carried out by a LightSquared led working group along with GPS industry and Federal agency participation. On February 14, 2012, the FCC initiated proceedings to vacate LightSquared's Conditional Waiver Order based on the NTIA's conclusion that there was currently no practical way to mitigate potential GPS interference.

GPS receiver manufacturers design GPS receivers to use spectrum beyond the GPS-allocated band. In some cases, GPS receivers are designed to use up to 400 MHz of spectrum in either direction of the L1 frequency of 1575.42 MHz, because mobile satellite services in those regions are broadcasting from space to ground, and at power levels commensurate with mobile satellite services.[187] As regulated under the FCC's Part 15 rules, GPS receivers are not warranted protection from signals outside GPS-allocated spectrum.[179] This is why GPS operates next to the Mobile Satellite Service band, and also why the Mobile Satellite Service band operates next to GPS. The symbiotic relationship of spectrum allocation ensures that users of both bands are able to operate cooperatively and freely.

The FCC adopted rules in February 2003 that allowed Mobile Satellite Service (MSS) licensees such as LightSquared to construct a small number of ancillary ground-based towers in their licensed spectrum to "promote more efficient use of terrestrial wireless spectrum."[188] In those 2003 rules, the FCC stated "As a preliminary matter, terrestrial [Commercial Mobile Radio Service ("CMRS")] and MSS ATC are expected to have different prices, coverage, product acceptance and distribution; therefore, the two services appear, at best, to be imperfect substitutes for one another that would be operating in predominantly different market segments... MSS ATC is unlikely to compete directly with terrestrial CMRS for the same customer base...". In 2004, the FCC clarified that the ground-based towers would be ancillary, noting that "We will authorize MSS ATC subject to conditions that ensure that the added terrestrial component remains ancillary to the principal MSS offering. We do not intend, nor will we permit, the terrestrial component to become a stand-alone service."[183] In July 2010, the FCC stated that it expected LightSquared to use its authority to offer an integrated satellite-terrestrial service to "provide mobile broadband services similar to those provided by terrestrial mobile providers and enhance competition in the mobile broadband sector."[189] GPS receiver manufacturers have argued that LightSquared's licensed spectrum of 1525 to 1559 MHz was never envisioned as being used for high-speed wireless broadband based on the 2003 and 2004 FCC ATC rulings making clear that the Ancillary Tower Component (ATC) would be, in fact, ancillary to the primary satellite component.[190] To build public support of efforts to continue the 2004 FCC authorization of LightSquared's ancillary terrestrial component vs. a simple ground-based LTE service in the Mobile Satellite Service band, GPS receiver manufacturer Trimble Navigation Ltd. formed the "Coalition To Save Our GPS."[191]

The FCC and LightSquared have each made public commitments to solve the GPS interference issue before the network is allowed to operate.[192][193] According to Chris Dancy of the Aircraft Owners and Pilots Association, airline pilots with the type of systems that would be affected "may go off course and not even realize it."[194] The problems could also affect the Federal Aviation Administration upgrade to the air traffic control system, United States Defense Department guidance, and local emergency services including 911.[194]

On February 14, 2012, the FCC moved to bar LightSquared's planned national broadband network after being informed by the National Telecommunications and Information Administration (NTIA), the federal agency that coordinates spectrum uses for the military and other federal government entities, that "there is no practical way to mitigate potential interference at this time".[195][196] LightSquared is challenging the FCC's action.

Similar systems

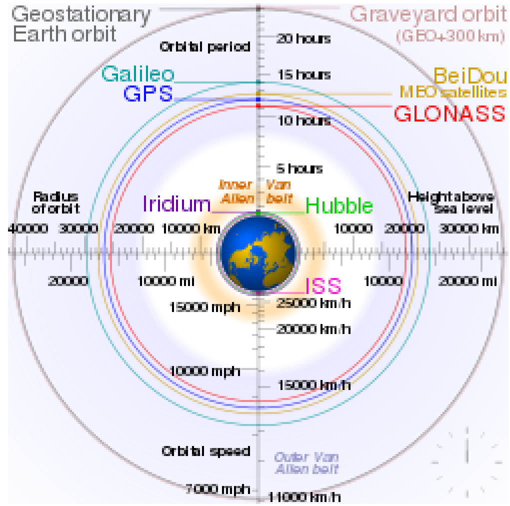
Other notable satellite navigation systems in use or various states of development include:

- Beidou – system deployed and operated by the People's Republic of China's, initiating global services in 2019.[197][198]
- Galileo – a global system being developed by the European Union and other partner countries, which began operation in 2016,[199] and is expected to be fully deployed by 2020.
- GLONASS – Russia's global navigation system. Fully operational worldwide.
- NavIC – a regional navigation system developed by the Indian Space Research Organisation.
- QZSS – a regional navigation system receivable in the Asia-Oceania regions, with a focus on Japan.

See also

- List of GPS satellites
- GPS satellite blocks
- GPS signals

- GPS navigation software
- GPS/INS
- GPS spoofing
- Indoor positioning system
- Local Area Augmentation System
- Local positioning system
- Military invention
- Mobile phone tracking
- Navigation paradox
- Notice Advisory to Navstar Users
- S-GPS



Orbit size comparison of GPS, GLONASS, Galileo, BeiDou-2, and Iridium constellations, the International Space Station, the Hubble Space Telescope, and geostationary orbit (and its graveyard orbit), with the Van Allen radiation belts and the Earth to scale.[b]

The Moon's orbit is around 9 times as large as geostationary orbit.[c] (In the SVG file, (https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg) hover over an orbit or its label to highlight it; click to load its article.)

Notes

a. In fact, the ship is unlikely to be at precisely 0m, because of tides and other factors which create a discrepancy between mean sea level and actual sea level. In the open ocean, high and low tide typically only differ by about 0.6m, but there are locations closer to land where they can differ by over 15m. See tidal range for more details and references.

b. Orbital periods and speeds are calculated using the relations $4\pi^2R^3 = T^2GM$ and $V^2R = GM$, where R is the radius of orbit in metres; T is the orbital period in seconds; V is the orbital speed in m/s; G is the gravitational constant, approximately 6.673×10^{-11} Nm^2/kg^2; M is the mass of Earth, approximately 5.98×10^{24} kg (1.318×10^{25} lb).

c. Approximately 8.6 times (in radius and length) when the Moon is nearest (that is, $\frac{363{,}104\text{ km}}{42{,}164\text{ km}}$), to 9.6 times when the Moon is farthest (that is, $\frac{405{,}696\text{ km}}{42{,}164\text{ km}}$).

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Satellite navigation

A **satellite navigation** or **satnav** system is a system that uses satellites to provide autonomous geo-spatial positioning. It allows satellite navigation devices to determine their location (longitude, latitude, and altitude/elevation) to high precision (within a few centimetres to metres) using time signals transmitted along a line of sight by radio from satellites. The system can be used for providing position, navigation or for tracking the position of something fitted with a receiver (satellite tracking). The signals also allow the electronic receiver to calculate the current local time to high precision, which allows time synchronisation. These uses are collectively known as Positioning, Navigation and Timing (PNT). Satnav systems operate independently of any telephonic or internet reception, though these technologies can enhance the usefulness of the positioning information generated.

The U.S. Space Force's Global Positioning System was the first global satellite navigation system and was the first to be provided as a free global service.

A satellite navigation system with global coverage may be termed a **global navigation satellite system** (**GNSS**). As of September 2020, the United States' Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), China's BeiDou Navigation Satellite System,[1] and the European Union's Galileo[2] are fully operational GNSSs. Japan's Quasi-Zenith Satellite System (QZSS) is a (US) GPS satellite-based augmentation system to enhance the accuracy of GPS, with satellite navigation independent of GPS scheduled for 2023.[3] The Indian Regional Navigation Satellite System (IRNSS) plans to expand to a global version in the long term.[4]

Global coverage for each system is generally achieved by a satellite constellation of 18–30 medium Earth orbit (MEO) satellites spread between several orbital planes. The actual systems vary, but all use orbital inclinations of >50° and orbital periods of roughly twelve hours (at an altitude of about 20,000 kilometres or 12,000 miles).

Contents

Classification

GNSS systems that provide enhanced accuracy and integrity monitoring usable for civil navigation are classified as follows:[5]

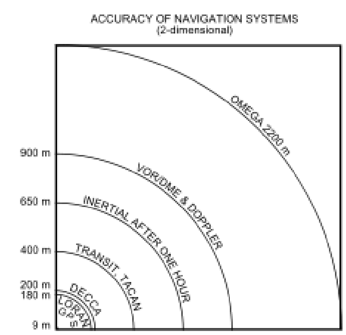
- **GNSS-1** is the first generation system and is the combination of existing satellite navigation systems (GPS and GLONASS), with Satellite Based Augmentation Systems (SBAS) or Ground Based Augmentation Systems (GBAS).[5] In the United States, the satellite based component is the Wide Area Augmentation System (WAAS), in Europe it is the European Geostationary Navigation Overlay Service (EGNOS), and in Japan it is the Multi-Functional Satellite Augmentation System (MSAS). Ground based augmentation is provided by systems like the Local Area Augmentation System (LAAS).[5]
- **GNSS-2** is the second generation of systems that independently provides a full civilian satellite navigation system, exemplified by the European Galileo positioning system.[5] These systems will provide the accuracy and integrity monitoring necessary for civil navigation; including aircraft. Initially, this system consisted of only Upper L Band frequency sets (L1 for GPS, E1 for Galileo, G1 for GLONASS). In recent years, GNSS systems have begun activating Lower L-Band frequency sets (L2 and L5 for GPS, E5a and E5b for Galileo, G3 for GLONASS) for civilian use; they feature higher aggregate accuracy and fewer problems with signal reflection.[6][7] As of late 2018, a few consumer grade GNSS devices are being sold that leverage both, and are typically called "Dual band GNSS" or "Dual band GPS" devices.

By their roles in the navigation system, systems can be classified as:

- Core Satellite navigation systems, currently GPS (United States), GLONASS (Russian Federation), Beidou (China) and Galileo (European Union).
- Global Satellite Based Augmentation Systems (SBAS) such as OmniSTAR and StarFire.
- Regional SBAS including WAAS (US), EGNOS (EU), MSAS (Japan), GAGAN (India), SDCM (Russia).
- Regional Satellite Navigation Systems such as India's NAVIC, and Japan's QZSS.
- Continental scale Ground Based Augmentation Systems (GBAS) for example the Australian GRAS and the joint US Coast Guard, Canadian Coast Guard, US Army Corps of Engineers and US Department of Transportation National Differential GPS (DGPS) service.
- Regional scale GBAS such as CORS networks.
- Local GBAS typified by a single GPS reference station operating Real Time Kinematic (RTK) corrections.

As many of the global GNSS systems (and augmentation systems) use similar frequencies and signals around L1, many "Multi-GNSS" receivers capable of using multiple systems have been produced. While some systems strive to interoperate with GPS as well as possible by providing the same clock, others do not.[8]

History



Ground based radio navigation is decades old. The DECCA, LORAN, GEE and Omega systems used terrestrial longwave radio transmitters which broadcast a radio pulse from a known "master" location, followed by a pulse repeated from a number of "slave" stations. The delay between the reception of the master signal and the slave signals allowed the receiver to deduce the distance to each of the slaves, providing a fix.

The first satellite navigation system was Transit, a system deployed by the US military in the 1960s. Transit's operation was based on the Doppler effect: the satellites travelled on well-known paths and broadcast their signals on a well-known radio frequency. The received frequency will differ slightly from the broadcast frequency because of the movement of the satellite with respect to the receiver. By monitoring this frequency shift over a short time interval, the receiver can determine its location to one side or the other of the satellite, and several such measurements combined with a precise knowledge of the satellite's orbit can fix a particular position. Satellite orbital position errors are caused by radio-wave refraction, gravity field changes (as the Earth's gravitational field is not uniform), and other phenomena. A team, led by Harold L Jury of Pan Am Aerospace Division in Florida from 1970-1973, found solutions and/or corrections for many error sources. Using real-time data and recursive estimation, the systematic and residual errors were narrowed down to accuracy sufficient for navigation.[9]

Principles

Part of an orbiting satellite's broadcast includes its precise orbital data. Originally, the US Naval Observatory (USNO) continuously observed the precise orbits of these satellites. As a satellite's orbit deviated, the USNO sent the updated information to the satellite. Subsequent broadcasts from an updated satellite would contain its most recent ephemeris.

Modern systems are more direct. The satellite broadcasts a signal that contains orbital data (from which the position of the satellite can be calculated) and the precise time the signal was transmitted. Orbital data include a rough almanac for all satellites to aid in finding them, and a precise ephemeris for this satellite. The orbital ephemeris is transmitted in a data message that is superimposed on a code that serves as a timing reference. The satellite uses an atomic clock to maintain synchronization of all the satellites in the constellation. The receiver compares the time of broadcast encoded in the transmission of three (at sea level) or four (which allows an altitude calculation also) different satellites, measuring the time-of-flight to each satellite. Several such measurements can be made at the same time to different satellites, allowing a continual fix to be generated in real time using an adapted version of trilateration: see GNSS positioning calculation for details.

Each distance measurement, regardless of the system being used, places the receiver on a spherical shell at the measured distance from the broadcaster. By taking several such measurements and then looking for a point where they meet, a fix is generated. However, in the case of fast-moving receivers, the position of the signal moves as signals are received from several satellites. In addition, the radio signals slow slightly as they pass through the ionosphere, and this slowing varies with the receiver's angle to the satellite, because that changes the distance through the ionosphere. The basic computation thus attempts to find the shortest directed line tangent to four oblate spherical shells centred on four satellites. Satellite navigation receivers reduce errors by using combinations of signals from multiple satellites and multiple correlators, and then using techniques such as Kalman filtering to combine the noisy, partial, and constantly changing data into a single estimate for position, time, and velocity.

Einstein's theory of general relativity is applied to GPS time correction, the net result is that time on a GPS satellite clock advances faster than a clock on the ground by about 38 microseconds per day. [10]

Applications

The original motivation for satellite navigation was for military applications. Satellite navigation allows precision in the delivery of weapons to targets, greatly increasing their lethality whilst reducing inadvertent casualties from mis-directed weapons. (See Guided bomb). Satellite navigation also allows forces to be directed and to locate themselves more easily, reducing the fog of war.

GNSS satellites used for navigation on a smartphone in 2021

Now a global navigation satellite system, such as Galileo, is used to determine users location and the location of other people or objects at any given moment. The range of application of satellite navigation in the future is enormous, including both the public and private sectors across numerous market segments such as science, transport, agriculture etc.[11]

The ability to supply satellite navigation signals is also the ability to deny their availability. The operator of a satellite navigation system potentially has the ability to degrade or eliminate satellite navigation services over any territory it desires.

Global navigation satellite systems

In order of first launch year:

GPS

First launch year: 1978

The United States' Global Positioning System (GPS) consists of up to 32 medium Earth orbit satellites in six different orbital planes. The exact number of satellites varies as older satellites are retired and replaced. Operational since 1978 and globally available since 1994, GPS is the world's most utilized satellite navigation system.

GLONASS

First launch year: 1982

The formerly Soviet, and now Russian, ***Glo**bal'naya **Na**vigatsionnaya **S**putnikovaya **S**istema*, (GLObal NAvigation Satellite System or GLONASS), is a space-based satellite navigation system that provides a civilian radionavigation-satellite service and is also used by the Russian Aerospace Defence Forces. GLONASS has full global coverage since 1995 and with 24 active satellites.

BeiDou

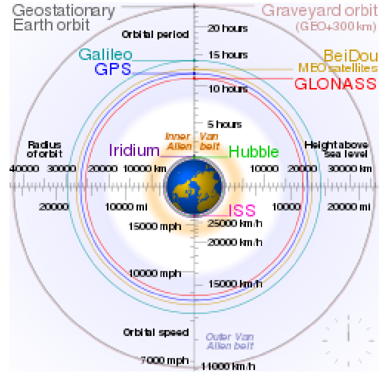
First launch year: 2000

BeiDou started as the now-decommissioned Beidou-1, an Asia-Pacific local network on the geostationary orbits. The second generation of the system BeiDou-2 became operational in China in December 2011.[12] The BeiDou-3 system is proposed to consist of 30 MEO satellites and five geostationary satellites (IGSO). A 16-satellite regional version (covering Asia and Pacific area) was completed by December 2012. Global service was completed by December 2018.[13] On 23 June 2020, the BDS-3 constellation deployment is fully completed after the last satellite was successfully launched at the Xichang Satellite Launch Center.[14]

Galileo

First launch year: 2011

The European Union and European Space Agency agreed in March 2002 to introduce their own alternative to GPS, called the Galileo positioning system. Galileo became operational on 15 December 2016 (global Early Operational Capability, EOC).[15] At an estimated cost of €10 billion,[16][17] the system of 30 MEO satellites was originally scheduled to be operational in 2010. The original year to become operational was 2014.[18] The first experimental satellite was launched on 28 December 2005.[19] Galileo is expected to be compatible with the modernized GPS system. The receivers will be able to combine the signals from both Galileo and GPS satellites to greatly increase the accuracy. The full Galileo constellation consists of 24 active satellites,[20] the last of which was launched in December 2021.[21][2] The main modulation used in Galileo Open Service signal is the Composite Binary Offset Carrier (CBOC) modulation.



Orbit size comparison of GPS, GLONASS, Galileo, BeiDou-2, and Iridium constellations, the International Space Station, the Hubble Space Telescope, and geostationary orbit (and its graveyard orbit), with the Van Allen radiation belts and the Earth to scale.[a]

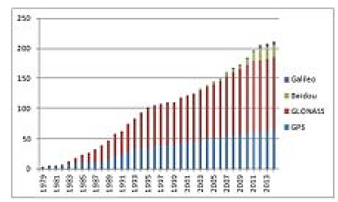
The Moon's orbit is around 9 times as large as geostationary orbit.[b] (In the SVG file, (https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg) hover over an orbit or its label to highlight it; click to load its article.)

Regional navigation satellite systems

NavIC

The NavIC or NAVigation with Indian Constellation is an autonomous regional satellite navigation system developed by Indian Space Research Organisation (ISRO). The government approved the project in May 2006, and consists of a constellation of 7 navigational satellites.[22] 3 of the satellites are placed in the Geostationary orbit (GEO) and the remaining 4 in the Geosynchronous orbit (GSO) to have a larger signal footprint and lower number of satellites to map the region. It is intended to provide an all-weather absolute position accuracy of better than 7.6 metres (25 ft) throughout India and within a region extending approximately 1,500 km (930 mi) around it.[23] An Extended Service Area lies between the primary service area and a rectangle area enclosed by the 30th parallel south to the 50th parallel north and the 30th meridian east to the 130th meridian east, 1,500–6,000 km beyond borders.[24] A goal of complete Indian control has been stated, with the space segment, ground segment and user receivers all being built in India.[25]

The constellation was in orbit as of 2018, and the system was available for public use in early 2018.[26] NavIC provides two levels of service, the "standard positioning service", which will be open for civilian use, and a "restricted service" (an encrypted one) for authorized users (including military). There are plans to expand NavIC system by increasing constellation size from 7 to 11.[27]



Launched GNSS satellites 1978 to 2014

QZSS

The Quasi-Zenith Satellite System (QZSS) is a four-satellite regional time transfer system and enhancement for GPS covering Japan and the Asia-Oceania regions. QZSS services were available on a trial basis as of January 12, 2018, and were started in November 2018. The first satellite was launched in September 2010.[28] An independent satellite navigation system (from GPS) with 7 satellites is planned for 2023.[29]

Comparison of systems

System	BeiDou	Galileo	GLONASS	GPS	NavIC	QZSS
Owner	China	European Union	Russia	United States	India	Japan
Coverage	Global	Global	Global	Global	Regional	Regional
Coding	CDMA	CDMA	FDMA & CDMA	CDMA	CDMA	CDMA
Altitude	21,150 km (13,140 mi)	23,222 km (14,429 mi)	19,130 km (11,890 mi)	20,180 km (12,540 mi)	36,000 km (22,000 mi)	32,600 km (20,300 mi) – 39,000 km (24,000 mi)[30]
Period	12.63 h (12 h 38 min)	14.08 h (14 h 5 min)	11.26 h (11 h 16 min)	11.97 h (11 h 58 min)	23.93 h (23 h 56 min)	23.93 h (23 h 56 min)
Rev./S. day	17/9 (1.888...)	17/10 (1.7)	17/8 (2.125)	2	1	1
Satellites	BeiDou-3: 28 operational (24 MEO, 3 IGSO, 1 GSO) 5 in orbit validation 2 GSO planned 20H1 BeiDou-2: 15 operational 1 in commissioning	By design: 27 operational + 3 spares Currently: 26 in orbit 24 operational 2 inactive 6 to be launched[31]	24 by design 24 operational 1 commissioning 1 in flight tests[32]	24 by design 30 operational[33]	8 operational (3 GEO, 5 GSO MEO)	4 operational (3 GSO, 1 GEO) 7 in the future
Frequency	1.561098 GHz (B1) 1.589742 GHz (B1-2) 1.20714 GHz (B2) 1.26852 GHz (B3)	1.559–1.592 GHz (E1) 1.164–1.215 GHz (E5a/b) 1.260–1.300 GHz (E6)	1.593–1.610 GHz (G1) 1.237–1.254 GHz (G2) 1.189–1.214 GHz (G3)	1.563–1.587 GHz (L1) 1.215–1.2396 GHz (L2) 1.164–1.189 GHz (L5)	1.17645 GHz(L5) 2.492028 GHz (S)	1.57542 GHz (L1C/A,L1C,L1S) 1.22760 GHz (L2C) 1.17645 GHz (L5,L5S) 1.27875 GHz (L6)[34]
Status	Operational[35]	Operating since 2016 2020 completion[31]	Operational	Operational	Operational	Operational
Accuracy	3.6 m or 12 ft (public) 0.1 m or 3.9 in (encrypted)	1 m or 3 ft 3 in (public) 0.01 m or 0.39 in (encrypted)	2–4 m or 6 ft 7 in – 13 ft 1 in	0.3–5 m or 1 ft 0 in – 16 ft 5 in (no DGPS or WAAS)	1 m or 3 ft 3 in (public) 0.1 m or 3.9 in (encrypted)	1 m or 3 ft 3 in (public) 0.1 m or 3.9 in (encrypted)
System	BeiDou	Galileo	GLONASS	GPS	NavIC	QZSS

Sources:[7]

Using multiple GNSS systems for user positioning increases the number of visible satellites, improves precise point positioning (PPP) and shortens the average convergence time.[36] The signal-in-space ranging error (SISRE) in November 2019 were 1.6 cm for Galileo, 2.3 cm for GPS, 5.2 cm for GLONASS and 5.5 cm for BeiDou when using real-time corrections for satellite orbits and clocks.[37]

Augmentation

GNSS augmentation is a method of improving a navigation system's attributes, such as accuracy, reliability, and availability, through the integration of external information into the calculation process, for example, the Wide Area Augmentation System, the European Geostationary Navigation Overlay Service, the Multi-functional Satellite Augmentation System, Differential GPS, GPS-aided GEO augmented navigation (GAGAN) and inertial navigation systems.

Related techniques

DORIS

Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) is a French precision navigation system. Unlike other GNSS systems, it is based on static emitting stations around the world, the receivers being on satellites, in order to precisely determine their orbital position. The system may be used also for mobile receivers on land with more limited usage and coverage. Used with traditional GNSS systems, it pushes the accuracy of positions to centimetric precision (and to millimetric precision for altimetric application and also allows monitoring very tiny seasonal changes of Earth rotation and deformations), in order to build a much more precise geodesic reference system.[38]

LEO satellites

The two current operational low Earth orbit (LEO) satellite phone networks are able to track transceiver units with accuracy of a few kilometres using doppler shift calculations from the satellite. The coordinates are sent back to the transceiver unit where they can be read using AT commands or a graphical user interface.[39][40] This can also be used by the gateway to enforce restrictions on geographically bound calling plans.

International regulation

The International Telecommunication Union (ITU) defines a **radionavigation-satellite service** (**RNSS**) as "a radiodetermination-satellite service used for the purpose of radionavigation. This service may also include feeder links necessary for its operation".[41]

RNSS is regarded as a safety-of-life service and an essential part of navigation which must be protected from interferences.

Classification

ITU Radio Regulations (article 1) classifies radiocommunication services as:

- Radiodetermination service (article 1.40)
- Radiodetermination-satellite service (article 1.41)
- Radionavigation service (article 1.42)
  - **Radionavigation-satellite service** (article 1.43)
  - Maritime radionavigation service (article 1.44)
    - Maritime radionavigation-satellite service (article 1.45)
  - Aeronautical radionavigation service (article 1.46)
    - Aeronautical radionavigation-satellite service (article 1.47)

Examples of RNSS use

- Augmentation system GNSS augmentation
- Automatic Dependent Surveillance–Broadcast
- BeiDou Navigation Satellite System (BDS)
- GALILEO, European GNSS
- Global Positioning System (GPS), with Differential GPS (DGPS)
- GLONASS
- NAVIC
- Quasi-Zenith Satellite System (QZSS)

Frequency allocation

The allocation of radio frequencies is provided according to *Article 5* of the ITU Radio Regulations (edition 2012).[42]

To improve harmonisation in spectrum utilisation, most service allocations are incorporated in national Tables of Frequency Allocations and Utilisations within the responsibility of the appropriate national administration. Allocations are:

- primary: indicated by writing in capital letters
- secondary: indicated by small letters
- exclusive or shared utilization: within the responsibility of administrations.

Allocation to services		
Region 1	Region 2	Region 3
5 000–5 010 MHz AERONAUTICAL MOBILE-SATELLITE (R) AERONAUTICAL RADIONAVIGATION **RADIONAVIGATION-SATELLITE (Earth-to-space)**		

See also

- Acronyms and abbreviations in avionics
- Geoinformatics
- GNSS positioning calculation
- GNSS reflectometry
- GPS spoofing
- GPS-aided geo-augmented navigation

- List of emerging technologies
- Pseudolite
- Receiver Autonomous Integrity Monitoring
- Software GNSS Receiver
- Space Integrated GPS/INS (SIGI)
- United Kingdom Global Navigation Satellite System
- UNSW School of Surveying and Geospatial Engineering

Notes

a. Orbital periods and speeds are calculated using the relations $4\pi^2R^3 = T^2GM$ and $V^2R = GM$, where R is the radius of orbit in metres; T is the orbital period in seconds; V is the orbital speed in m/s; G is the gravitational constant, approximately 6.673×10^{-11} Nm^2/kg^2; M is the mass of Earth, approximately 5.98×10^{24} kg (1.318×10^{25} lb).

b. Approximately 8.6 times (in radius and length) when the Moon is nearest (that is, $\frac{363{,}104 \text{ km}}{42{,}164 \text{ km}}$), to 9.6 times when the Moon is farthest (that is, $\frac{405{,}696 \text{ km}}{42{,}164 \text{ km}}$).

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Further reading

- Office for Outer Space Affairs of the United Nations (2010), *Report on Current and Planned Global and Regional Navigation Satellite Systems and Satellite-based Augmentation Systems*. [1] (http://www.oosa.unvienna.org/pdf/publications/icg_ebook.pdf)

External links

Information on specific GNSS systems

- ESA information on EGNOS (http://www.esa.int/esaNA/GGG63950NDC_egnos_0.html)
- Information on the Beidou system (https://web.archive.org/web/20020621064652/http://www.astronautix.com/craft/beidou.htm)
- Global Navigation Satellite System Fundamentals (https://www.ieee.li/pdf/viewgraphs/gnss_fundamentals.pdf)

Organizations related to GNSS

- United Nations International Committee on Global Navigation Satellite Systems (ICG) (http://www.unoosa.org/oosa/en/SAP/gnss/icg.html)
- Institute of Navigation (ION) GNSS Meetings (http://www.ion.org/meetings/#gnss)
- The International GNSS Service (IGS) (http://www.igs.org/)
- International Global Navigation Satellite Systems Society Inc (IGNSS) (http://www.ignss.org/)
- International Earth Rotation and Reference Systems Service (IERS) International GNSS Service (IGS) (http://www.iers.org/MainDisp.csl?pid=84-63)
- US National Executive Committee for Space-Based Positioning, Navigation, and Timing (http://www.pnt.gov/)
- US National Geodetic Survey (http://www.ngs.noaa.gov/orbits/) Orbits for the Global Positioning System satellites in the Global Navigation Satellite System
- UNAVCO GNSS Modernization (http://facility.unavco.org/science_tech/gnss_modernization.html)
- Asia-Pacific Economic Cooperation (APEC) GNSS Implementation Team (http://www.apecgit.org/)

Supportive or illustrative sites

- GPS and GLONASS Simulation (http://rhp.detmich.com/gps.html) (Java applet) Simulation and graphical depiction of the motion of space vehicles, including DOP computation.

- GPS, GNSS, Geodesy and Navigation Concepts in depth (http://northsurveying.com/index.php/soporte/gnss-and-geodesy-concepts)
- Overview of Military Satellite Navigation Technology - Defense Advancement (https://www.defenseadvancement.com/suppliers/military-satellite-navigation-gps-gnss/)

WIKIPEDIA

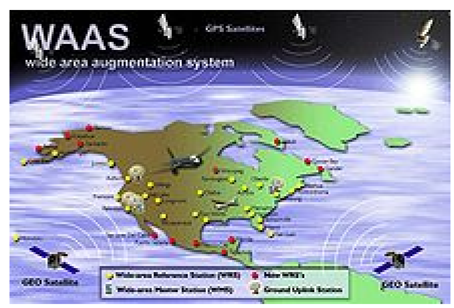
Wide Area Augmentation System

The **Wide Area Augmentation System** (**WAAS**) is an air navigation aid developed by the Federal Aviation Administration to augment the Global Positioning System (GPS), with the goal of improving its accuracy, integrity, and availability. Essentially, WAAS is intended to enable aircraft to rely on GPS for all phases of flight, including precision approaches to any airport within its coverage area.[1] It may be further enhanced with the Local Area Augmentation System (LAAS) also known by the preferred ICAO term Ground-Based Augmentation System (GBAS) in critical areas.

Wide Area Augmentation System (WAAS)

Country/ies of origin	United States
Operator(s)	FAA
Status	Operational
Coverage	United States, Canada, Mexico
Constellation size	
First launch	2003

WAAS uses a network of ground-based reference stations, in North America and Hawaii, to measure small variations in the GPS satellites' signals in the western hemisphere. Measurements from the reference stations are routed to master stations, which queue the received Deviation Correction (DC) and send the correction messages to geostationary WAAS satellites in a timely manner (every 5 seconds or better). Those satellites broadcast the correction messages back to Earth, where WAAS-enabled GPS receivers use the corrections while computing their positions to improve accuracy.



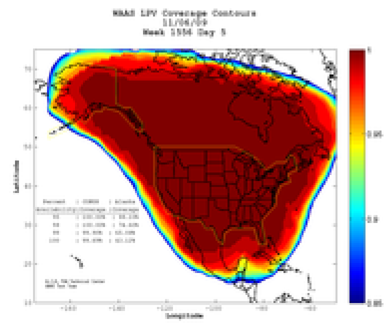
WAAS system overview

The International Civil Aviation Organization (ICAO) calls this type of system a satellite-based augmentation system (SBAS). Europe and Asia are developing their own SBASs, the Indian GPS Aided Geo Augmented Navigation (GAGAN), the European Geostationary Navigation Overlay Service (EGNOS), the Japanese Multi-functional Satellite Augmentation System (MSAS) and the Russian System for Differential Corrections and Monitoring (SDCM), respectively. Commercial systems include StarFire, OmniSTAR, and Atlas.

Contents

WAAS objectives

Accuracy



Typical WAAS service area. Dark red indicates best WAAS coverage. The service contours change over time with satellite geometry and ionospheric conditions.

A primary goal of the WAAS system was to allow aircraft to make a Category I approach without any equipment being installed at the airport. This would allow new GPS-based instrument landing approaches to be developed for any airport, even ones without any ground equipment. A Category I approach requires an accuracy of 16 metres (52 ft) laterally and 4.0 metres (13.1 ft) vertically.[2]

To meet this goal, the WAAS specification requires it to provide a position accuracy of 7.6 metres (25 ft) or less (for both lateral and vertical measurements), at least 95% of the time.[3] Actual performance measurements of the system at specific locations have shown it typically provides better than 1.0 metre (3 ft 3 in) laterally and 1.5 metres (4 ft 11 in) vertically throughout most of the contiguous United States and large parts of Canada and Alaska.[4]

Integrity

Integrity of a navigation system includes the ability to provide timely warnings when its signal is providing misleading data that could potentially create hazards. The WAAS specification requires the system detect errors in the GPS or WAAS network and notify users within 6.2 seconds.[3] Certifying that WAAS is safe for instrument flight rules (IFR) (i.e. flying in the clouds) requires proving there is only an extremely small probability that an error exceeding the requirements for accuracy will go undetected. Specifically, the probability is stated as 1×10^{-7}, and is equivalent to no more than 3 seconds of bad data per year. This provides integrity information equivalent to or better than Receiver Autonomous Integrity Monitoring (RAIM).[5]

Availability

Availability is the probability that a navigation system meets the accuracy and integrity requirements. Before the advent of WAAS, GPS specifications allowed for system unavailability for as much as a total time of four days per year (99% availability). The WAAS specification mandates availability as 99.999% (five nines) throughout the service area, equivalent to a downtime of just over 5 minutes per year.[3][5]

Operation

WAAS reference station in Utqiagvik, Alaska

WAAS is composed of three main segments: the ground segment, space segment, and user segment.

Ground segment

The ground segment is composed of multiple Wide-area Reference Stations (WRS). These precisely surveyed ground stations monitor and collect information on the GPS signals, then send their data to three Wide-area Master Stations (WMS) using a terrestrial communications network. The reference stations also monitor signals from WAAS geostationary satellites, providing integrity information regarding them as well. As of October 2007 there were 38 WRSs: twenty in the contiguous United States (CONUS), seven in Alaska, one in Hawaii, one in Puerto Rico, five in Mexico, and four in Canada.[6][7]

Using the data from the WRS sites, the WMSs generate two different sets of corrections: fast and slow. The fast corrections are for errors which are changing rapidly and primarily concern the GPS satellites' instantaneous positions and clock errors. These corrections are considered user position-independent, which means they can be applied instantly by any receiver inside the WAAS broadcast footprint. The slow corrections include long-term ephemeric and clock error estimates, as well as ionospheric delay information. WAAS supplies delay corrections for a number of points (organized in a grid pattern) across the WAAS service area[1] (see User Segment, below, to understand how these corrections are used).

Once these correction messages are generated, the WMSs send them to two pairs of Ground Uplink Stations (GUS), which then transmit to satellites in the Space segment for rebroadcast to the User segment.[8]

Reference stations

Each FAA Air Route Traffic Control Center in the 50 states has a WAAS reference station, except for Indianapolis. There are also stations positioned in Canada, Mexico and Puerto Rico.[1] See List of WAAS reference stations for the coordinates of the individual receiving antennas.[9]

Space segment

The space segment consists of multiple communication satellites which broadcast the correction messages generated by the WAAS Master Stations for reception by the user segment. The satellites also broadcast the same type of range information as normal GPS satellites, effectively increasing the number of satellites available for a position fix. The space segment currently consists of three commercial satellites: *Eutelsat 117 West B*, *SES-15*, and *Galaxy 30*.[10][11][12]

Satellite History

The original two WAAS satellites, named *Pacific Ocean Region* (POR) and *Atlantic Ocean Region-West* (AOR-W), were leased space on Inmarsat III satellites. These satellites ceased WAAS transmissions on July 31, 2007. With the end of the Inmarsat lease approaching, two new satellites (Galaxy 15 and Anik F1R) were launched in late 2005. Galaxy 15 is a PanAmSat and Anik F1R is a Telesat. As with the previous satellites, these are leased services under the FAA's Geostationary Satellite Communications Control Segment contract with Lockheed Martin for WAAS geostationary satellite leased services, who were contracted to provide up to three satellites through the year 2016.[13]

A third satellite was later added to the system. From March to November 2010, the FAA broadcast a WAAS test signal on a leased transponder on the Inmarsat-4 F3 satellite.[14] The test signal was not usable for navigation, but could be received and was reported with the identification numbers PRN 133 (NMEA #46). In November 2010, the signal was certified as operational and made available for navigation.[15] Following in orbit testing, Eutelsat 117 West B, broadcasting signal on PRN 131 (NMEA #44), was certified as operational and made available for navigation on March 27, 2018. The SES 15 satellite was launched on May 18, 2017 and following an in-orbit test of several months, was set operational on July 15, 2019. In 2018, a contract was awarded to place a WAAS L-band payload on the Galaxy 30 satellite. The satellite was successfully launched on August 15, 2020, and the WAAS transmissions were set operational on April 26, 2022, re-using PRN 135 (NMEA #48).[16][17] After approximately three weeks with four active WAAS satellites, operational WAAS transmissions on Anik F1-R were ended on May 17, 2022.[17]

Satellite name and details	PRN	NMEA	Designator	Location	Active Period (Not in Test Mode)	Status	Signal Capability
Atlantic Ocean Region-West (https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1997-027A)	122	35	AORW	54°W, later moved to 142°W[18]	July 10, 2003 – July 31, 2017	*Ceased operational WAAS transmissions on July 31, 2017*	L1 Narrowband
Pacific Ocean Region (POR) (https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1996-070A)	134	47	POR	178°E	July 10, 2003 – July 31, 2017	*Ceased operational WAAS transmissions on July 31, 2017*	L1
Galaxy 15	135	48	CRW	133°W	November 2006 – July 25, 2019	*Ceased operational WAAS transmissions on July 25, 2019.*	L1, L5 (Test Mode)
Anik F1R	138	51	CRE	107.3°W	July 2007 – May 17, 2022	*Ceased operational WAAS transmissions on May 17, 2022.*[17]	L1, L5 (Test Mode)
Inmarsat-4 F3	133	46	AMR	98°W	November 2010 – November 9, 2017	*Ceased operational WAAS transmissions as of November 9, 2017.*[19]	L1 Narrowband, L5 (Test Mode)
Eutelsat 117 West B	131	44	SM9	117°W	March 2018 – Present	Operational	L1, L5 (Test Mode)
SES 15	133	46	S15	129°W	July 15, 2019 – Present	Operational	L1, L5 (Test Mode)
Galaxy 30	135	48	G30	125°W	April 26, 2022 – Present	Operational	L1, L5 (Test Mode)

In the table above, PRN is the satellite's actual Pseudo-Random Number code. NMEA is the satellite number sent by some receivers when outputting satellite information (NMEA = PRN - 87).

User segment

The user segment is the GPS and WAAS receiver, which uses the information broadcast from each GPS satellite to determine its location and the current time, and receives the WAAS corrections from the Space segment. The two types of correction messages received (fast and slow) are used in different ways.

The GPS receiver can immediately apply the fast type of correction data, which includes the corrected satellite position and clock data, and determines its current location using normal GPS calculations. Once an approximate position fix is obtained the receiver begins to use the slow corrections to improve its accuracy. Among the slow correction data is the ionospheric delay. As the GPS signal travels from the satellite to the receiver, it passes through the ionosphere. The receiver calculates the location where the signal pierced the ionosphere and, if it has received an ionospheric delay value for that location, corrects for the error the ionosphere created.

While the slow data can be updated every minute if necessary, ephemeris errors and ionosphere errors do not change this frequently, so they are only updated every two minutes and are considered valid for up to six minutes.[20]

History and development

The WAAS was jointly developed by the United States Department of Transportation (DOT) and the Federal Aviation Administration (FAA) as part of the Federal Radionavigation Program (http://gauss.gge.unb.ca/us1996frp.pdf) (DOT-VNTSC-RSPA-95-1/DOD-4650.5), beginning in 1994, to provide performance comparable to category 1 instrument landing system (ILS) for all aircraft possessing the appropriately certified equipment.[1] Without WAAS, ionospheric disturbances, clock drift, and satellite orbit errors create too much error and uncertainty in the GPS signal to meet the requirements for a precision approach (see GPS sources of error). A precision approach includes altitude information and provides course guidance, distance from the runway, and elevation information at all points along the approach, usually down to lower altitudes and weather minimums than non-precision approaches.

Prior to the WAAS, the U.S. National Airspace System (NAS) did not have the ability to provide lateral and vertical navigation for precision approaches for all users at all locations. The traditional system for precision approaches is the instrument landing system (ILS), which used a series of radio transmitters each broadcasting a single signal to the aircraft. This complex series of radios needs to be installed at every runway end, some offsite, along a line extended from the runway centerline, making the implementation of a precision approach both difficult and very expensive. The ILS system is composed of 180 different transmitting antennas at each point built. The newer system is free of huge antenna systems at each airport.

For some time the FAA and NASA developed a much improved system, the microwave landing system (MLS). The entire MLS system for a particular approach was isolated in one or two boxes located beside the runway, dramatically reducing the cost of implementation. MLS also offered a number of practical advantages that eased traffic considerations, both for aircraft and radio channels. Unfortunately, MLS would also require every airport and aircraft to upgrade their equipment.

During the development of MLS, consumer GPS receivers of various quality started appearing. GPS offered a huge number of advantages to the pilot, combining all of an aircraft's long-distance navigation systems into a single easy-to-use system, often small enough to be hand held. Deploying an aircraft navigation system based on GPS was largely a problem of developing new techniques and standards, as opposed to new equipment. The FAA started planning to shut down their existing long-distance systems (VOR and NDBs) in favor of GPS. This left the problem of approaches, however. GPS is simply not accurate enough to replace ILS systems. Typical accuracy is about 15 metres (49 ft), whereas even a "CAT I" approach, the least demanding, requires a vertical accuracy of 4 metres (13 ft).

This inaccuracy in GPS is mostly due to large "billows" in the ionosphere, which slow the radio signal from the satellites by a random amount. Since GPS relies on timing the signals to measure distances, this slowing of the signal makes the satellite appear farther away. The billows move slowly, and can be characterized using a variety of methods from the ground, or by examining the GPS signals themselves. By broadcasting this information to GPS receivers every minute or so, this source of error can be significantly reduced. This led to the concept of Differential GPS, which used separate radio systems to broadcast the correction signal to receivers. Aircraft could then install a receiver which would be plugged into the GPS unit, the signal being broadcast on a variety of frequencies for different users (FM radio for cars, longwave for ships, etc.). Broadcasters of the required power generally cluster around larger cities, making such DGPS systems less useful for wide-area navigation. Additionally, most radio signals are either line-of-sight, or can be distorted by the ground, which made DGPS difficult to use as a precision approach system or when flying low for other reasons.

The FAA considered systems that could allow the same correction signals to be broadcast over a much wider area, such as from a satellite, leading directly to WAAS. Since a GPS unit already consists of a satellite receiver, it made much more sense to send out the correction signals on the same frequencies used by GPS units, than to use an entirely separate system and thereby double the probability of failure. In addition to lowering implementation costs by "piggybacking" on a planned satellite launch, this also allowed the signal to be broadcast from geostationary orbit, which meant a small number of satellites could cover all of North America.

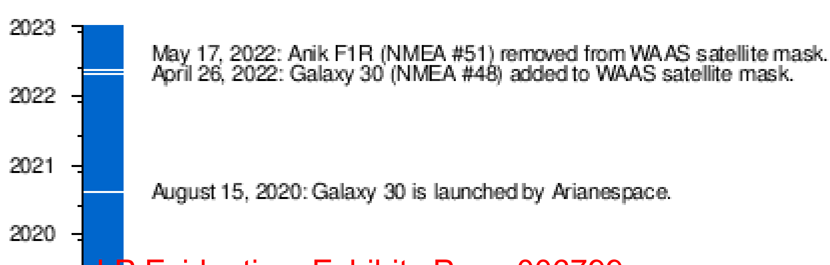
On July 10, 2003, the WAAS signal was activated for general aviation, covering 95% of the United States, and portions of Alaska offering 350 feet (110 m) minimums.

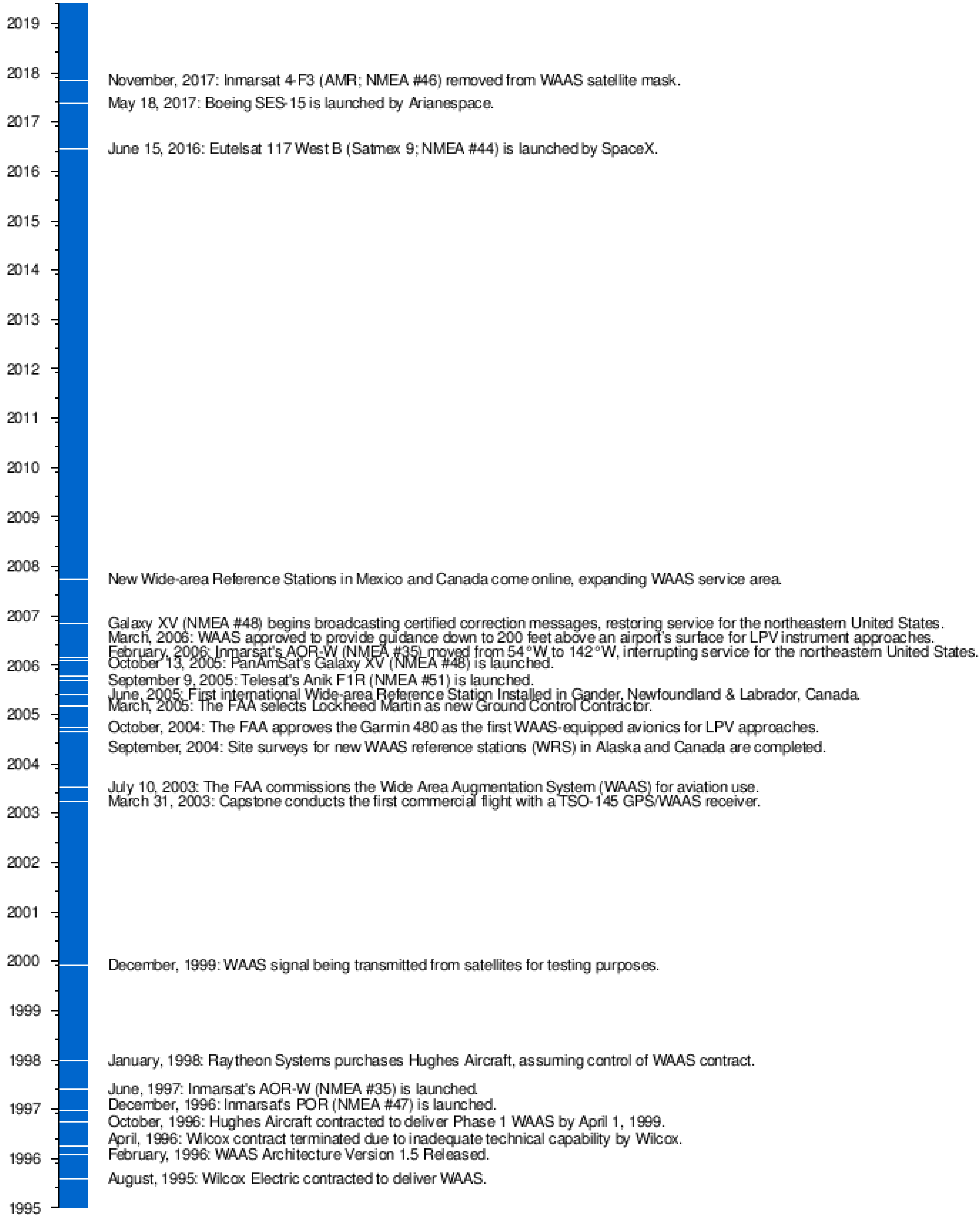
On January 17, 2008, Alabama-based Hickok & Associates became the first designer of helicopter WAAS with Localizer Performance (LP) and Localizer Performance with Vertical guidance (LPV) approaches, and the only entity with FAA-approved criteria (which even FAA has yet to develop).[21][22][23] This helicopter WAAS criteria offers as low as 250 foot minimums and decreased visibility requirements to enable missions previously not possible. On April 1, 2009, FAA AFS-400 approved the first three helicopter WAAS GPS approach procedures for Hickok & Associates' customer California Shock/Trauma Air Rescue (CALSTAR). Since then they have designed many approved WAAS helicopter approaches for various EMS hospitals and air providers, within the United States as well as in other countries and continents.

On December 30, 2009, Seattle-based Horizon Air flew the first scheduled-passenger service flight[24] using WAAS with LPV on flight 2014, a Portland to Seattle flight operated by a Bombardier Q400 with a WAAS FMS from Universal Avionics (http://www.uasc.com). The airline, in partnership with the FAA, will outfit seven Q400-aircraft with WAAS and share flight data to better determine the suitability of WAAS in scheduled air service applications.

Timeline

Wide-Area Augmentation System (WAAS) Timeline





[25]

Comparison of accuracy

A comparison of various radionavigation system accuracies

System	95% Accuracy (Lateral / Vertical)	Details
LORAN-C Specification	460 m / 460 m	The specified absolute accuracy of the LORAN-C system.
Distance Measuring Equipment (DME) Specification	185 m (Linear)	DME is a radionavigation aid that can calculate the linear distance from an aircraft to ground equipment.
GPS Specification	100 m / 150 m	The specified accuracy of the GPS system with the Selective Availability (SA) option turned on. SA was employed by the U.S. Government until May 1, 2000.
LORAN-C Measured Repeatability	50 m / 50 m	The U.S. Coast Guard reports "return to position" accuracies of 50 meters in time difference mode.
eLORAN Repeatability		Modern LORAN-C receivers, which use all the available signals simultaneously and H-field antennas.
Differential GPS (DGPS)	10 m / 10 m	This is the Differential GPS (DGPS) worst-case accuracy. According to the 2001 Federal Radionavigation Systems (FRS) report published jointly by the U.S. DOT and Department of Defense (DoD), accuracy degrades with distance from the facility; it can be < 1 m but will normally be < 10 m.
Wide Area Augmentation System (WAAS) Specification	7.6 m / 7.6 m	The worst-case accuracy that the WAAS must provide to be used in precision approaches.
GPS Measured	2.5 m / 4.7 m	The actual measured accuracy of the system (excluding receiver errors), with SA turned off, based on the findings of the FAA's National Satellite Test Bed, or NSTB.
WAAS Measured	0.9 m / 1.3 m	The actual measured accuracy of the system (excluding receiver errors), based on the NSTB's findings.
Local Area Augmentation System (LAAS) Specification		The goal of the LAAS program is to provide Category IIIC ILS capability. This will allow aircraft to land with zero visibility utilizing 'autoland' systems and will indicate a very high accuracy of < 1 m.[26]

Benefits

WAAS addresses all of the "navigation problem", providing highly accurate positioning that is extremely easy to use, for the cost of a single receiver installed on the aircraft. Ground- and space-based infrastructure is relatively limited, and no on-airport system is needed. WAAS allows a precision approach to be published for any airport, for the cost of developing the procedures and publishing the new approach plates. This means that almost any airport can have a precision approach and the cost of implementation is dramatically reduced.

Additionally WAAS works just as well between airports. This allows the aircraft to fly directly from one airport to another, as opposed to following routes based on ground-based signals. This can cut route distances considerably in some cases, saving both time and fuel. In addition, because of its ability to provide information on the accuracy of each GPS satellite's information, aircraft equipped with WAAS are permitted to fly at lower en-route altitudes than was possible with ground-based systems, which were often blocked by terrain of varying elevation. This enables pilots to safely fly at lower altitudes, not having to rely on ground-based systems. For unpressurized aircraft, this conserves oxygen and enhances safety.

WAAS ground uplink station (GUS) in Napa, California

The above benefits create not only convenience, but also have the potential to generate significant cost savings. The cost to provide the WAAS signal, serving all 5,400 public use airports, is just under US$50 million per year. In comparison, the current ground based systems such as the Instrument Landing System (ILS), installed at only 600 airports, cost US$82 million in annual maintenance. Without ground navigation hardware to purchase, the total cost of publishing a runway's WAAS approach is approximately US$50,000; compared to the $1,000,000 to $1,500,000 cost to install an ILS radio system.[27]

Drawbacks and limitations

For all its benefits, WAAS is not without drawbacks and critical limitations:

- Space weather. All man-made satellite systems are subject to space weather and space debris threats. For example, a solar super-storm event composed of an extremely large and fast earthbound Coronal Mass Ejection (CME) could disable the geosynchronous or GPS satellite elements of WAAS.
- The broadcasting satellites are geostationary, which causes them to be less than 10° above the horizon for locations north of 71.4° latitude. This means aircraft in areas of Alaska or northern Canada may have difficulty maintaining a lock on the WAAS signal.[28]
- To calculate an ionospheric grid point's delay, that point must be located between a satellite and a reference station. The low number of satellites and ground stations limit the number of points which can be calculated.
- Aircraft conducting WAAS approaches must possess certified GPS receivers, which are much more expensive than non-certified units. In 2006, Garmin's least expensive certified receiver, the GNS 430W, had a suggested retail price of US$10,750.[29]
- WAAS is not capable of the accuracies required for Category II or III ILS approaches. Thus, WAAS is not a sole-solution and either existing ILS equipment must be maintained or it must be replaced by new systems, such as the Local Area Augmentation System (LAAS).[30]
- WAAS Localizer Performance with Vertical guidance (LPV) approaches with 200-foot minimums will not be published for airports without medium intensity lighting, precision runway markings and a parallel taxiway. Smaller airports, which currently may not have these features, would have to upgrade their facilities or require pilots to use higher minimums.[27]
- As precision increases and error approaches zero, the navigation paradox states that there is an increased collision risk, as the likelihood of two craft occupying the same space on the shortest distance line between two navigational points has increased.

Future of WAAS

Improvement to aviation operations

In 2007, WAAS vertical guidance was projected to be available nearly all the time (greater than 99%), and its coverage encompasses the full continental U.S., most of Alaska, northern Mexico, and southern Canada.[31] At that time, the accuracy of WAAS would meet or exceed the requirements for Category 1 ILS approaches, namely, three-dimensional position information down to 200 feet (60 m) above touchdown zone elevation.[2]

Software improvements

Software improvements, to be implemented by September 2008, significantly improve signal availability of vertical guidance throughout the CONUS and Alaska. Area covered by the 95% available LPV solution in Alaska improves from 62% to 86%. And in the CONUS, the 100% availability LPV-200 coverage rises from 48% to 84%, with 100% coverage of the LPV solution.[7]

Space segment upgrades

Both Galaxy XV (PRN #135) and Anik F1R (PRN #138) contain an L1 & L5 GPS payload. This means they will potentially be usable with the L5 modernized GPS signals when the new signals and receivers become available. With L5, avionics will be able to use a combination of signals to provide the most accurate service possible, thereby increasing availability of the service. These avionics systems will use ionospheric corrections broadcast by WAAS, or self-generated onboard dual frequency corrections, depending on which one is more accurate.[32]

See also

- Satellite-based augmentation system (SBAS)
- EGNOS - the European operational SBAS
- MSAS - the Japanese operational SBAS
- GPS aided Geo Augmented Navigation (GAGAN), the Indian SBAS, currently under implementation.
- CDGPS Canadian Differential GPS
- Local Area Augmentation System (LAAS)
- Joint Precision Approach and Landing System (JPALS)
- Distance measuring equipment (DME)
- Instrument flight rules (IFR)
- Instrument landing system (ILS)
- Long-range radio navigation (LORAN)
- Microwave landing system (MLS)
- Non-directional beacon (NDB)
- Tactical air navigation system (TACAN)
- Transponder landing system (TLS)
- VHF omnidirectional range (VOR)
- Localizer performance with vertical guidance (LPV)

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External links

- FAA WJHTC's Real-Time Interactive WAAS Performance Display (http://www.nstb.tc.faa.gov/sms)
- FAA's WAAS program (http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/)
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WIKIPEDIA

Real-time kinematic positioning

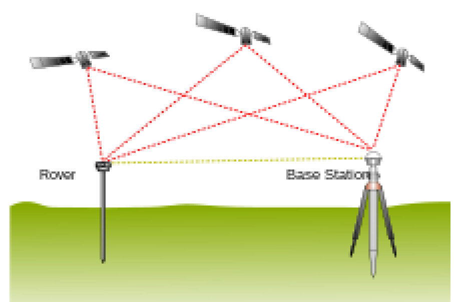
Real-time kinematic positioning (**RTK**) is the application of surveying to correct for common errors in current satellite navigation (GNSS) systems. It uses measurements of the phase of the signal's carrier wave in addition to the information content of the signal and relies on a single reference station or interpolated virtual station to provide real-time corrections, providing up to centimetre-level accuracy (see DGPS).[1] With reference to GPS in particular, the system is commonly referred to as **carrier-phase enhancement**, or **CPGPS**.[2] It has applications in land survey, hydrographic survey, and in unmanned aerial vehicle navigation.

GNSS RTK receiver being used to survey the forest population in Switzerland

Contents

Background

The distance between a satellite navigation receiver and a satellite can be calculated from the time it takes for a signal to travel from the satellite to the receiver. To calculate the delay, the receiver must align a pseudorandom binary sequence contained in the signal to an internally generated pseudorandom binary sequence. Since the satellite signal takes time to reach the receiver, the satellite's sequence is delayed in relation to the receiver's sequence. By increasingly delaying the receiver's sequence, the two sequences are eventually aligned.



RTK concept

The accuracy of the resulting range measurement is essentially a function of the ability of the receiver's electronics to accurately process signals from the satellite, and additional error sources such as non-mitigated ionospheric and tropospheric delays, multipath, satellite clock and ephemeris errors.[3]

Carrier-phase tracking

RTK follows the same general concept, but uses the satellite signal's carrier wave as its signal, ignoring the information contained within. RTK uses a fixed base station and a rover to reduce the rover's position error. The base station transmits correction data to the rover.

As described in the previous section, the range to a satellite is essentially calculated by multiplying the carrier wavelength times the number of whole cycles between the satellite and the rover and adding the phase difference. Determining the number of cycles is non-trivial, since signals may be shifted in phase by one or more cycles. This results in an error equal to the error in the estimated number of cycles times the wavelength, which is 19 cm for the L1 signal. Solving this so-called **integer ambiguity search** problem results in centimeter precision. The error can be reduced with sophisticated statistical methods that compare the measurements from the C/A signals and by comparing the resulting ranges between multiple satellites.

The improvement possible using this technique is potentially very high if one continues to assume a 1% accuracy in locking. For instance, in the case of GPS, the coarse-acquisition (C/A) code, which is broadcast in the L1 signal, changes phase at 1.023 MHz, but the L1 carrier itself is 1575.42 MHz, which changes phase over a thousand times more often. A ±1% error in L1 carrier-phase measurement thus corresponds to a ±1.9 mm error in baseline estimation.[4]

Practical considerations

In practice, RTK systems use a single base-station receiver and a number of mobile units. The base station re-broadcasts the phase of the carrier that it observes, and the mobile units compare their own phase measurements with the one received from the base station. There are several ways to transmit a correction signal from base station to mobile station. The most popular way to achieve real-time, low-cost signal transmission is to use a radio modem, typically in the UHF Band. In most countries, certain frequencies are allocated specifically for RTK purposes. Most land-survey equipment has a built-in UHF-band radio modem as a standard option. RTK provides accuracy enhancements up to about 20 km from the base station.[5]

RTK setup

This allows the units to calculate their *relative* position to within millimeters, although their absolute position is accurate only to the same accuracy as the computed position of the base station. The typical nominal accuracy for these systems is 1 centimetre ± 2 parts-per-million (ppm) horizontally and 2 centimetres ± 2 ppm vertically.[6]

Although these parameters limit the usefulness of the RTK technique for general navigation, the technique is perfectly suited to roles like surveying. In this case, the base station is located at a known surveyed location, often a benchmark, and the mobile units can then produce a highly accurate map by taking fixes relative to that point. RTK has also found uses in autodrive/autopilot systems, precision farming, machine control systems and similar roles.

The **RTK networks** extend the use of RTK to a larger area containing a network of reference stations.[7] Operational reliability and accuracy depend on the density and capabilities of the reference-station network.

A **Continuously Operating Reference Station** (CORS) network is a network of RTK base stations that broadcast corrections, usually over an Internet connection. Accuracy is increased in a CORS network, because more than one station helps ensure correct positioning and guards against a false initialization of a single base station.[8]

A **Virtual Reference Network** (VRN) can similarly enhance precision without using a base station.[9]

See also

- Differential GPS
- European Geostationary Navigation Overlay Service (EGNOS)
- Galileo positioning system
- Global Positioning System
- GLONASS
- BeiDou
- NavIC
- NTRIP

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External links

- RTK Detailed Concepts (http://northsurveying.com/index.php/soporte/gnss-and-geodesy-concepts) GNSS, RTK and Satellite Positioning concepts in depth.
- CORS Map (http://www.ngs.noaa.gov/CORS_Map/) Global Network of Continuously Operating Reference Stations.
- GBAS Map (https://www.google.com/maps/d/viewer?mid=zQ_LgHuo0o1o.k3Mrjox9GVjw) Global Map Coverage of Ground Based Augmentation Reference Beacons (GBAS).
- Guidelines (https://www.ngs.noaa.gov/PUBS_LIB/NGSRealTimeUserGuidelines.v2.1.pdf) User Guidelines for Single Base Real Time GNSS Positioning (NOAA)
- RTK Integration (http://gnssrtkmodule.com/index.php/manuals) Manual to integrate RTK Receivers into UAVs and Robotics
- History of RTK (https://amerisurv.com/2021/04/18/history-of-rtk-part-1-a-really-tough-problem-to-solve/) An article by people involved in the early days of RTK

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System integration

System Integration is defined in engineering as the process of bringing together the component sub-systems into one system (an aggregation of subsystems cooperating so that the system is able to deliver the overarching functionality) and ensuring that the subsystems function together as a system,[1] and in information technology[2] as the process of linking together different computing systems and software applications physically or functionally,[3] to act as a coordinated whole.

The system integrator integrates discrete systems utilizing a variety of techniques such as computer networking, enterprise application integration, business process management or manual programming.[4]

System integration involves integrating existing, often disparate systems in such a way "that focuses on increasing value to the customer"[5] (e.g., improved product quality and performance) while at the same time providing value to the company (e.g., reducing operational costs and improving response time).[5] In the modern world connected by Internet, the role of system integration engineers is important: more and more systems are designed to connect, both within the system under construction and to systems that are already deployed.[6]

Contents

Methods of integration

Vertical integration (as opposed to "horizontal integration") is the process of integrating subsystems according to their functionality by creating functional entities also referred to as silos.[7] The benefit of this method is that the integration is performed quickly and involves only the necessary vendors, therefore, this method is cheaper in the short term. On the other hand, cost-of-ownership can be substantially higher than seen in other methods, since in case of new or enhanced functionality, the only possible way to implement (scale the system) would be by implementing another silo. Reusing subsystems to create another functionality is not possible.[8]

Star integration, also known as **spaghetti integration**, is a process of systems integration where each system is interconnected to each of the remaining subsystems. When observed from the perspective of the subsystem which is being integrated, the connections are reminiscent of a star, but when the overall diagram of the system is presented, the connections look like spaghetti, hence the name of this method. The cost varies because of the interfaces that subsystems are exporting. In a case where the subsystems are exporting heterogeneous or proprietary interfaces, the integration cost can substantially rise. Time and costs needed to integrate the systems increase exponentially when adding additional subsystems. From the feature perspective, this method often seems preferable, due to the extreme flexibility of the reuse of functionality.[8]

Horizontal integration or **Enterprise Service Bus** (ESB) is an integration method in which a specialized subsystem is dedicated to communication between other subsystems. This allows cutting the number of connections (interfaces) to only one per subsystem which will connect directly to the ESB. The ESB is capable of translating the interface into another interface. This allows cutting the costs of integration and provides extreme flexibility. With systems integrated using this method, it is possible to completely replace one subsystem with another subsystem which provides similar functionality but exports different interfaces, all this completely transparent for the rest of the subsystems. The only action required is to implement the new interface between the ESB and the new subsystem.[8]

The horizontal scheme can be misleading, however, if it is thought that the cost of intermediate data transformation or the cost of shifting responsibility over business logic can be avoided.[8]

Industrial lifecycle integration is a system integration process that considers four categories or stages of integration: initial system implementation, engineering and design, project services, and operations.[9] This approach incorporates the requirements of each lifecycle stage of the industrial asset when integrating systems and subsystems. The key output is a standardized data architecture that can function throughout the life of the asset.

A **common data format** is an integration method to avoid every adapter having to convert data to/from every other applications' formats, Enterprise application integration (EAI) systems usually stipulate an application-independent (or common) data format.[10] The EAI system usually provides a data transformation service as well to help convert between application-specific and common formats. This is done in two steps: the adapter converts information from the application's format to the bus' common format. Then, semantic transformations are applied on this (converting zip codes to city names, splitting/merging objects from one application into objects in the other applications, and so on).

Challenges of integration

System integration can be challenging for organizations and these challenges can diminish their overall return on investment after implementing new software solutions. Some of these challenges include lack of trust and willing to share data with other companies, unwillingness to outsource various operations to a third party, lack of clear communication and responsibilities, disagreement from partners on where functionality should reside, high cost of integration, difficulty finding good talents, data silos, and common API standards.[11] These challenges result in creating hurdles that “prevent or slow down business systems integration within and among companies”.[12] Clear communication and simplified information exchange are key elements in building long term system integrations that can support business requirements.

Benefits of integration

On the other hand, system integration projects can be incredibly rewarding. For out-of-date, legacy systems, different forms of integration offer the ability to enable real-time data sharing. This can enable, for example, publisher-subscriber data distribution models, consolidated databases, event-driven architectures, reduce manual user data entry (which can also help reduce errors), refresh or modernize the application's front-end, and offload querying and reporting from expensive operational systems to cheaper commodity systems (which can save costs, enable scalability, and free up processing power on the main operational system). Usually, an extensive cost-benefit analysis is undertaken to help determine whether an integration project is worth the effort.

See also

- Artificial intelligence systems integration
- Continuous integration
- System in package and system on a chip
- Enterprise application integration
- Integration platform
- Integration Competency Center
- Interoperability
- System of record
- Systems integrator
- Multidisciplinary approach
- Cloud-based integration
- System design
- Modular design
- Connectivity Integrator
- Configuration design

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External links

- CSIA (Control System Integrators Association) (http://www.controlsys.org)

Examples

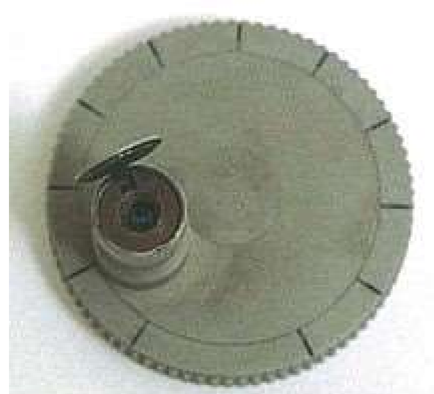
Tradecraft

Tradecraft, within the intelligence community, refers to the techniques, methods and technologies used in modern espionage (spying) and generally, as part of the activity of intelligence assessment. This includes general topics or techniques (dead drops, for example), or the specific techniques of a nation or organization

- Agent handling is the management of espionage agents, principal agents, and agent networks (called "assets") by intelligence officers, who are typically known as case officers.
- Analytic tradecraft is the body of specific methods for intelligence analysis.
- Black bag operations are covert or clandestine entries into structures or locations to obtain information for human intelligence operations. This may require breaking and entering, lock picking, safe cracking, key impressions, fingerprinting, photography, electronic surveillance (including audio and video surveillance), mail manipulation ("flaps and seals"), forgery, and a host of other related skills.

- Concealment devices are used to hide things for the purpose of secrecy or security. Examples in espionage include dead drop spikes for transferring notes or small items to other people, and hollowed-out coins or teeth for concealing suicide pills.
- Cryptography is the practice and study of techniques for secure communication in the presence of third parties (called adversaries).[1] More generally, it is about constructing and analyzing communications protocols that block adversaries.

(the particular form of encryption (encoding) used by the National Security Agency, for example).



This Mark IV microdot camera could be used to take pictures of documents. The microdot film was so tiny it could be hidden in a spy's personal effects and smuggled out of a location.

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- A cut-out is a mutually trusted intermediary, method or channel of communication, facilitating the exchange of information between agents. People playing the role of cutouts usually only know the source and destination of the information to be transmitted, but are unaware of the identities of any other persons involved in the espionage process. Thus, a captured cutout cannot be used to identify members of an espionage cell.
- A dead drop or "dead letter box" is a method of espionage tradecraft used to pass items between two individuals using a secret location and thus does not require them to meet directly. Using a dead drop permits a case officer and agent to exchange objects and information while maintaining operational security. The method stands in contrast to the 'live drop', so-called because two persons meet to exchange items or information.
- "Drycleaning" is a countersurveillance technique for discerning how many "tails" (following enemy agents) an agent is being followed by, and by moving about, seemingly oblivious to being tailed, perhaps losing some or all of those doing surveillance.[2]

Caltrop used by the US Office of Strategic Services. When scattered on a roadway or runway, the hollow spikes puncture self-sealing rubber tires. The hole in the center allows air to escape even if the other ends of the tube are sealed by soft ground.

- Eavesdropping is secretly listening to the conversation of others without their consent, typically using a hidden microphone or a "bugged" or "tapped" phone line.
- False flag operations is a covert military or paramilitary operation designed to deceive in such a way that the operations appear as though they are being carried out by entities, groups, or nation other than those who actually planned and executed them. Operations carried out during peacetime by civilian organizations, as well as covert government agencies, may by extension be called false flag.
- A front organization is any entity set up by and controlled by another organization, such as intelligence agencies. Front organizations can act for the parent group without the actions being attributed to the parent group. A front organization may appear to be a business, a foundation, or another organization.
- A honey trap is a deceptive operation in which an attractive agent lures a targeted person into a romantic liaison and encourages them to divulge secret information during or after a sexual encounter.
- Interrogation is a type of interviewing employed by officers of the police, military, and intelligence agencies with the goal of eliciting useful information from an uncooperative suspect. Interrogation may involve a diverse array of techniques, ranging from developing a rapport with the subject, to repeated questions, to sleep deprivation or, in some countries, torture.
- A legend refers to a person with a well-prepared and credible made-up identity (cover background) who may attempt to infiltrate a target organization, as opposed to recruiting a preexisting employee whose knowledge can be exploited.
- A limited hangout is a partial admission of wrongdoing, with the intent of shutting down the furthe inquiry.
- A microdot is text or an image substantially reduced in size onto a small disc to prevent detection by unintended recipients or officials who are searching for them. Microdots are, fundamentally, a steganographic approach to message protection. In Germany after the Berlin Wall was erected, special cameras were used to generate microdots that were then adhered to letters and sent through the mail. These microdots often went unnoticed by inspectors, and information could be read by the intended recipient using a microscope.

- A one-time pad is an encryption technique that cannot be cracked if used correctly. In this technique, a plaintext is paired with random, secret key (or *pad*).
- One-way voice link is typically a radio-based communication method used by spy networks to communicate with agents in the field typically (but not exclusively) using shortwave radio frequencies. Since the 1970s *infrared point to point communication systems* have been used that offer one-way voice links, but the number of users was always limited. A numbers station is an example of a one-way voice link, often broadcasting to a field agent who may already know the intended meaning of the code, or use a one-time pad to decode. These numbers stations will continue to broadcast gibberish or random messages according to their usual schedule; this is done to expend the resources of one's adversaries as they try in vain to make sense of the data, and to avoid revealing the purpose of the station or activity of agents by broadcasting solely when needed.

"Belly-buster", a hand-cranked audio drill strapped to an agent's stomach. It was used during the late 1950s and early 1960s to covertly drill holes into masonry for implanting audio devices, such as microphones.

- Steganography is the art or practice of concealing a message, image, or file within another message, image, or file. Generally, the hidden message will appear to be (or be part of) something else: images, articles, shopping lists, or some other *cover text*. For example, the hidden message may be in invisible ink between the visible lines of a private letter.[3] The advantage of steganography over cryptography alone is that the intended secret message does not attract attention to itself as an object of scrutiny. Plainly visible encrypted messages—no matter how unbreakable—will arouse interest, and may in themselves be incriminating in countries where encryption is illegal.[4] Cover achieves the same end by making the communication appear random or innocuous.
- Surveillance is the monitoring of the behavior, activities, or other changing information, usually of people for the purpose of influencing, managing, directing, or protecting them. This can include observation from a distance by means of electronic equipment (such as CCTV cameras), or interception of electronically transmitted information (such as Internet traffic or phone calls); and it can include simple, relatively no- or low-technology methods such as human intelligence agents watching a person and postal interception. The word surveillance comes from a French phrase for "watching over" ("sur" means "from above" and "veiller" means "to watch").
- TEMPEST is a National Security Agency specification and NATO certification[5][6] referring to spying on information systems through compromising emanations such as unintentional radio or electrical signals, sounds, and vibrations. TEMPEST covers both methods to spy upon others and also how to shield equipment against such spying. The protection efforts are also known as emission security (EMSEC), which is a subset of communications security (COMSEC).[7][8]

In popular culture

In books

In the books of such authors as thriller writer Grant Blackwood, espionage writer Tom Clancy, and spy novelists Ian Fleming and John le Carré, characters frequently engage in tradecraft, e.g., making or retrieving items from "dead drops", "dry cleaning", and wiring, using, or sweeping for intelligence gathering devices, such as cameras or microphones hidden in the subjects' quarters, vehicles, clothing, or accessories.

In film

- In the 2012 film *Zero Dark Thirty*, the main CIA operative Maya noted that her suspected senior al-Qaeda courier was exhibiting signs of using tradecraft.[9]
- In the 2006 action thriller motion picture *Mission: Impossible III*, an operative hid a microdot on the back of a postage stamp. The microdot contained a magnetically stored video file.
- In the 2003 sci-fi film *Paycheck*, a microdot is a key plot element; the film shows how well a microdot can be made to blend into an environment and how much information such a dot can carry.

See also

- Clandestine HUMINT operational techniques
- United States Geospatial Intelligence Foundation

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External links

- Tradecraft Notes - via Professor J. Ransom Clark, Muskingum College (http://intellit.muskingum.edu/analysis_folder/di_catn_Folder/contents.htm)

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Clandestine HUMINT operational techniques

The **Clandestine HUMINT** page adheres to the functions within the discipline, including espionage and active counterintelligence.

The page deals with **Clandestine HUMINT operational techniques**, also known as "tradecraft". It applies to clandestine operations for espionage, and a clandestine phase before direct action (DA) or unconventional warfare (UW). Clandestine HUMINT sources at certain times act as local guides for special reconnaissance (SR).

Many of the techniques are important in counterintelligence. Defensive counterintelligence personnel needs to recognize espionage, sabotage, and so on, in process. Offensive counterintelligence specialists may use them against foreign intelligence services (FIS). While DA and UW can be conducted by national military or paramilitary organizations, al-Qaeda and similar non-state militant groups that appear to use considerably different clandestine cell system structure, for command, control and operations, from those used by national forces. Cell systems are evolving to more decentralized models, sometimes because they are enabled by new forms of electronic communications.

This page deals primarily with one's assets. See double agent for additional information adversary sources that a country has turned to its side.

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Staff and skills in a clandestine HUMINT operations station

This description is based around the foreign intelligence service, of **country B**, operating in and against **country A**. It may also include operations against non-state organizations operating in **country B**, with or without **country B** support. It may also involve offensive counterintelligence against **country D** assets operating in **country B**.

The basic structure here can be pertinent to a domestic service operating against a non-national group within its borders. Depending on the legal structure of the country, there may be significant, or very few, restrictions on domestic HUMINT. The most basic question will be whether criminal prosecution, or stopping operations, is the goal. Typically, criminal prosecution will be the primary goal against drug and slavery groups, with breaking up their operations the secondary goal. These priorities, however, are apt to reverse in dealing with terrorist groups.

If there are separate organizations with diplomatic and nonofficial cover, there may be two chiefs. Sufficiently large stations may have several independent, compartmented groups.

Description	Soviet terminology	US terminology
Officers with diplomatic immunity	Diplomatic cover, emphasizing that GRU assumed that the host nation assumed all military attaches were intelligence officers but that some diplomats might actually be diplomats	Diplomatic cover
Public association with the service's country, but no diplomatic immunity	Civilian cover (e.g., Tass news agency, trade or scientific delegation)	Not often used. Personnel with Peace Corps and certain other backgrounds are barred from intelligence. Some, decreasing, cover as journalists now rarely used
No affiliation with host nation government	Illegal (usually with an assumed identity)	Nonofficial cover (NOC). May use real name or not, but often some invented background

Station under diplomatic cover

Nations vary as to how well hidden they choose to have all, part or none of their intelligence personnel under the guise of diplomatic immunity. Frequently, at least one individual is known to the host country, so there can be a deniable channel of communications. If the nations are allies, many of the intelligence personnel may be known and actively cooperating.

Certain diplomatic titles were often assumed to be cover jobs. With the United Kingdom, "passport control officer" was, much of the time, an intelligence position.[1] Today, it may be confusing that some passport control officers actually control passports. With other countries, "cultural attaché" was often a cover job, although, again, it might be legitimate. An intelligence officer covered as a cultural attaché might still do some cultural things.

- Chief of station or *rezident*. There may also be multiple chiefs if "country B" has both military and civilian human intelligence. Fairly recently, the US consolidated military and civilian into the National Clandestine Service. Russia still probably separates GRU military and SVR civilian, and the KGB, the USSR-era predecessor of the SVR, ran both illegal and legal residencies.
- Operations Officer, also called case officer: interacts with local assets or leaders of local agent subnetwork. Israel's Mossad refers to these as katsas.
- Collection Management Officer (aka Reports Officer, Intelligence Officer): does preliminary report categorization and organization. May be the administrative chief.
    - Communications and encryption personnel
    - Drivers and guards
- Operational Targeting Officer: not always used. May be more focused on access agents and recruiting, handing off recruited agents to case officers. Might make the decision to use non-HUMINT collection, such as SIGINT based in the embassy.
    - Technical collection specialists (e.g., the US Special Collection Service, a joint NSA-CIA operation)

Stations under official but nondiplomatic cover

An intermediate approach has the officers clearly working for their country but without diplomatic immunity and with a cover role that does not immediately suggest intelligence affiliation. For example, the Soviet GRU covered some intelligence officers under the TASS news agency, or as part of a trade or technical mission, or even as diplomats. The last might seem surprising but this was under a GRU assumption that military attaches would always be assumed to be intelligence officers, but that members of the civilian part of an embassy might actually be diplomats rather than intelligence officers.[2]

It was easier, of course, for the socialist USSR to assign people to state agencies. Western sensitivities tend to be much greater about using, for example, journalistic cover. The US has been emphatic in prohibiting any relationship between intelligence and the Peace Corps.

US military intelligence doctrine forbids a HUMINT specialist to pose as:

- A doctor, medic, or any other type of medical personnel.
- Any member of the International Committee of the Red Cross (ICRC) or its affiliates. Such a ruse is a violation of treaty obligations.
- A chaplain or clergyman.
- A journalist.
- A member of the civilian government, such as a Member of Parliament.[3]

An example of civilian cover for an American officer involved a German refugee, with the pseudonym "Stephan Haller", who had widely ranging interests and special skills in mathematics and physics, as well as native language skill. His overt role, in 1949, was directing a program that paid subsidies to German scientists, part of a larger program of denying German talent to the Soviets. Initially, he was based in Pforzheim, (West) Germany.[4]

During two years in Pforzheim, with a well-established cover, he collected political and scientific intelligence from the scientists and also Germans that he knew in political circles before emigrating. In 1951, he moved to Berlin, directing overall "operations against scientific targets in the East Zone of Germany", while still managing the subsidy program. His new work included encouraging defection of key craftsmen working for the Soviets. He was considered a master craftsman,

> He did not grow careless or conceited with success. Here remained a meticulous craftsman. Before he debriefed a source, he mastered the subject to be discussed. His agents were made comfortable not only by his cigars and beer but also by the easy flow of communication. And he did not end until he had every last scrap of useful information. He never failed, moreover, to remain alert for operational leads--potential agents, counterintelligence indicators, propaganda possibilities. When Haller was finished, there were no more questions to be asked. And though he groaned over the chore of putting it on paper, his reporting became thorough-and more than thorough, illuminating-for he rarely failed to make interpretive comments. [quotation?] [citation?]

Stations under non-official cover

According to Victor Suvorov, the Soviet reaction to losing networks operated from diplomatic missions – after the countries in which those embassies were located were overrun in the Second World War – was to emphasize "illegal" (i.e., what the US calls non-official cover) stations (i.e., residencies) for HUMINT networks. The illegal residencies were preferred to be in safe locations, perhaps of allies such as the United States, Great Britain and Canada.

Soviet operations were tightly compartmentalized, with strict need-to-know an absolute rule. "Undercover residencies support illegals, but only on instructions from the Centre without having any idea for whom they are working. All operations in support of illegals are worked out in such a way that the officers of the GRU undercover residency do not have one crumb of information which is not necessary. Operations are planned in such a way that there is no possibility of the illegals becoming dependent on the actions of the undercover residency." A lesson learned from the loss of espionage networks was to keep them small, subdividing them, with independent reporting to Center, when more agents were recruited.[5]

Moving new agents into illegal residencies

Suvorov explained that new agents were separated from official Soviet institutions only after the agent has compromised himself by giving Soviet Intelligence a significant quantity of secret material; making it impossible for the agent to go to the police. The separated agent then occupies one of three guises: the separated acting agent, the agent group and the agent residency.

Separated acting agent

Greatest resources are devoted to these agents; which provide the most important material. Once the central headquarters assesses the materials as sufficiently valuable, the doctrine is to temporarily stop obtaining new material from the agent and improve their security as well as their knowledge of espionage tradecraft. This training is preferably done in a third country, from which the agent might or might not be moved to the Soviet Union. Typical cover for an agent absence would be taking a vacation or holiday.

> Thence he will go back to his own country, but as an independently acting agent. He will be run exclusively by the Centre, in concrete terms the head of a section, even, in special cases, the head of a directorate and in extreme cases the deputy head of the GRU or the head himself. The running of such an agent is thus carried out exactly as the running of illegals is.

Agent group

Less valuable than a separated acting agent but still of importance, was the agent group, which migrated from diplomatic or civilian contact, to the in-country illegal *rezidentura* (resident and infrastructure), to direct communications with the Center. The leader of such a group is called, in Soviet terminology, a *gropovod*, and is conceptually the only member of the group that communicates with Moscow. In reality, clandestine communications personnel may be aware of the direct contact, but newer electronics allow the leader to manage his or her only communications.

Suvorov makes the important point that "A group automatically organises itself. The GRU obviously considers family groups containing the head of the family and his wife and children to be more secure and stable. The members of such a group may work in completely different fields of espionage." The pattern of having groups that are self-organizing and have preexisting ties, making them virtually impossible to infiltrate, has survived the GRU and is common in terrorist networks.

> Other agents recruited by residencies are gradually organised into agent groups of three to five men each. Usually, agents working in one particular field of espionage are put together in one group. Sometimes a group consists of agents who for various reasons are known to each other. Let us suppose that one agent recruits two others. ... Thus to a certain extent the members of agent groups are completely isolated from Soviet diplomatic representation. The agent group is in contact with the undercover residency for a period of time, then gradually the system of contact with the residency comes to an end and orders begin to be received directly from Moscow. By various channels the group sends it material directly to Moscow. Finally the contact with Moscow becomes permanent and stable and the agent group is entirely separated from the residency. With gradual changes in personnel at the residency, like the resident himself, the cipher officers and the operational officers with whom there was once direct contact, nobody outside the Centre will know of the existence of this particular group. Should it happen that operating conditions become difficult, or that the embassy is blockaded or closed down, the group will be able to continue its activities in the same way as before.[5]

Agent residency

When the GRU attaches one or more illegals (i.e., Soviet officer under an assumed identity), the residency changes from "an agent residency into an illegal residency. This process of increasing the numbers and the gradual self-generation of independent organisations continues endlessly." Suvorov uses a medical metaphor of quarantine designed to contain infection to describe separating agents for improved security.

The GRU kept certain officers immediately ready to go into illegal status, should the host nation intensify security.

> These officers are in possession of previously prepared documents and equipment, and gold, diamonds and other valuables which will be of use to them in their illegal activities will have been hidden in secret hiding-places beforehand. In case of war actually breaking out, these officers will unobtrusively disappear from their embassies. The Soviet government will register a protest and will for a short time refuse to exchange its diplomats for the diplomats of the aggressive country. Then it will capitulate, the exchange will take place and the newly fledged illegals will remain behind in safe houses and flats. Afterwards they will gradually, by using the system of secret rendezvous, begin to establish the system of contacts with agents and agent groups which have recently been subordinated to the undercover residency. Now they all form a new illegal residency. The new illegals never mix and never enter into contact with the old ones who have been working in the country for a long time. This plainly makes life more secure for both parties.[5]

Again, Suvorov emphasizes that the process of forming new illegal residencies was the Soviet doctrine for imposing compartmentation. Western countries, especially those in danger of invasion, have a related approach, the stay-behind network. The US military definition, used by most NATO countries, is

> Agent or agent organization established in a given country to be activated in the event of hostile overrun or other circumstances under which normal access would be denied.[6]

In such an approach, both clandestine intelligence and covert operations personnel live normal lives, perhaps carrying out regular military or government functions, but have prepared documentation of assumed identities, safehouses, secure communications, etc.

A representative illegal residency

Vilyam Genrikhovich Fisher, usually better known by his alias, Rudolf Abel, was a Soviet intelligence officer who came to the US under the false identity of a US citizen, Emil Robert Goldfus, who had died in infancy but was used by the USSR to create an elaborate **legend** for Fisher. On coming to the US, entering through Canada, Fisher/Abel took over the control of several existing Soviet HUMINT assets, and also recruited new assets. Key assets for whom he was the case officer included Lona Cohen and Morris Cohen, who were not direct intelligence collectors but **couriers** for a number of agents reporting on US nuclear information, including Julius Rosenberg, Ethel Rosenberg, David Greenglass, and Klaus Fuchs.

His role was that of the "illegal" resident in the US, under nonofficial cover. Soviet practice often was to have two **rezidents**, one illegal and one a diplomat under official cover. He was betrayed to the US by an alcoholic assistant who defected to the FBI.

That Fisher/Abel only had one assistant, with operational responsibilities, is not surprising. Unless a clandestine station has a strong cover identity, the larger the station, the larger the possibility it may be detected by counterintelligence organizations. Beyond the station chief, the most likely person to be associated with the station, not as a case officer, is a communicator, especially if highly specialized secure communication methods are used.

Support services

Some clandestine services may have additional capabilities for operations or support. Key operational agents of influence are apt to be run as singletons, although political considerations may require communication through cutouts. Useful idiots can be run by diplomatic case officers, since there is no particular secrecy about their existence or loyalty. Valuable volunteers, depending on the size of the volunteer group, may work either with case officers, or operations officers brought clandestinely into the area of operations.

Transportation, Infiltration, exfiltration, logistics

Proprietaries, which can be large businesses (e.g., the CIA proprietary airlines such as Air America, which, in the interest of cover, often had the latest aircraft and flew commercial as well as secret cargo), often are not controlled from the local area, but by headquarters. Especially when the proprietary is a multinational company, and has some commercial business of its own, central control makes the most sense.

In looking at internal as well as external assets, remember the fundamental rule of clandestine operations: the more secure, the less efficient. Because espionage operations need rigorous security, they are always inefficient — they take a lot of time, energy, and money. Proprietaries can be an exception, but, even though they make money, they can require additional capital to be able to expand in the same way a comparable private business would do so.[7]

Volunteer and proprietary support

Another kind of resource could include foreign offices owned or operated by nationals of the country in question. A step farther is a **proprietary**, or business, not just individuals, under non-official cover. Both kinds of business can provide information from recruitment, unwitting agents, or support functions. Small and medium aviation-related businesses have been popular US proprietaries, including Air America and Southern Air Transport.

Once the service has a presence in aviation, it may become aware of persons, in private business, civil service, or the military, who fly to destinations of interest. They may mention it in innocent conversation, such as at the airport's restaurant or bar. They also may be assumed to be going there, based by analysis of flight departure times, aircraft type, duration of trip, and their passengers or cargo.

Having routine access to an airport can reveal: "Who's coming and going, on and off the record? What's in the hangars and warehouses? What are the finances? Political connections and loyalties? Access to planes on the ground? Flight plans?" It must be emphasized that a transportation-related proprietary—truck stops, boat maintenance, and other industry-specific businesses, have to operate as a real business. Occasionally, they may produce a profit, and that can be confusing for headquarters financial managers, provide a local but perhaps traceable source of funds, or both.

Public relations firms have long been useful proprietaries.[8] In a given country of operations, or perhaps adjacent countries that are concerned about the actions of their neighbor, news releases placed by experienced public relations professionals can help mold relevant opinion. Care must be taken that the news release does not "blow back" on the clandestinely sponsoring country.

Another viable industry for proprietaries is natural resources exploration. If, hypothetically, a mining company operated in a country where there are both resources deposits and non-national group sanctuaries, a proprietary company could get information on both, and also provide access and support services. If the proprietary began mining operations, it would naturally have access to explosives, which might be made available to sabotage groups in neighboring areas.

Use of nongovernmental organizations (NGO) is politically sensitive and may require approval at the highest level of an agency. Sometimes, there is a broader policy need not to have the possibility of drawing suspicion onto an NGO. For example, in World War II, it was occasionally necessary to send supplies to Allied POWs, but Red Cross parcels were never ever used for this purpose. The decision had been made that Red Cross parcels were important to the survival of the POWs and could never be jeopardized.

Safehouses

"Safehouse" is a term of intelligence tradecraft whose origins may be lost in antiquity. "The Bible is also replete with instances of espionage, including Yahweh's instruction to Moses to send spies into the land of Canaan. The account of the harlot Rahab sheltering Israelite spies and betraying the city of Jericho might be the first documented instance of a "safe house."[9]

The term is not strictly limited to houses, although many intelligence services use rural houses for extended functions such as debriefing defectors. In a city, a safehouse may be an apartment or house that is not known to be associated with an intelligence service.

Another usage refers to mailing addresses (postal and electronic) and telephone numbers, to which messages can be sent with a reasonable chance of not coming into the awareness of counter-intelligence.

Useful idiots

Useful idiot is a term attributed to Lenin, principally in Soviet use, for a person overtly supporting the interests of one country (e.g., the USSR) in another (e.g., a member of the overt Communist Party of the second country). Soviet intelligence practice was to avoid such people in the actual clandestine operations, regarding them at most useful as distractions to the counterintelligence services.

Agents of influence, who were witting of Communist plans and intended to influence their own country's actions to be consistent with Soviet goals, went to great lengths to conceal any affiliation. "Witting" is a term of intelligence art that indicates that one is not only aware of a fact or piece of information, but also aware of its connection to intelligence activities. the Venona project communications intelligence exposes that Alger Hiss and Harry Dexter White, accused of Communist sympathies, were indeed Soviet spies. They were Communist agents, and the Soviets certainly did not treat them as useful idiots. There were communications with them, and the dialogues were clandestine.

Gus Hall also had overt Communist affiliation, and it is extremely unlikely Soviet clandestine operatives would have had anything to do with him. Still, in situations such as emergency exfiltration, Party members in a Western country might be called upon as a last desperate resort.

The propaganda model of communication explains that people write news favorable to those who pay for their job or that people are hired with favorable viewpoints to the hirer.

Basic agent recruiting

This section deals with the recruiting of human resources who do not work for a foreign intelligence service (FIS). For techniques of recruiting FIS personnel, see Counterintelligence.

In principle and best practice, all country B officers in country A report to an executive function in their home country. In CIA terms, this might be a head of a country desk or a regional desk. Russian practice was to refer to "Center".

Actual recruiting involves a direct approach by a case officer who has some existing access to the potential recruit, an indirect approach through an access agent or proprietary, or has reason to risk a "cold" approach. Before the direct recruitment, there may be a delicate period of development. For details, see Clandestine HUMINT asset recruiting.

Basic agent operations

This section deals with the general structure of running espionage operations. A subsequent section deals with Specialized Clandestine Functions, and another with Support Services for both basic and specialized operations

The agent may join, or even create, a new network. In the latter case, the agent may be called a *lead agent* or a *principal agent*. The latter term is also refers to access agents, who only help in recruiting.

Well-managed agent relationships can run for years and even decades; there are cases where family members, children at the time their parents were recruited, became full members of the network. Not all agents, however, operate in networks. A Western term for agents controlled as individuals is **singleton**. This term usually is reserved for the first or most sensitive recruitments, although specialized support personnel, such as radio operatives acting alone, are called singletons.[10] In Soviet tradecraft, the equivalent of a singleton is a separated acting agent. Professional intelligence officers, such as Robert Hanssen, may insist on being singletons, and go even farther, as with Hanssen, refuse in-person meetings. Even as a singleton, the agent will use security measures such as secure communications.

Agents also may operate in networks, for which the classic security structure is the **cell system**.

The agent may join a proprietary, although that is more likely to be for access or support agents.

Training

Before the agent actually starts to carry out assignment, training in tradecraft may be necessary. For security reasons, this ideally will be done outside the agent's own country, but such may not always be possible. Increasingly less desirable alternatives might be to conduct the training away from the operational area, as in a safe house in a resort, and then a safe house inside the operational area.

Among the first things to be taught are communications tradecraft, beginning with recording the material of interest. Skills here can include the operation of cameras appropriate for espionage, methods of carrying out documents without detection, secret writing.

Once the information is captured, it must be transmitted. The transmission may be impersonal, as with dead drops or car tosses. It may involve carriers. It may be electronic. If there is a need for personal meetings, the agent must know how to request them, and also to alert the network leader or case officer that the agent may be under suspicion.

Teaching countersurveillance techniques to agents is a calculated risk.[11] While it may be perfectly valid for an agent to abort a drop or other relatively innocent action, even at the cost of destroying valuable collected material, it is much more dangerous to teach the agent to elude active surveillance. The ability to elude professional counterintelligence personnel following the agent, for example, may confirm the counterintelligence organization's suspicion that they are dealing with a real agent.

Still, the agent may need to have an emergency escape procedure if he confirms he is under surveillance, or even if he is interrogated but released.

Continued testing during operations

Case officers should constantly test their agents for changes in motivation or possible counterintelligence compromise. While "name traces cannot be run on every person mentioned by the agent, do not be stingy with them on persons who have familial, emotional, or business ties with him" to detect any linkages to hostile counterintelligence.[11] Until an agent is well established as reliable, meetings must always be done with care to avoid detection. "The prime emphasis is put on vigilance and checking-has he been planted by the local counterintelligence, are his motives in agreeing to collaborate sincere? The need for personal meetings with such an agent is increased, for they give the opportunity to assess him more completely."[12]

An experienced US operations officer emphasized that field operations personnel should report status and progress often. Only with such reporting can a headquarters staff remain vigilant, looking globally for penetrations, and also aware of political implications. Reporting and headquarters advice is critical for joint operations (i.e., with the intelligence service of another country). Headquarters, aware of all joint operations with a given service, can give advice from a broader viewpoint without compromising the need for local initiative.[11]"

Operating the agent

Even with the most sensitive agents, occasional personal meetings are important in maintaining psychological control. Nevertheless, some agents, especially trained intelligence officers like Robert Hanssen, will almost never meet, but provide material good enough to prove their bona fides. A Soviet officer commented, whatever an agent's role in the intelligence net, personal contact should be made with him only when it is impossible to manage without it. The number of meetings should be kept as low as possible, especially with sources of valuable information.

> Personal meetings may be held to give an agent his next assignment and instructions for carrying it out, to train him in tradecraft or the use of technical or communications equipment, to transmit documents, reports, technical equipment, money, or other items, or to fulfill several of these purposes. In actual practice several purposes are usually served by a meeting. In addition to its particular objectives more general needs can be filled. A meeting held for training purposes may be a means for clarifying biographic data on the agent or his views on various subjects. At every meeting with an agent one should study him and obtain new data on his potential and talents, thereby providing a better basis for judging his sincerity and deciding how much trust to place in him.[12]

Agents, to varying extents, need reinforcement. Salary is important and also gives a lever of compromise, although pressing it too hard can offend a truly ideologically motivated agent. Some agents benefit from recognition that they can never show, such as a uniform of your service, or decorations from it.

Agents will be more comfortable if they believe that they will have protection, preferably exfiltration, if compromised. Protecting their families may be even more important. When the agent operates in a country with a particularly brutal counterintelligence service, providing them with a "final friend", or means for suicide, can be comforting even if they never use it.[13]

Agent communications

This section deals with skills required of individuals, either agents or support personnel. Most skills are concerned with communications.

Meeting places for personal meetings

A Soviet officer commented, perhaps counterintuitively, that it is harder to have longer meetings with agents when the case officer is under diplomatic cover. The reason is that local counterintelligence is aware of the case officer, where the existence of an illegal (i.e., nonofficial cover in US terms) officer may not be known to them. For the legal officer, "here it is best either to have reliable safehouses or to deliver the agent discreetly to the official residency building. The latter is a serious operational move. If neither is feasible, it is better to have Headquarters dispatch an officer to a third country, either legally or illegally, for the meeting."[12]

Clandestine transfer operated by humans

It is a case-by-case decision whether the material exchanged should have safeguards against accessing it in other than a precise manner. One straightforward protection method is to have the material on exposed photographic film, in a container that does not suggest that it contains film and might be, innocently, opened in a lighted room. Self-destruct devices also are possibilities, but they confirm that the transfer involved sensitive material.

Brush pass and other physical exchange with couriers

Under the general term "brush pass" is a wide range of techniques in which one clandestine operative passes a physical item to another operative.[14] "Brush" implies that the two people "brush" past one another, typically in a public place and preferably a crowd, where random people interfere with any visual surveillance. In a properly executed brush pass, the agents do not even stop walking; at most, they may appear to bump into one another.

During the brief contact, a common means of executing the exchange is for both to be carrying otherwise identical objects, such as a newspaper, briefcase, or magazine. The information being exchanged is in one of them. As the two people separate, they still appear to be holding the same object in the same hand.

More challenging versions are reminiscent of passing a baton in a relay race, and would be most commonly done with small objects such as a photographic film cartridge. In this more dangerous method, the transfer is from hand to hand, or from hand into a pocket. While this technique obviously takes better manual dexterity and is more prone to error, it has the countersurveillance advantage that the operatives are not carrying anything after the transfer, and can blend into a crowd even more easily.

A variation of the brush pass is the **live letter drop,** in which one agent follows a predefined route, on foot, with a prepared report hidden in a pocket. En route, a second agent unknown to the first agent picks his/her pocket and then passes the report on unread, either to a cut-out or to an intelligence officer. This technique presents opportunities both for plausible deniability and for penetration by hostile agents.

Dead drop

A dead drop is a container not easily found, such as a magnetized box attached to a metal rack in an out-of-sight alley. The box could be loosely buried. It should be possible to approach the container to fill or empty it, and not be easily observed from a street or window.

Typically, a clandestine collector will put espionage material, perhaps in encrypted form, into the box, and use some prearranged signal (i.e. signal site) to let a courier know that something needs to be taken out of the box and delivered to the next point on the route to the case officer. Such a route might have several dead drops. In some cases, the dead drop might be equipped with a device to destroy its contents unless it is opened properly.

Signals to tell a courier, or a case officer if there is no intermediate courier, that the dead drop needs service can be as simple as a piece of colored tape on a lamp post or perhaps a set of window shades raised and lowered in a specific pattern. While "wrong number" calls with a predefined apology can be used, they are more vulnerable to surveillance if the phone in question is tapped.

Representative dead drop device

Car tosses

A car toss can take many forms, one of which can be considered a moving dead drop. An agent or courier can put a magnetized box inside a bumper on a parked car.

In some cases, if a car can drive slowly down a street or driveway not easily observed, a courier can toss a message container into an open window, making the transfer method intermediate between a brush pass and a dead drop.

Cars with diplomatic immunity have advantages and disadvantages for tosses. They cannot be searched if the toss is observed, but they also are followed more easily. Diplomatic cars usually have distinctive markings or license plates, and may be equipped with electronic tracking devices. Counterintelligence could wait until the car is out of sight following a toss, then apprehend and interrogate the courier, or simply keep the courier under surveillance to discover another link in the message route.

Methods of protecting message content

A message left in a dead drop, or dropped during an improperly executed brush pass, is quite incriminating if counterintelligence personnel can immediately see suspicious information written on it. The ideal material for transfer looks quite innocuous.

At one time, invisible ink, a subset of steganography, was popular in espionage communications, because it was not visible to the naked eye without development by heat or chemicals. While computer-based steganographic techniques still are viable, modern counterintelligence laboratories have chemical and photographic techniques that detect the disturbance of paper fibers by the act of writing, so the invisible ink will not resist systematic forensic analysis. Still, if its existence is not suspected, the analysis may not be done.

Microphotography

Another technique, for hiding content that will resist casual examination, is to reduce the message to a photographic transparency or negative, perhaps the size of the dot over the letter "i" in this article. Such a technique needs both a laboratory and considerable technical skill, and is prone to damage and to accidentally falling off the paper. Still, it does have a countersurveillance value.[15]

Encryption

Encryption, especially using a theoretically secure method, when properly executed, such as the one-time pad,[16] is highly secure, but a counterintelligence agent seeing nonsense characters will immediately become suspicious of the message that has been captured. The very knowledge that a dead drop exists can cause it to be trapped or put under surveillance, and the member of a brush pass that carries it will be hard-pressed to explain it.

One-time pad encryption has the absolute requirement that the cryptographic key is used only once. Failure to follow this rule caused a serious penetration into Soviet espionage communications, through the Venona project analysis.[17]

It is extremely difficult for a nonprofessional to develop a cryptosystem, especially without computer support, that is impervious to the attack by a professional cryptanalyst, working for an agency with government resources, such as the US NSA or Russian *Spetssvyaz*.[16] Still, when the message is very short, the key is random or nearly random, some methods, like the Nihilist Straddling checkerboard may offer some resistance. Improvised methods are most useful when they only have to protect the information for a very short time, such as changing the location or time of an agent meeting scheduled in the same day.

Plain language code

Less suspicious when examined, although very limited in its ability to transfer more than simple content, is plain language code. For example, the final attack order for the Battle of Pearl Harbor came in a radio broadcast of the Japanese phrase, "Climb Mount Niitaka". Subsequent espionage communications referred to ships as different types of dolls at a doll repair shop.

Plain language code is most effective when used to trigger a preplanned operation, rather than transfer any significant amount of information.

Steganography, covert channels, and spread spectrum

Steganography, in the broadest sense of the word, is a technique of hiding information "in plain sight" within a larger message or messaging context. It is hard to detect because the secret message is a very small component of the larger amount, such as a few words hidden in a Web graphic.

Even more sophisticated computer-dependent methods can protect information. The information may or may not be encrypted. In spread-spectrum communications, the information is sent, in parallel, at very low level through a set of frequencies. Only when the receiver knows the frequencies, the time relationship on when a given frequency or other communications channel will carry content, and how to extract the content, can information be recovered. Basic spread spectrum uses a fixed set of frequencies, but the signal strength in any one frequency is too low to detect without correlation to other frequencies.

Frequency-hopping spread spectrum is a related technique, which can use the parallel transmission of true spread spectrum, not using any one frequency long enough for plausible interception. The pattern of variation among channels may be generated and received using cryptographic methods.

Methods of protecting against electronic detection of the fact of messaging

Avoiding detection of radio signals means minimizing the clandestine transmitter's exposure to hostile direction-finding. Modern techniques generally combine several methods:

- Burst transmission or otherwise minimizing
- High-gain antenna and/or directional antenna
- Receiver or relay away from detectors, as, for example, satellites.

Exploring agent information often meant a good deal of interaction, in which the home service would clarify what the agent reported, give new orders, etc. One approach used in World War II was the Joan-Eleanor system, which put the case officer into an aircraft at high altitude. From that altitude, there could be fast interaction in voice, so that they get to the key issues faster than with many separately encrypted and transmitted messages.[18] The modern equivalent is a small, low probability of intercept radio transceiver, using a directional antenna aimed at an orbiting satellite communications relay. Avoiding detection of radio communications involves all the principles of transmission and reception security.

Termination

For any number of reasons, a human source operation may need to be suspended for an indefinite time, or definitively terminated. This need rarely eliminates the need for protecting the fact of espionage, the support services, and the tradecraft and tools provided.

One of the most difficult challenges is ending an emotional relationship between the case officer and agent, which can exist in both directions. Sometimes, an agent is unstable, and this is a major complication; perhaps even requiring the evacuation of the agent. More stable agents may be happy with termination bonuses, and perhaps a future emigration opportunity, that do not draw attention to their own side's counterintelligence. In some instances, an intelligence agency may issue a "burn notice," indicating to other such agencies that an individual is an unreliable source of information.

Especially in the case of non-national organizations, termination can be very literal, ranging from having a trusted operative kill the problematic agent, or, when culturally appropriate, sending the agent on a suicide mission.

When the clandestine phase is preparation for a DA mission such as the 9/11 attacks, or the assassination attacks, using suicide bombers, by the Liberation Tigers of Tamil Eelam, termination of the operational cells is rather obvious. If there are support cells in the operational area, they may be vulnerable, but it would be good tradecraft to withdraw them shortly before the attack.

Special clandestine services

Agents of influence

An agent of influence, being witting or unwitting of the goals of a foreign power B, can influence the policy of Country A to be consistent with the goals of Country B.

In Soviet theory, influencing policy was one aspect of what they termed **active measures** (*aktivnyye meropriyatiya*). Active measures have a different connotation than the Western concept of direct action (DA), although Soviet active measures could include wet affairs (*mokrie dela*) conducted by Department V of the KGB, "wet" referring to the spilling of blood.

Strategic deception

Intelligence organizations occasionally use live, or even dead, persons to deceive the enemy about their intentions. One of the best-known such operations was the British Operation Mincemeat, in which a dead body, bearing carefully misleading documents, was put in British uniform, and floated onto a Spanish beach. In World War II, Spanish security services, while officially neutral, often passed information to the Germans, which, in this case, is exactly what the British wanted done. This operation was under the control of the Twenty Committee, part of the British strategic deception organization, the London Controlling Section. A related British operation in World War I was run by a controversial military officer, Richard Meinertzhagen, who prepared a knapsack containing false military plans, which the Ottoman allies of the Germans were allowed to capture. The plans related to false British strategy for the Sinai and Palestine Campaign, setting up a successful surprise attack in the Battle of Beersheba and the Third Battle of Gaza.

Active measures, however, reflected a national effort to influence other countries to act in concert with Soviet goals. These measures could involve state organizations up to and including the Politburo, much as the World War II British organization for strategic deception, the London Controlling Section, and its US counterpart, Joint Security Control, could get direct support from the head of government. Much of the Soviet responsibilities for active measures was focused in the KGB. Its "First Main Directorate uses active measures such as agents of influence, propaganda, and disinformation to promote Soviet goals."

In the present political context of Western democracies, the sensitivity, and separation, of clandestine and open contacts do not lend themselves to the process of building agents of influence.

"Active measures is not exclusively an intelligence activity, and in this sense it differs from the similar American concept of covert action. There are many differences between active measures and covert action. One is the Soviet ability to mesh overt and covert influence activities through centralized coordination of party, government, and ostensibly private organizations dealing with foreigners. Despite interagency coordination mechanisms, the United States is too pluralistic to achieve full coordination between all the overt and covert means of exercising influence abroad. Other major differences are in scope, intensity, and importance attributed to active measures and covert action, and in immunity from legal and political constraints."

While deception and influence operations could involve the highest levels of Allied governments in World War II, it is worth noting that while the West generally speaks of military deception, strategic deception operates at a higher level. A Soviet, and presumably Russian, term of art, *maskirovka* or 'denial and deception', is much broader than the current Western doctrine of deception being run by lower-level staff groups.

In the military, responsibility for maskirovka easily can be at the level of a deputy chief of the General Staff, who can call upon all levels of government.

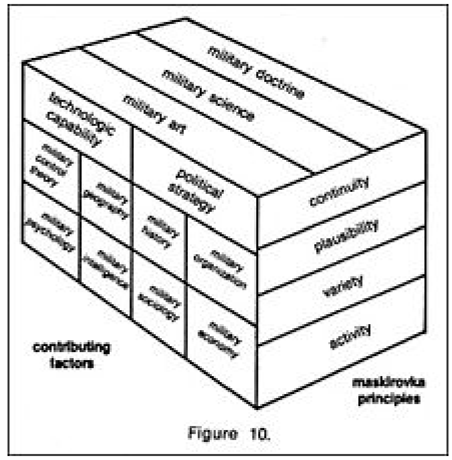
Returning to KGB doctrine, presumably still present in the SVR, "Influence operations integrate Soviet views into foreign leadership groups. Propaganda operations take the form of disinformation articles placed in the foreign press. Disinformation operations are false documents designed to incite enmity toward the United States."

"The Second Main Directorate of the KGB", whose responsibilities are now primarily in the Russian FSB, is responsible for the recruitment of agents among foreigners stationed in the Soviet Union. The KGB influences these people unwittingly, as most regard themselves too sophisticated to be manipulated.

"The second deception program is counterintelligence, which aims to neutralize the efforts of foreign intelligence services. It achieves this through the use of non-Soviet double agents and Soviet double agents. Non-Soviet double agents are foreign nationals who have been "turned". A Soviet double agent is a Soviet with access to classified information. These officials may be used as false defectors....[19]

"Influence operations integrate Soviet views into leadership groups. The agent of influence may be a well- placed, "trusted contact" who

- consciously serves Soviet interests on some matters while retaining his integrity on others
- an unwitting contact who is manipulated to take actions that advance Soviet interests on specific issues of common concern.



Russian concepts involve the full scope of grand strategy

Direct action services

There is no consensus on whether it is, or is not, advisable to intermingle espionage and direct action organizations, even at the headquarters level. See Clandestine HUMINT and Covert Action for more history and detail. A terminology point: current US terminology, ignoring an occasional euphemism, has now consolidated espionage into the National Clandestine Services. These are part of the CIA Directorate of Operations, which has some responsibility for Direct Action (DA) and Unconventional Warfare (UW), although the latter two, when of any appreciable size, are the responsibility of the military.

There is much more argument for doing so at headquarters, possibly not as one unit but with regular consultation. Certain services, such as name checks, communications, cover identities, and technical support may reasonably be combined, although the requirements of a particular field network should be held on a need-to-know basis.

Other countries might have the functions under the same organization, but run them in completely different networks. The only commonality they might have is emergency use of diplomatic facilities.

See also

- Tradecraft
- Undercover
- Honey trapping

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A Tradecraft Primer:
Structured Analytic Techniques
for Improving Intelligence Analysis

Prepared by the US Government

March 2009

This primer highlights structured analytic techniques—some widely used in the private sector and academia, some unique to the intelligence profession. It is not a comprehensive overview of how intelligence officers conduct analysis. Rather, the primer highlights how structured analytic techniques can help one challenge judgments, identify mental mindsets, stimulate creativity, and manage uncertainty. In short, incorporating regular use of techniques such as these can enable one to structure thinking for wrestling with difficult questions.

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THE "MIND-SET" CHALLENGE

Using the analytic techniques contained in this primer will assist analysts in dealing with the perennial problems of intelligence: the complexity of international developments, incomplete and ambiguous information, and the inherent limitations of the human mind. Understanding the intentions and capabilities of adversaries and other foreign actors is challenging, especially when either or both are concealed. Moreover, transnational threats today pose even greater complexity, in that they involve multiple actors—including nonstate entities—that can adapt and transform themselves faster than those who seek to monitor and contain them. Finally, globalization has increased the diversity of outcomes when complex, interactive systems such as financial flows, regional economies or the international system as a whole are in flux.[2]

The first hurdle for analysts is identifying the relevant and diagnostic information from the increasing volume of ambiguous and contradictory data that is acquired through open source and clandestine means. Analysts must also pierce the shroud of secrecy—and sometimes deception—that state and nonstate actors use to mislead. A systematic approach that considers a range of alternative explanations and outcomes offers one way to ensure that analysts do not dismiss potentially relevant hypotheses and supporting information resulting in missed opportunities to warn.

Cognitive and perceptual biases in human perception and judgment are another important reason for analysts to consider alternatives. As Richards Heuer and others have argued, all individuals assimilate and evaluate information through the medium of "mental models" (sometimes also called "frames" or "mind-sets"). These are experience-based constructs of assumptions and expectations both about the world in general and more specific domains. These constructs strongly influence what information analysts will accept—that is, data that are in accordance with analysts' unconscious mental models are more likely to be perceived and remembered than information that is at odds with them.

Mental models are critical to allowing individuals to process what otherwise would be an incomprehensible volume of information. Yet, they can cause analysts to overlook, reject, or forget important incoming or missing information that is not in accord with their assumptions and expectations. Seasoned analysts may be more susceptible to these mind-set problems as a result of their expertise and past success in using time-tested mental models. The key risks of mind-sets are that: analysts perceive what they expect to perceive; once formed, they are resistant to change; new information is assimilated, sometimes erroneously, into existing mental models; and conflicting information is often dismissed or ignored.

"Intelligence analysts should be self-conscious about their reasoning processes. They should think about how they make judgments and reach conclusions, not just about the judgments and conclusions themselves."

—Richards Heuer, *The Psychology of Intelligence Analysis*[1]

[1] Richards J. Heuer, Jr., *The Psychology of Intelligence Analysis* (Washington: Center for the Study of Intelligence, 1999).

[2] These observations were drawn from a lengthier treatment of cognitive bias found in the Sherman Kent Center's Occasional Paper, *Making Sense of Transnational Threats*, Vol. 3, No. 1, October 2004.

Common Perceptual and Cognitive Biases

Perceptual Biases	Biases in Evaluating Evidence
Expectations. We tend to perceive what we expect to perceive. More (unambiguous) information is needed to recognize an unexpected phenomenon. **Resistance**. Perceptions resist change even in the face of new evidence. **Ambiguities**. Initial exposure to ambiguous or blurred stimuli interferes with accurate perception, even after more and better information becomes available.	**Consistency.** Conclusions drawn from a small body of consistent data engender more confidence than ones drawn from a larger body of less consistent data. **Missing Information**. It is difficult to judge well the potential impact of missing evidence, even if the information gap is known. **Discredited Evidence**. Even though evidence supporting a perception may be proved wrong, the perception may not quickly change.
Biases in Estimating Probabilities	**Biases in Perceiving Causality**
Availability. Probability estimates are influenced by how easily one can imagine an event or recall similar instances. **Anchoring.** Probability estimates are adjusted only incrementally in response to new information or further analysis. **Overconfidence.** In translating feelings of certainty into a probability estimate, people are often overconfident, especially if they have considerable expertise.	**Rationality.** Events are seen as part of an orderly, causal pattern. Randomness, accident and error tend to be rejected as explanations for observed events. For example, the extent to which other people or countries pursue a coherent, rational, goal-maximizing policy is overestimated. **Attribution.** Behavior of others is attributed to some fixed nature of the person or country, while our own behavior is attributed to the situation in which we find ourselves.

Intelligence analysts must actively review the accuracy of their mind-sets by applying structured analytic techniques that will make those mental models more explicit and expose their key assumptions. The techniques found in this primer are designed to assist in this regard by:

- Instilling more structure into the intelligence analysis.
- Making analytic arguments more transparent by articulating them and challenging key assumptions.
- Stimulating more creative, "out-of-the-box" thinking and examining alternative outcomes, even those with low probability, to see if available data might support these outcomes.
- Identifying indicators of change (or signposts) that can reduce the chances of surprise.

Incorporating findings derived from these techniques into our intelligence products also serves the policymaker by:

- Highlighting potential changes that would alter key assessments or predictions.
- Identifying key assumptions, uncertainties, intelligence gaps and disagreements that might illuminate risks and costs associated with policy choices.
- Exploring alternative outcomes for which policy actions might be necessary.

Strategic Assumptions That Were Not Challenged
1941 World War II Japan would avoid all-out war because it recognized US military superiority. *Given that US superiority would only increase, Japan might view a first strike as the only way to knock America out of the war.*
1950s Korean War China would not cross the Yalu River in support of the North Korean government. *Red China could make good on its threats to counter "US aggression" against the North.*
1962 Cuban Missile Crisis The Soviet Union would not introduce offensive nuclear weapons into Cuba. *The Kremlin could miscalculate and believe it could create a fait accompli that a young US President would not be prepared to reverse.*
1973 Yom Kippur War Arabs knew they could not win because they had failed to cooperate in the past and still lacked sufficient air defenses to counter Israeli airpower. *A surprise Arab attack, even if repelled, could wound Israel psychologically and prompt international calls for cease-fires and diplomatic negotiations.*
1989 German Unification East Germany could not unify with the West Germany against the wishes of the Soviet Union. *The Soviet Union—under Gorbachev—might not be prepared to intervene militarily in Eastern Europe as it had in the past.*
1998 Indian Nuclear Test Conducting a nuclear test risked international condemnation and US sanctions and would threaten a newly elected coalition government. *A successful and surprise nuclear test could boost Indian nationalist pride and solidify public support for a shaky coalition government.*
2003 Iraq's WMD Programs Saddam failed to cooperate with UN inspectors because he was continuing to develop weapons of mass destruction. *If Iraqi authorities had destroyed their WMD stocks and abandoned their programs, they might refuse to fully acknowledge this to the UN to maintain Iraq's regional status, deterrence, and internal regime stability.*

The analytic techniques in this primer are designed to help individual analysts, as well as teams, explore and challenge their analytical arguments and mind-sets. Some techniques are fairly simple to understand and employ—such as Brainstorming and Devil's Advocacy. Others are more complex and demand a greater degree of analytical sophistication, resource commitment, and time. All the techniques are included because they have helped other analysts avoid rigid ways of thinking or assisted them in exploring new outcomes or implications of an intelligence problem.

The techniques are grouped by their purpose: **diagnostic** techniques are primarily aimed at making analytic arguments, assumptions, or intelligence gaps more transparent; **contrarian** techniques explicitly challenge current thinking; and **imaginative thinking** techniques aim at developing new insights, different perspectives and/or develop alternative outcomes. In fact, many of the techniques will do some combination of these functions. However, analysts will want to select the tool that best accomplishes the specific task they set out for themselves. Although application of these techniques alone is no guarantee of analytic precision or accuracy of judgments, it does improve the sophistication and credibility of intelligence assessments as well as their usefulness to policymakers. As Richards Heuer notes in his own work on cognitive bias, "analysis can be improved."[3]

[3] Heuer, *Psychology of Intelligence Analysis*, p. 184.

KEY ASSUMPTIONS CHECK

List and review the key working assumptions on which fundamental judgments rest.

WHEN TO USE

A Key Assumptions Check is most useful at the beginning of an analytic project. An individual analyst or a team can spend an hour or two articulating and reviewing the key assumptions. Rechecking assumptions also can be valuable at any time prior to finalizing judgments, to insure that the assessment does not rest on flawed premises. Identifying hidden assumptions can be one of the most difficult challenges an analyst faces, as they are ideas held—often unconsciously—to be true and, therefore, are seldom examined and almost never challenged.

A key assumption is any hypothesis that analysts have accepted to be true and which forms the basis of the assessment. For example, military analysis may focus exclusively on analyzing key technical and military variables (sometimes called factors) of a military force and "assume" that these forces will be operated in a particular environment (desert, open plains, arctic conditions, etc.). Postulating other conditions or assumptions, however, could dramatically impact the assessment. Historically, US analysis of Soviet-Warsaw Pact operations against NATO had to "assume" a level of non-Soviet Warsaw Pact reliability (e.g., would these forces actually fight?). In this case, there was high uncertainty and depending on what level of reliability one assumed, the analyst could arrive at very different conclusions about a potential Soviet offensive operation. Or when economists assess the prospects for foreign economic reforms, they may consciously, or not, assume a degree of political stability in those countries or the region that may or may not exist in the future. Likewise, political analysts reviewing a developing country's domestic stability might unconsciously assume stable oil prices, when this key determinant of economic performance and underlying social peace might fluctuate. All of these examples highlight the fact that analysts often rely on stated and unstated assumptions to conduct their analysis. The goal is not to undermine or abandon key assumptions; rather, it is to make them explicit and identify what information or developments would demand rethinking them.

VALUE ADDED

Explicitly identifying working assumptions during an analytic project helps:

- Explain the logic of the analytic argument and expose faulty logic.
- Understand the key factors that shape an issue.
- Stimulate thinking about an issue.
- Uncover hidden relationships and links between key factors.
- Identify developments that would cause you to abandon an assumption.
- Prepare analysts for changed circumstances that could surprise them.

Key Assumptions Check: The 2002 DC Sniper Case

The outbreak of sniper shootings in the Washington, DC area in the fall of 2002 provides a good example of how this technique could have been applied. After the initial flurry of shootings, the operating assumption that quickly emerged was that the shootings were the work of a single, white male who had some military training and was driving a white van. If law enforcement officials had conducted a Key Assumptions Check, they could have broken this statement into its key components and assessed the validity of each statement as follows:

Key Assumption	Assessment
The sniper is a male.	Highly likely (but not certain) given past precedent with serial killers. We are taking little risk by not looking for a female.
The sniper is acting alone.	Highly likely (but not certain) given past precedents.
The sniper is white.	Likely, but not as certain, given past precedents. We would be taking some risk if we rule out nonwhites as suspects.
The sniper has military training/experience.	Possible, but not sufficient reason to exclude from consideration potential suspects who have not had any military training.
The sniper is driving a white van.	Possible because you have a credible eyewitness account but worthy of continuing scrutiny given the number of white vans in the area (more than 70,000 registered in the Maryland suburbs of Metropolitan Washington, DC) and that different kinds of vehicles are being described.

A Key Assumptions Check could have allowed law enforcement officials to:

- Avoid jumping to conclusions (the sniper is white, has military training, and is driving a white van) that did not hold up under closer scrutiny. By explicitly examining each assumption, officials could have avoided prematurely narrowing down the potential pool of suspects to a group that did not include the actual perpetrator. Similarly, they might have been more cautious about accepting that the sniper was driving a white van.
- Be receptive to new leads and citizen tips, such as eyewitness reports that the sniper fled the scene driving a specific model Chevrolet.
- More seriously consider evidence that subsequently became available, which contradicted a key assumption. If officials had stated explicitly that they were assuming the sniper was acting alone, they might have been sensitive to new information that contradicted that key assumption. Often this type of information gets “lost in the noise” if the analyst has not already thought about what key assumptions he or she is making.

THE METHOD

Checking for key assumptions requires analysts to consider how their analysis depends on the validity of certain premises, which they do not routinely question or believe to be in doubt. A four-step process will help analysts:

1. Review what the current analytic line on this issue appears to be; write it down for all to see.

2. Articulate all the premises, both stated and unstated in finished intelligence, which are accepted as true for this analytic line to be valid.

3. Challenge each assumption, asking why it "must" be true and whether it remains valid under all conditions.

4. Refine the list of key assumptions to contain only those that "must be true" to sustain your analytic line; consider under what conditions or in the face of what information these assumptions might not hold.

QUESTIONS TO ASK DURING THIS PROCESS INCLUDE:

- How much confidence exists that this assumption is correct?

- What explains the degree of confidence in the assumption?

- What circumstances or information might undermine this assumption?

- Is a key assumption more likely a key uncertainty or key factor?

- Could the assumption have been true in the past but less so now?

- If the assumption proves to be wrong, would it significantly alter the analytic line? How?

- Has this process identified new factors that need further analysis?

QUALITY OF INFORMATION CHECK

Evaluates completeness and soundness of available information sources.

WHEN TO USE

Weighing the validity of sources is a key feature of any critical thinking. Moreover, establishing how much confidence one puts in analytic judgments should ultimately rest on how accurate and reliable the information base is. Hence, checking the quality of information used in intelligence analysis is an ongoing, continuous process. Having multiple sources on an issue is not a substitute for having good information that has been thoroughly examined. Analysts should perform periodic checks of the information base for their analytic judgments. Otherwise, important analytic judgments can become anchored to weak information, and any "caveats" attached to those judgments in the past can be forgotten or ignored over time.

If a major analytic assessment is planned, analysts should individually or collectively review the quality of their information and refresh their understanding of the strengths and weaknesses of past reporting on which an analytic line rests. Without understanding the context and conditions under which critical information has been provided, it will be difficult for analysts to assess the information's validity and establish a confidence level in an intelligence assessment.

VALUE ADDED

A thorough review of information sources provides analysts—as well as policymakers—with an accurate assessment of "what we know" and "what we do not know." It is also an opportunity to confirm that sources have been cited accurately. In the case of HUMINT, this will require extensive review of the sources' background information and access as well as his or her motivation for providing the information. Similarly, reviewing technical sourcing can sometimes reveal inadvertent errors in processing, translation, or interpretation that otherwise might have gone unnoticed.

In addition, a quality of information check can be valuable to both collectors and policymakers:

- It can help to detect possible deception and denial strategies by an adversary.
- It can identify key intelligence gaps and new requirements for collectors.
- It can assist policymakers in understanding how much confidence analysts are placing on analytic judgments.

THE METHOD

An analyst or a team might begin a quality of information check by developing a database in which information is stored according to source type and date, with additional notations indicating strengths or weaknesses in those sources.[4] Ideally, analysts would have a retrieval and search capability on the database, so that periodic reviews are less labor intensive and result in a more complete review of all sources used in past analysis. For the information review to be fully effective, analysts will need as much background information on sources as is feasible. Knowing the circumstances in which reporting was obtained is often critical to understanding its validity. With the data in hand, analysts can then:

- Review systematically all sources for accuracy.
- Identify information sources that appear most critical or compelling.
- Check for sufficient and strong corroboration of critical reporting.
- Reexamine previously dismissed information in light of new facts or circumstances that cast it in a different light.
- Ensure that any recalled reporting is identified and properly flagged for other analysts; analysis based on recalled reporting should also be reviewed to determine if the reporting was essential to the judgments made.
- Consider whether ambiguous information has been interpreted and caveated properly.
- Indicate a level of confidence that analysts can place in sources, which are likely to figure in future analytic assessments.

[4] Analysis of Competing Hypotheses (ACH), discussed later in the primer, is a useful technique for exploring the possibility that deception could explain the absence of evidence.

Quality of Information Problem on Iraq

"… Analysts community wide are unable to make fully informed judgments on the information they received, relying instead on nonspecific source lines to reach their assessments. Moreover, relevant operational data is nearly always withheld from analysts, putting them at a further analytical disadvantage …"

—*Senate Select Committee on Intelligence, Report on the US Intelligence Community's Prewar Intelligence Assessments on Iraq*

"Analytic errors included over-reliance on a single, ambiguous source, [and, in addition to collection shortfalls] failure of analysts to understand fully the limitations of technical collection …"

"The Intelligence Community relied too heavily on ambiguous imagery indicators …"

—*Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction.*

INDICATORS OR SIGNPOSTS OF CHANGE

Periodically review a list of observable events or trends to track events, monitor targets, spot emerging trends, and warn of unanticipated change.

WHEN TO USE

An analyst or team can create an indicators or signposts list of observable events that one would expect to see if a postulated situation is developing; e.g., economic reform, military modernization, political instability, or democratization. Constructing the list might require only a few hours or as much as several days to identify the critical variables associated with the targeted issue. The technique can be used whenever an analyst needs to track an event over time to monitor and evaluate changes. However, it can also be a very powerful aid in supporting other structured methods explained later in this primer. In those instances, analysts would be watching for mounting evidence to support a particular hypothesis, low-probability event, or scenario.

When there are sharply divided views on an issue, an indicators or signposts list can also "depersonalize" the argument by shifting analytic attention to a more objective set of criteria. Using an indicators list can clarify substantive disagreements, once all sides agree on the set of objective criteria used to measure the topic under study.

VALUE ADDED

By providing an objective baseline for tracking events or targets, indicators instill rigor into the analytic process and enhance the credibility of analytic judgments. An indicators list included in a finished product also allows the policymaker to track developments and builds a more concrete case for the analytic judgments. By laying out a list of critical variables, analysts also will be generating hypotheses regarding why they expect to see the presence of such factors. In so doing, analysts make the analytic line much more transparent and available for scrutiny by others.

THE METHOD

Whether used alone, or in combination with other structured analysis, the process is the same:

- Identify a set of competing hypotheses or scenarios.

- Create separate lists of potential activities, statements, or events expected for each hypothesis or scenario.

- Regularly review and update the indicators lists to see which are changing.

- Identify the most likely or most correct hypotheses or scenarios, based on the number of changed indicators that are observed.

Developing two lists of indicators for each hypothesis or scenario may prove useful to distinguish between indicators that a development is or is not emerging. This is particularly useful in a "What If?" Analysis, when it is important to make a case that a certain event is unlikely to happen.

Tracking the Potential for Political Instability in a Foreign Country								
Topics	**Indicators**	**1999**				**2000**		
		I	*II*	*III*	*IV*	*I*	*II*	*III*
Government Capacity	Quality of leadership/organizational capabilities	● Moderate	● Moderate	● Moderate	■ Serious	● Substantial	● Moderate	● Moderate
	Responsiveness to popular demands	● Moderate	● Low	● Substantial	● Moderate	● Moderate	● Moderate	● Moderate
	Ability to deliver basic goods and services							
	Internal Security Capabilities							
	Effectiveness of civil/criminal justice systems							
Legitimacy of Regime	Breadth and depth of political participation	● Low	● Low	● Low	● Moderate	● Moderate	● Moderate	● Moderate
	Perceived level of corruption	● Moderate	● Low	● Low	● Low	● Low	● Moderate	● Moderate
	Human rights violations	● Low	● Low	● Low	● Low	● Low	● Low	● Low
	Weakness of civil society							
	Pervasiveness of transnational criminal organizations							
	External support for government							
Opposition Activity	Ethnic/religious discontent	● Moderate	● Low	● Moderate	● Moderate	● Substantial	● Substantial	● Substantial
	Military discontent with civilian government	● Moderate	● Moderate	● Moderate	● Substantial	● Substantial	● Substantial	● Substantial
	Popular demonstrations/strikes/riots							
	Insurgent/separatist/terrorist group activity							
	External support for opposition							
	Threat of conflict with or in neighboring state							
Economic Factors	Weakness of domestic economy/unemployment/inflation							
	Degree of income disparity							
	Capital flight							
	Decreased access to foreign funds							
	Reduced trade openness							
Environmental Issues	Extent of environmental degradation							
	Food/energy shortages							
	Ability to respond to natural disasters							

Presence of Trigger Mechanisms (▶ if present)	*I*	*II*	*III*	*IV*	*I*	*II*	*III*
Contested elections				▶			
Unpopular changes in food/energy prices			▶				
Sudden imposition of unpopular policies							
Coup plotting				▶			
Government mismanagement of natural disaster or national emergency							
Death of key figure							

- ■ Serious concern
- ● Substantial concern
- ● Moderate concern
- ● Low concern
- • Negligible concern

Tracking the Potential for Political Instability in an Indicators Matrix. Analysts tracked the potential for regime change in 2000 and identified a list of indicators, to which they posed the question, "is this occurring or not? Analysts also went further and developed a list of "trigger mechanisms" that might bring about a political shift.

ANALYSIS OF COMPETING HYPOTHESES (ACH)

Identification of alternative explanations (hypotheses) and evaluation of all evidence that will disconfirm rather than confirm hypotheses.

WHEN TO USE

Analysis of Competing Hypotheses (ACH) has proved to be a highly effective technique when there is a large amount of data to absorb and evaluate. While a single analyst can use ACH, it is most effective with a small team that can challenge each other's evaluation of the evidence. Developing a matrix of hypotheses and loading already collected information into the matrix can be accomplished in a day or less. If the data must be reassembled, the initial phases of the ACH process may require additional time. Sometimes a facilitator or someone familiar with the technique can lead new analysts through this process for the first time.

ACH is particularly appropriate for controversial issues when analysts want to develop a clear record that shows what theories they have considered and how they arrived at their judgments. Developing the ACH matrix allows other analysts (or even policymakers) to review their analysis and identify areas of agreement and disagreement. Evidence can also be examined more systematically, and analysts have found that this makes the technique ideal for considering the possibility of deception and denial.

VALUE ADDED

ACH helps analysts overcome three common mistakes that can lead to inaccurate forecasts:

- Analysts often are susceptible to being unduly influenced by a first impression, based on incomplete data, an existing analytic line, or a single explanation that seems to fit well enough.

- Analysts seldom generate a full set of explanations or hypotheses at the outset of a project.

- Analysts often rely on evidence to support their preferred hypothesis, but which also is consistent with other explanations.

In essence, ACH helps analysts to avoid picking the first solution that seems satisfactory instead of going through all the possibilities to arrive at the very best solution.

THE METHOD

ACH demands that analysts explicitly identify all the reasonable alternative hypotheses, then array the evidence against each hypothesis—rather than evaluating the plausibility of each hypothesis one at a time. To create a level playing field, the process must:

- Ensure that all the information and argumentation is evaluated and given equal treatment or weight when considering each hypothesis.

- Prevent the analyst from premature closure on a particular explanation or hypothesis.

- Protect the analyst against innate tendencies to ignore or discount information that does not fit comfortably with the preferred explanation at the time.

To accomplish this, the process should follow these steps:

- Brainstorm among analysts with different perspectives to identify all possible hypotheses.

- List all significant evidence and arguments relevant to all the hypotheses.

- Prepare a matrix with hypotheses across the top and each piece of evidence on the side. Determine whether each piece of evidence is consistent, inconsistent, or not applicable to each hypothesis.[5]

- Refine the matrix and reconsider the hypotheses—in some cases, analysts will need to add new hypotheses and re-examine the information available.

- Focus on disproving hypotheses rather than proving one. Talley the pieces of evidence that are inconsistent and consistent with each hypothesis to see which explanations are the weakest and strongest.

[5] The "diagnostic value" of the evidence will emerge as analysts determine whether a piece of evidence is found to be consistent with only one hypothesis, or could support more than one or indeed all hypotheses. In the latter case, the evidence can be judged as unimportant to determining which hypothesis is more likely correct.

- Analyze how sensitive the ACH results are to a few critical items of evidence; should those pieces prove to be wrong, misleading, or subject to deception, how would it impact an explanation's validity?

- Ask what evidence is not being seen but would be expected for a given hypothesis to be true. Is denial and deception a possibility?

- Report all the conclusions, including the weaker hypotheses that should still be monitored as new information becomes available.

- Establish the relative likelihood for the hypotheses and report all the conclusions, including the weaker hypotheses that should still be monitored as new information becomes available.

- Identify and monitor indicators that would be both consistent and inconsistent with the full set of hypotheses. In the latter case, explore what could account for inconsistent data.

Terrorism in Tokyo From Aum Shinrikyo

		Weight	H: 1	H: 4	H: 2	H: 3
			Kooky Cult	Terrorist Group	Political Movement	Criminal Group
	Inconsistency Score ⇨		-1.0	-1.0	-2.0	-3.0
E3	Attacks on Journalists	MEDIUM	I	N	I	I
E2	Religious Affiliation	MEDIUM	C	I	I	I
E4	Established Party	MEDIUM	N	N	C	I
E1	Blind Leader Mastsumoto	MEDIUM	C	C	C	C

ACH Matrix of Terrorism in Tokyo. In March 1995, a largely unknown group attacked the Tokyo subways by using a highly lethal nerve agent known as sarin. ACH provides a mechanism to carefully examine all the evidence and possible explanations for understanding what type of group could have been responsible. In simplified form, the above matrix arrays each piece of evidence on the vertical axis and then evaluates each in terms of the item's consistency with four possible explanations for the terrorist attack in Tokyo (horizontal axis). Analysts rate a piece of evidence as consistent (C); inconsistent (I); or neutral (N). This process allows analysts to see that some evidence will be consistent with more than one hypothesis and be less valuable in disproving hypotheses.

DEVIL'S ADVOCACY

Challenging a single, strongly held view or consensus by building the best possible case for an alternative explanation.

WHEN TO USE

Devil's Advocacy is most effective when used to challenge an analytic consensus or a key assumption regarding a critically important intelligence question. On those issues that one cannot afford to get wrong, Devil's Advocacy can provide further confidence that the current analytic line will hold up to close scrutiny. An individual analyst can often assume the role of the Devil's Advocate if he or she has some doubts about a widely held view, or a manager might designate a courageous analyst to challenge the prevailing wisdom in order to reaffirm the group's confidence in those judgments. In some cases, the analyst or a team can review a key assumption of a critical judgment in the course of their work, or more likely, a separate analytic product can be generated that arrays all the arguments and data that support a contrary hypothesis. While this can involve some analytic time and effort, when a group of analysts have worked on an issue for a long period of time, it is probably wise to assume that a strong mind-set exists that deserves the closer scrutiny provided by Devil's Advocacy.

VALUE ADDED

Analysts have an obligation to policymakers to understand where their own analytic judgments might be weak and open to future challenge. Hence, the Devil's Advocacy process can highlight weaknesses in a current analytic judgment or alternatively help to reaffirm one's confidence in the prevailing judgments by:

- Explicitly challenging key assumptions to see if they will not hold up under some circumstances.
- Identifying any faulty logic or information that would undermine the key analytic judgments.
- Presenting alternative hypotheses that would explain the current body of information available to analysts.

Its primary value is to serve as a check on a dominant mind-set that can develop over time among even the best analysts who have followed an issue and formed strong consensus that there is only one way of looking at their issue. This mind-set phenomenon makes it more likely that contradictory evidence is dismissed or not given proper weight or consideration. An exercise aimed at highlighting such evidence and proposing another way of thinking about an issue can expose hidden assumptions and compel analysts to review their information with greater skepticism about their findings. The analyst could come away from the exercise more certain that: 1) the current analytic line was sound; 2) the argument is still the strongest, but that there are areas where further analysis is needed; or 3) some serious flaws in logic or supporting evidence suggest that the analytic line needs to be changed or at least caveated more heavily.

THE METHOD

To challenge the prevailing analytic line, the Devil's Advocate must:

- Outline the mainline judgment and key assumptions and characterize the evidence supporting that current analytic view.
- Select one or more assumptions—stated or not—that appear the most susceptible to challenge.
- Review the information used to determine whether any is of questionable validity, whether deception is possibly indicated, or whether major gaps exist.

- Highlight the evidence that could support an alternative hypothesis or contradicts the current thinking.

- Present to the group the findings that demonstrate there are flawed assumptions, poor quality evidence, or possible deception at work.

- Consider drafting a separate contrarian paper that lays out the arguments for a different analytic conclusion if the review uncovers major analytic flaws.

- Be sure that any products generated clearly lay out the conventional wisdom and are identified as an explicitly “Devil’s Advocate” project; otherwise, the reader can become confused as to the current official view on the issue.

TEAM A/TEAM B

Use of separate analytic teams that contrast two (or more) strongly held views or competing hypotheses.

WHEN TO USE

A Team A/Team B approach is different from Devil's Advocacy, where the purpose is to challenge a single dominant mind-set. Instead, Team A/Team B recognizes that there may be competing and possibly equally strong mind-sets held on an issue that need to be clarified. Sometimes analysts confuse the two techniques by drafting a Team B exercise that is really a Devil's Advocacy exercise.

If there are at least two competing views within an analytic office or perhaps competing opinions within the policymaking community on a key issue, then Team A/Team B analysis can be the appropriate technique to use. Developing a full-blown Team A/Team B exercise requires a significant commitment of analytic time and resources, so it is worthwhile considering if the analytic issue merits this kind of attention.

A longstanding policy issue, a critical decision that has far-reaching implications, or a dispute within the analytic community that has obstructed effective cross-agency cooperation would be grounds for using Team A/Team B. If those circumstances exist, then analysts will need to review all of the data to develop alternative papers that can capture the essential differences between the two viewpoints.

VALUE ADDED

Managers have found that when there are office tensions among competing factions of analysts, a Team A/Team B approach can help opposing experts see the merit in the other group's perspective. The process of conducting such an exercise can reduce the friction and even narrow the differences. At a minimum, it allows those holding opposing views to feel that their views have been given equal attention.

For the policymaker, this technique helps to surface and explain important analytic differences within the expert community. Often senior officials can learn more by weighing well-argued conflicting views than from reading an assessment that masks substantive differences or drives analysis to the lowest common denominator. By making the key assumptions and information used for each argument more transparent, a policymaker can judge the merits of each case, pose questions back to the analysts, and reach an independent judgment on which argument is the strongest. Moreover, highlighting alternative views puts collectors on notice that they need to be searching for new information that can confirm or disconfirm a range of hypotheses.

If opposing positions are well established, it can be useful to place analysts on teams that will advocate positions they normally do not support; forcing analysts to argue "the other side" can often make them more aware of their own mind-set.

A Team A/Team B View: China's Military

A: *China's Hollow Military* by Bates Gill and Michael O'Hanlon	**B: *China's Military: A Second Opinion* by James Lilley and Carl Ford**
". . . We believe that the recent clamor over China's strategic ambitions is greatly overblown. Most of the Chinese aims that run counter to US interests are in fact not global or ideological but territorial in nature and confined primarily to the islands and waterways to China's south and southeast . . . An enormous gap separates China's military capabilities from its aspirations. The PRC's armed forces are not very good and not getting better very fast. Whatever China's concerns and intentions, its capacity to act upon them in ways inimical to US interests is severely limited, and will remain so for many years . . . The PRC's power projection capabilities, too, are constrained by huge weaknesses– especially in areas such as aerial refueling, electronic warfare, command and control and amphibious and air assault assets. China owns considerably less top-level equipment than medium powers like Japan and Britain; it owns even less than smaller powers such as Italy, South Korea or The Netherlands . . . The resources it devotes to acquiring modern weaponry are akin to those of countries spending $10-20 billion a year on defense . . ."	". . . We think they got it half right. China is no military superpower and will not acquire that status for some years to come. But measured in terms of its capacity to challenge key US allies in East Asia, China's capabilities have grown exponentially . . . By emphasizing direct comparisons between the defense capabilities of the United States and the PRC, the authors create an artificial and misleading construct . . . What the regime gives every indication of striving for is sufficient military clout to achieve its aims in Asia. In the short term, it wishes to intimidate Taiwan sufficiently to bring about unification on Beijing's terms . . . . . . Investments of the sort Beijing is making can mean only one thing: China is determined to improve the PLA's fighting capability. While most nations are reducing defense expenditures in the post–Cold War era, China is one of the few doing the opposite . . . Across the board, the PLA is engaged in a major spending effort to upgrade weapons and equipment and improve its operational capability. According to the Pentagon, these efforts have already enhanced China's ability to project military power . . ."

—Excerpted from journal articles found in The National Interest, Fall and Winter 2000/2001.

THE METHOD

Analysis Phase. A Team A/Team B exercise can be conducted on an important issue to:

- Identify the two (or more) competing hypotheses or points of view.
- Form teams or designate individuals to develop the best case that can be made for each hypothesis.
- Review all pertinent information that supports their respective positions.
- Identify missing information that would buttress their hypotheses.
- Structure each argument with an explicit presentation of key assumptions, key pieces of evidence, and careful articulation of the logic behind the argument.

Debate Phase. An oral presentation of the alternative arguments and rebuttals in parallel fashion can then be organized for the benefit of other analysts:

- Set aside time for an oral presentation of the alternative team findings; this can an informal brainstorming session or a more formal "debate."
- Have an independent "jury of peers" listen to the oral presentation and be prepared to question the teams regarding their assumptions, evidence, or logic.
- Allow each team to present their case, challenge the other team's arguments, and rebut the opponent's critique of its case.
- Let the jury consider the strength of each presentation and recommend possible next steps for further research and collection efforts.

HIGH-IMPACT/LOW-PROBABILITY ANALYSIS

Highlights a seemingly unlikely event that would have major policy consequences if it happened.

WHEN TO USE

High-Impact/Low-Probability Analysis is a contrarian technique that sensitizes analysts to the potential impact of seemingly low probability events that would have major repercussions on US interests. Using this technique is advisable when analysts and policymakers are convinced that an event is unlikely but have not given much thought to the consequences of its occurrence. In essence, this can be a warning that the intelligence and policy communities must be alert to an unexpected but not impossible event. For example, the fall of the Shah, the collapse of the Soviet Union, and the reunification of Germany were all considered low probability events at one time; however, analysts might have benefited from considering the consequences of such events and how they might plausibly have come about.

VALUE ADDED

Mapping out the course of an unlikely, yet plausible, event can uncover hidden relationships between key factors and assumptions; it also can alert analysts to oversights in the mainstream analytic line. In addition, an examination of the "unthinkable" allows analysts to develop signposts that may provide early warning of a shift in the situation. By periodically reviewing these indicators an analyst is more likely to counter any prevailing mind-set that such a development is highly unlikely.

THE METHOD

If there is a strongly held view that an event is unlikely, then postulating precisely the opposite should not be difficult.

- Define the high-impact outcome clearly. This process is what will justify examining what most analysts believe to be a very unlikely development.

- Devise one or more plausible explanations for or "pathways" to the low probability outcome. This should be as precise as possible, as it can help identify possible indicators for later monitoring.

- Insert possible triggers or changes in momentum if appropriate. These can be natural disasters, sudden health problems of key leaders, or new economic or political shocks that might have occurred historically or in other parts of the world.

- Brainstorm with analysts having a broad set of experiences to aid the development of plausible but unpredictable triggers of sudden change.

- Identify for each pathway a set of indicators or "observables" that would help you anticipate that events were beginning to play out this way.

- Identify factors that would deflect a bad outcome or encourage a positive outcome.

High Impact of a Low-Probability Event: Pearl Harbor

". . . So far as relations directly between the United States and Japan are concerned, there is less reason today than there was a week ago for the United States to be apprehensive lest Japan make "war" on this country.

Were it a matter of placing bets, the undersigned would give odds of five to one that the United States and Japan will not be at "war" on or before December 15; would wager three to one that the United States and Japan will not be at 'war' on or before the 15th of January (i.e, seven weeks from now); would wager even money that the United States and Japan will not be at "war" on or before March 1 (a date more than 90 days from now) . . ."

—State Department Special Assessment, 27 November 1941

High-Impact/Low-Probability Analysis on 9/11

The 9/11 Commission report includes examination of speculative analysis that was provided to senior policymakers highlighting what were thought to be highly unlikely scenarios that would have a very high impact. One of those items was the 6 August 2001 President's Daily Brief, which stated:

Al-Qai'da members—including some who are US citizens—have resided in or traveled to the US for years, and the group apparently maintains a support structure that could aid attacks. Two al-Qai'da members found guilty in the conspiracy to bomb our embassies in East Africa were US citizens, and a senior EIJ [Egyptian Islamic Jihad] member lived in California in the mid-1990s.

- A clandestine source said in 1998 that a Bin Ladin cell in New York was recruiting Muslim-American youth for attacks.

We have not been able to corroborate some of the more sensational threat reporting, such as that from a service in 1998 saying that Bin Ladin wanted to hijack a US aircraft to gain the release of "Blind Shaykh" 'Umar Abd al-Rahman and other US-held extremists.

—9/11 Commission Report, declassified and approved for release 10 April 2004.

"WHAT IF?" ANALYSIS

Assumes that an event has occurred with potential (negative or positive) impact and explains how it might come about.

WHEN TO USE

"What If?" analysis is another contrarian technique for challenging a strong mind-set that an event will not happen or that a confidently made forecast may not be entirely justified. It is similar to a High-Impact/Low-Probability analysis, but it does not dwell on the consequences of the event as much as it accepts the significance and moves directly to explaining how it might come about.

VALUE ADDED

By shifting the focus from whether an event could occur to how it may happen, analysts allow themselves to suspend judgment about the likelihood of the event and focus more on what developments—even unlikely ones—might enable such an outcome. An individual analyst or a team might employ this technique and repeat the exercise whenever a critical analytic judgment is made.

Using this technique is particularly important when a judgment rests on limited information or unproven assumptions. Moreover, it can free analysts from arguing about the probability of an event to considering its consequences and developing some indicators or signposts for its possible emergence. It will help analysts address the impact of an event, the factors that could cause—or alter—it, and likely signposts that an event is imminent.

A "What If?" analysis can complement a difficult judgment reached and provide the policymaker a thoughtful caution to accepting the conventional wisdom without considering the costs and risks of being wrong. This can help decision-makers consider ways to hedge their bets, even if they accept the analytic judgment that an event remains unlikely.

THE METHOD

Like other contrarian methods, "What If?" analysis must begin by stating clearly the conventional analytic line and then stepping back to consider what alternative outcomes are too important to dismiss, even if unlikely. Brainstorming over a few days or weeks can develop one or more plausible scenarios by which the unlikely event occurs:

- Assume the event has happened.
- Select some triggering events that permitted the scenario to unfold to help make the "what if" more plausible; for example, analysts might postulate the death of a leader, a natural disaster, or some economic event that would start a chain of other events.
- Develop a chain of argumentation based as much on logic as evidence to explain how this outcome could have come about.
- "Think backwards" from the event in concrete ways–that is, specifying what must actually occur at each stage of the scenario is often very useful.
- Identify one or more plausible pathways or scenarios to the unlikely event; very often more than one will appear possible.
- Generate a list of indicators or "observables" for each scenario that would help to detect the beginnings of the event.
- Consider the scope of the positive and negative consequences of each scenario and their relative impacts.
- Monitor the indicators developed on a periodic basis.

“What If?” Analysis: An Unlikely Outcome in Yugoslavia, 1990.

The possibility of muddling through is very low. In the unlikely event that it happens, this is what it would look like.

Memories of the internecine civil war during World War II and fear of another destructive conflict would lead the two most numerous South Slav people—Serbs and Croats—to reach some political accommodation. A compromise that preserves Yugoslavia would include:

- Basic principles:
  - -No change in existing Republic borders.
  - -No change in Yugoslavia’s existing international status.
  - -Mutually recognized sovereignty of each republic

- Confederal institutions:
  - -A single foreign ministry, to which diplomatic representatives would be accredited.
  - -A central military organization with a joint General Staff responsible for planning.
  - -A central bank, determining macroeconomic policy, a common currency,

- Powers reserved to republics.
  - -Veto over actions of the Confederal Authority.
  - -Control of internal security, including guarantee of minority rights.
  - -Operational control over some or all military units stationed on the republic’s territory.
  - -Raising taxes and allocating funds to discharge mutually agreed confederal responsibilities.

Only the Serbs can open the door to a confederal Yugoslavia, and Serbia’s leader, Slobodan Milosevic, holds the key. Some observers felt there are pressures on him to try. If he does not, he would give his opponents the leverage to remove him. The potential penalties of failure to compromise would be too great, in this view, for the peoples and leaders of Yugoslavia to forgo every effort to find a compromise.

—*Excerpts from the declassified* NIE: Prospects for Yugoslavia*, October 1990.*

BRAINSTORMING

An unconstrained group process designed to generate new ideas and concepts.

WHEN TO USE

Brainstorming is a widely used technique for stimulating new thinking and it can be applied to virtually all of the other structured analysis techniques as an aid to thinking. Typically, analytic will brainstorm when they begin a project to help generate a range of hypotheses about their issue.

Brainstorming, almost by definition, involves a group of analysts meeting to discuss a common challenge; a modest investment of time at the beginning or critical points of a project can take advantage of their different perspectives to help structure a problem. This group process allows others to build on an initial idea suggested by a member of the brainstorming session.

An individual analyst also can brainstorm to produce a wider range of ideas than a group might generate, without regard for other analysts' egos, opinions, or objections. However, an individual will not have the benefit of others' perspectives to help develop the ideas as fully. Moreover, an individual may have difficulty breaking free of his or her cognitive biases without the benefit of a diverse group.

VALUE ADDED

This technique can maximize creativity in the thinking process, force analysts to step outside their normal analytic mind-sets, and suspend their typical "good judgment" about the practicality of ideas or approaches. More generally, brainstorming allows analysts to see a wider range of factors that might bear on the topic than they would otherwise consider. Analysts typically censor out ideas that seem farfetched, poorly sourced, or seemingly irrelevant to the question at hand. Brainstorming gives permission to think more radically or "outside the box." In particular, it can spark new ideas, ensure a comprehensive look at a problem or issues, raise unknowns, and prevent premature consensus around a single hypothesis.

THE METHOD

Paradoxically, brainstorming should be a very structured process to be most productive. An unconstrained, informal discussion might produce some interesting ideas, but usually a more systematic process is the most effective way to break down mind-sets and produce new insights. In particular, the process involves a divergent thinking phase to generate and collect new ideas and insights, followed by a convergent phase in which ideas are grouped and organized around key concepts. Some of the simple rules to be followed include:

- Never censor an analyst's ideas no matter how unconventional they might sound.

- Rather find out what prompted the thought, as it might contain the seeds of an important connection between the topic and an unstated assumption.

- Give yourself enough time to do brainstorming correctly. It usually takes one hour to set the "rules" of the game, get the group comfortable, and exhaust the conventional wisdom on the topic. Only then will the truly creative ideas begin to emerge.

- Involve at least one "outsider" in the process—that is, someone who does not share the same educational background, culture, technical knowledge or mind-set as the core group but has some familiarity with the topic.

A two-phase, twelve-step, structured process is often used to get the most out of the brainstorming sessions:

Brainstorming and Divergent Thinking: Perspectives of an Experienced Practitioner

". . . First, leave rank at the door and focus on "a democracy of ideas." Thoughts from experts, senior officers, and supervisors are of course, valuable and welcome, but such experts are not permitted to cut off debate by citing their seniority. In fact, it pays to invite junior officers as well as senior ones who are not involved directly in working the issue under discussion. Some of the most creative ideas at brainstorming sessions frequently come from relatively junior people who can look at a problem with fresh perspective, or from senior ones who are not experts on the issue.

Second, make sure there is no official analytic line. One of the most significant blocks to new thinking is the presence of a long held analytic line that analysts—and even more so managers—are reluctant to change. Rather than trying to fit ideas into the framework of "what we've said before," analysts need to feel free to go wherever bits of the evidence and informed supposition take them. They must feel free to throw out seemingly strange but plausible ideas that might be based on historical precedent and instinct rather than on concrete information. Facilitators can stimulate this process by deliberately posing an alternative outcome to a problem that differs starkly from the accepted analysis or by proposing a contrary way to think about an issue.

Third, don't permit killer phrases like "that would not work" or "that could not happen" to be voiced out loud. Effective brainstorming starts with ideas and possibilities, not with practicalities and self-imposed obstacles to fresh perspectives. Force the group to get as wide a range of ideas out for discussion as possible. At some point, a set of ideas might be winnowed down and subject to tests of workability, but that comes later—not during brainstorming.

Fourth, keep the brainstorming session to no more than 90 minutes. There is no hard and fast rule, but somewhere between 60 and 90 minutes, the idea stream starts to dry up, people repeat themselves, and jokes replace creative ideas.

Fifth, record ideas in a visible way. Lots of people take notes at brainstorming sessions for their own use, and that is good. We have found it valuable to have someone jot down the ideas presented on large paste-a-note sheets that we put on the walls. This allows participants in brainstorming sessions to react to ideas generated earlier. Moreover, analysts are encouraged to participate in such exercises if they see their own ideas put down in writing. Having a notional record of brainstorming also helps the analyst who ends up writing a report based on the discussion. Ideas that may not be used in one report are invariably put to use later, so it is good to have a record of them . . ."

Divergent Thinking Phase:

- Distribute "Post-It" notes and pens or markers to all participants. Typically, 10-12 people works best.
- Pose the problem in terms of a "focal question." Display it in one sentence on a large easel or whiteboard.
- Ask the group to write down responses to the question, using key words that will fit on the small "Post-It" note.
- Stick all the notes on a wall for all to see—treat all ideas the same.
- When a pause follows the initial flow of ideas, the group is reaching the end of their conventional thinking and the new divergent ideas are then likely to emerge.
- End the "collection stage" of the brainstorming after two or three pauses.

Convergent Thinking Phase:

- Ask the participants as a group to rearrange the notes on the wall according to their commonalities or similar concepts. No talking is permitted. Some notes may be moved several times as notes begin to cluster. Copying some notes is permitted to allow ideas to be included in more than one group.
- Select a word or phrase that characterizes each grouping or cluster once all the notes have been arranged.
- Identify any notes that do not easily fit with others and consider them either useless noise or the beginning of an idea that deserves further attention.
- Assess what the group has accomplished in terms of new ideas or concepts identified or new areas that need more work or further brainstorming.
- Instruct each participant to select one or two areas that deserve the most attention. Tabulate the votes.
- Set the brainstorming group's priorities based on the voting and decide on the next steps for analysis.

OUTSIDE-IN THINKING

Used to identify the full range of basic forces, factors, and trends that would indirectly shape an issue.

WHEN TO USE

Analysts find this technique most useful at the conceptualization of an analytic project, when the goal is to identify all the critical, external factors that could influence how a particular situation will develop. It would work well for a group of analysts responsible for a range of functional and/or regional issues. When assembling a large database that must identify a number of information categories or database fields, this technique can aid in visualizing the entire set of categories that might be needed in a research effort. Often analysts realize only too late that some additional information categories will be needed and then must go back and review all previous files and recode the data. With a modest amount of effort, "Outside-in Thinking" can reduce the risk of missing important variables early in the analytic process.

VALUE ADDED

Most analysts spend their time concentrating on familiar factors within their field or analytic issue. That is, they think from the "inside"—namely, what they control—out to the broader world. Conversely, "thinking from the outside-in" begins by considering the external changes that might, over time, profoundly affect the analysts' own field or issue. This technique encourages analysts to get away from their immediate analytic tasks (the so-called "inbox") and think about their issues in a wider conceptual and contextual framework. By recasting the problem in much broader and fundamental terms, analysts are more likely to uncover additional factors, an important dynamic, or a relevant alternative hypothesis.

THE METHOD

The process begins by developing a generic description of the problem or the phenomenon under study. Then, analysts should:

- List all the key forces (social, technological, economic, environmental, and political) that could have an impact on the topic, but over which one can exert little influence (e.g., globalization, social stress, the Internet, or the global economy).

- Focus next on key factors over which an actor or policymaker can exert some influence. In the business world this might be the market size, customers, the competition, suppliers or partners; in the government domain it might include the policy actions or the behavior of allies or adversaries.

- Assess how each of these forces could affect the analytic problem.

- Determine whether these forces actually do have an impact on the particular issue based on the available evidence.

RED TEAM ANALYSIS

Models the behavior of an individual or group by trying to replicate how an adversary would think about an issue.

WHEN TO USE

Frequently, analysts face the challenge of forecasting how a foreign leader or decisionmaking group may behave when it is clear that there is a risk of falling into a "mirror-image" problem. That is, analysts can sometimes impute to a foreign actor the same motives, values, or understanding of an issue that they hold. Traditional analysis sometimes assumes that foreign leaders or groups will behave "rationally" and act as the analysts would if faced with the same threats or opportunities. History has shown that foreign leaders often respond differently to events because of different cultural, organizational, or personal experiences.

Red Team analysis tries to consciously place analysts in the same cultural, organizational, and personal setting ("putting them in their shoes") in which the target individual or group operates. Whereas analysts normally work from the position of the "blue" (friendly forces), a "red" team of analysts attempts to work in the environment of the hostile forces.

VALUE ADDED

Like Devil's Advocacy and Team A/Team B techniques, Red Team analysis is aimed at freeing the analyst from the prison of a well-developed mind-set; in this case, the analyst's own sense of rationality, cultural norms, and personal values. Whereas analysts usually operate as "observers" of a foreign adversary, the Red Team technique transforms the analyst into an "actor" operating within the adversary's culture and political milieu. This form of "role playing" is useful when trying to replicate the mind-set of authoritarian leaders, terrorist cells, or other non-Western groups that operate under very different codes of behavior or motivations.

Often this technique can introduce new or different stimuli that might not have been factored into traditional analysis—such as the target's familial ties or the international political, economic, and military pressures felt by the individual. For example, Red Team participants might ask themselves: "What would my peers, family, or tribe expect me to do? Alternatively, a Red Team analyst might pose the question to his colleagues: "How do we perceive the external threats and opportunities?" Finally, the Red Team technique can factor into its analysis the way in which personal power and status might influence a target's behavior.

THE METHOD

On issues that lend themselves to Red Team analysis, a manager needs to build a team of experts with in-depth knowledge of the operating environment, the target's personality, and the style of thinking used. The team should be populated not just with those who understand the language, but also with people who might have experienced the culture, share the ethnic background, or have worked in a similar operational environment. Once established and separated from traditional analysis, the team members should:

- Put themselves in the adversary's circumstances and react to foreign stimuli as the target would.

- Develop a set of "first-person" questions that the adversary would ask, such as: "How would I perceive incoming information; what would be my personal concerns; or to whom would I look for an opinion?"

- Draft a set of policy papers in which the leader or group makes specific decisions, proposes recommendations, or lays out courses of actions. The more these papers reflect the cultural and personal norms of the target, the more they can offer a different perspective on the analytic problem.

A Red Team Perspective
Iran's Military Strategy Vis-a-vis the United States

". . . The United States and Israel may be contemplating military operations against Iran, as per recent media reports . . . A week-long combined air and ground maneuver has just concluded in five of the southern and western provinces of Iran, mesmerizing foreign observers, who have described as 'spectacular' the massive display of high-tech, mobile operations, including rapid-deployment forces relying on squadrons of helicopters, air lifts, missiles, as well as hundreds of tanks and tens of thousands of well-coordinated personnel using live munitions.

Learning from both the 2003 Iraq war and Iran's own previous experiences of the 1980-88 war with Iraq and the 1987-88 confrontation with US forces in the Persian Gulf, Iranians have focused on the merits of a fluid and complex defensive strategy that seeks to take advantage of certain weaknesses in the US military superpower while maximizing the precious few areas where they may have the upper hand, e.g.; numerical superiority in ground forces, guerrilla tactics, terrain, etc.

Any US attack on Iran will likely be met first and foremost by missile counter-attacks engulfing the southern Persian Gulf states playing host to US forces, as well as any other country—e.g., Azerbaijan, Iraq, or Turkey allowing their territory or airspace to be used against Iran. The rationale for this strategy is precisely to pre-warn Iran's neighbors of the dire consequences, with potential debilitating impacts on their economies for a long time, should they become accomplices of foreign invaders of Iran.

Another key element of Iran's strategy is to "increase the arch of crisis" in places such as Afghanistan and Iraq, where it has considerable influence, to undermine the United States' foothold in the region, hoping to create a counter-domino effect wherein instead of gaining inside Iran, the US would actually lose territory partly as a result of thinning its forces and military 'overreach.'

Iran's counter-psychological warfare, on the other hand, seeks to take advantage of the 'death-fearing' American soldiers who typically lack a strong motivation to fight wars not necessarily in defense of the homeland. A war with Iran would definitely require establishing the draft in the US, without which it could not possibly protect its flanks in Afghanistan and Iraq.

There is a sense of national-security siege in Iran these days, in light of a tightening "security belt" by the US benefiting from military bases in Iraq, Turkey, Azerbaijan, Uzbekistan, Tajikistan, Kyrgyzstan, as well as Kuwait, Saudi Arabia, Qatar, Bahrain, Oman, and the island-turned garrison of Diego Garcia. From Iran's vantage point, the US, having won the Cold War, has turned into a 'leviathan unhinged' capable of manipulating and subverting the rule of international law and the United Nations with impunity, thus requiring a sophisticated Iranian strategy of deterrence, that, in the words of certain Iranian media pundits, would even include the use of nuclear weapons . . ."

—Excerpts from Kaveh L. Afrasiabi (Tehran University), "How Iran Will Fight Back," cited in Asia Times Online Ltd., 2004.

Red Team analysis is not easy to conduct. It requires significant time to develop a team of qualified experts who can think like the adversary. The team has to distance itself from the normal analysis and work as though living in the target's world. Without a sophisticated understanding of the culture, operational environment, and personal histories of the foreign group, analysts will not be able to behave or think like the enemy. Analysts can never truly escape their own experiences and mind-sets, but this technique can at least prevent them from falling into "mirror-imaging" unconsciously.

The most novel feature of Red Team analysis is its presentation.

- The analysis is often in a "first person" format—that is, drafted as memos to or from a leader or group.

- Red Team analysis avoids the use of caveats or qualifications and assumes that the recipient understands that the paper is aimed more at provoking thought or challenging the conventional understanding of how an adversary thinks.

- Such papers are rarely coordinated among other experts and do not purport to represent the consensus view on an issue.

Red Team papers do not plot out all possible courses of action but seek to give a prediction based on the target's special personal, organizational, or cultural experiences.

ALTERNATIVE FUTURES ANALYSIS

Systematically explores multiple ways a situation can develop when there is high complexity and uncertainty.

WHEN TO USE

Alternative futures analysis (often referred to as "scenarios") is most useful when a situation is viewed as too complex or the outcomes as too uncertain to trust a single outcome assessment. First, analysts must recognize that there is high uncertainty surrounding the topic in question. Second, they, and often their customers, recognize that they need to consider a wide range of factors that might bear on the question. And third, they are prepared to explore a range of outcomes and are not wedded to any preconceived result. Depending on how elaborate the futures project, the effort can amount to considerable investment in time, analytic resources, and money. A team of analysts can spend several hours or days organizing, brainstorming, and developing multiple futures; alternatively, a larger-scale effort can require preparing a multi-day workshop that brings together participants (including outside experts). Such an undertaking often demands the special skills of trained scenario-development facilitators and conferencing facilities.

This technique is a sharp contrast to contrarian techniques, which try to challenge the analysts' high confidence and relative certitude about an event or trend. Instead, multiple futures development is a divergent thinking technique that tries to use the complexity and uncertainty of a situation to describe multiple outcomes or futures that the analyst and policymaker should consider, rather than to predict one outcome.

VALUE ADDED

Alternative futures analysis is extremely useful in highly ambiguous situations, when analysts confront not only a lot of "known unknowns" but also "unknown unknowns." What this means is that analysts recognize that there are factors, forces, and dynamics among key actors that are difficult to identify without the use of some structured technique that can model how they would interact or behave. As the outcomes are not known prior to the futures exercise, analysts must be prepared for the unexpected and willing to engage in a more free-wheeling exchange of views than typically occurs in order to "imagine the future." Given the time and resources involved, scenario analysis is best reserved for situations that could potentially pose grave threats or otherwise have significant consequences.

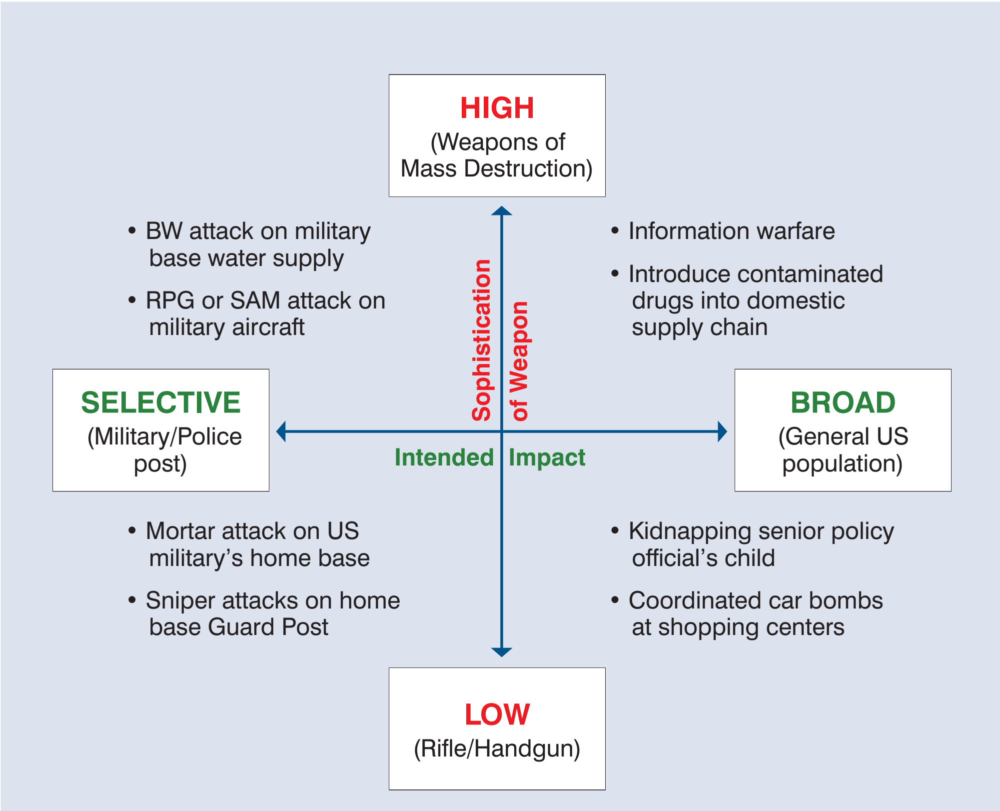
From past experience, analysts have found that involving policymakers in the alternative futures exercise is the most effective way to communicate the results of this exploration of alternative outcomes and sensitize them to key uncertainties. Most participants find the process of developing such scenarios as useful as any finished product that attempts to capture the results of the exercise. Analysts and policymakers can benefit from this technique in several ways:

- It provides an effective means of weighing multiple unknown or unknowable factors and presenting a set of plausible outcomes.
- It can help to bound a problem by identifying plausible combinations of uncertain factors.
- It provides a broader analytic framework for calculating the costs, risks, and opportunities presented to policymakers by different outcomes.

"*The future is plural.*"

—Peter Schwartz, author of *The Art of the Long View* and a widely acclaimed scenario developer.

Hypothetical Threats to the Homeland: Using Spectrums to Define Potential Targets



A Futures Exercise. The graphic captures four potential futures to understand how foreign insurgents might carry out an attack on the United States. A brainstorming exercise helped analysts identify two key uncertainties (the sophistication of weapons used by the insurgents and the intended impact of the attack) and arrayed these factors on a graph as the "x" and "y" axes. The four resulting quadrants in the 2 x 2 matrix allowed analysts to visualize potential targets from the various combinations (low to high sophistication of weapons and selective to broad intended impact of an attack). For example, if a group possessed highly sophisticated weapons and intended a broad attack on the United States, potential targets could include computer networks and domestic drug supplies. Having filled in a quadrant, analysts can then turn to devising likely indicators or signposts of such a future.

- It aids analysts and policymakers in anticipating what otherwise would be surprising developments by forcing them to challenge assumptions and consider possible "wild cards" or discontinuous events.

- It generates indicators to monitor for signs that a particular future is becoming more or less likely, so that policies can be reassessed.

THE METHOD

Although there are a variety of ways to develop alternative futures, the most common approach used in both the public and private sectors involves the following steps:

- Develop the "focal issue" by systematically interviewing experts and officials who are examining the general topic.

- Convene a group of experts (both internal and external) to brainstorm about the forces and factors that could affect the focal issue.

- Select by consensus the two most critical and uncertain forces and convert these into axes or continua with the most relevant endpoints assigned.

- Establish the most relevant endpoints for each factor; e.g., if economic growth were the most critical, uncertain force, the endpoints could be "fast" and "slow" or "transformative" and "stabilizing" depending on the type of issue addressed.

- Form a futures matrix by crossing the two chosen axes. The four resulting quadrants provide the basis for characterizing alternative future worlds.

- Generate colorful stories that describe these futures and how they could plausibly come about. Signposts or indicators can then be developed.

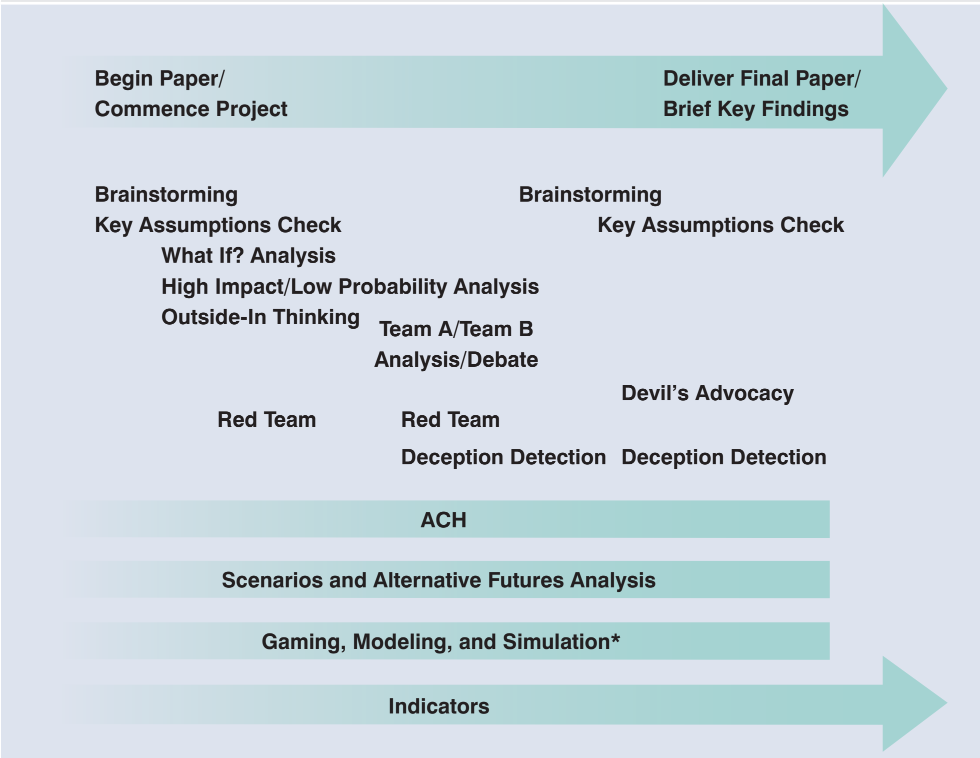
Participants, especially policymakers, can then consider how current decisions or strategies would fare in each of the four worlds and identify alternative policies that might work better either across all the futures or in specific ones. By anticipating alternative outcomes, policymakers have a better chance of either devising strategies flexible enough to accommodate multiple outcomes or of being prepared and agile in the face of change.

These structured analytic techniques can be used in a variety of ways when analysts begin a new assessment. Some can be used equally effectively at multiple points in the process and can promote an analyst's ability to keep an open mind, to consider multiple—including highly unlikely—hypotheses, to challenge conventional wisdom, and to assess the impact of important information gaps or deception on analytic judgments and confidence levels. The Timeline for Using Analytic Techniques provides some thoughts on when to use one or more of them during the course of an analyst's research and writing.

Starting Out

At the beginning of an analytic project, analysts are always wise to consider brainstorming and assumptions checks to insure that important factors are not being missed or taken for granted. Similarly, outside-in-thinking can sometimes put an analytic project into a broader international context, in which factors outside the lead analyst's area of responsibility might impact on his or her analytic judgments. For instance, economic assumptions about the price of oil might be key to a regional political analyst's understanding the prospects for political stability in an oil-exporting

A Timeline for Using Analytic Techniques Throughout an Analytic Project



*Gaming, Modeling, and Simulation are among the more sophisticated techniques taught in a more advanced analytic methods course and usually require substantial commitments of analyst time and corporate resources.

country or a underdeveloped country entirely dependent on expensive energy imports. A High Impact/Low Probability assessment can also sensitize analysts early on to the significance of dramatic events that might affect their analytic lines.

Some techniques like Indicators and Signposts or Analysis of Competing Hypotheses (ACH) can be useful throughout a project and revisited periodically as new information is absorbed and analyzed. ACH, in particular, is a good tool to use throughout a project to prevent premature closure and to highlight evidence that is most "discriminating" in making an analytic argument. Alternative Futures analysis is similarly useful at the beginning of a project, but can amount to the structure for the entire project.

Hypothesis Testing

As an analytic project takes shape, and hypotheses are being formed about the key intelligence question, it can be appropriate to use one or another contrarian technique to challenge the conventional analytic line that is being developed. If the assessment contains strong judgments about an adversary's behavior, then challenging this view with a "Red Team" effort might be a good corrective to too much of a rational actor approach. Also, a review of intelligence gaps at this juncture can also help give the analysts a better degree of confidence in the information base and judgments reached in the assessment.

A Final Check

As the assessment is being finalized, it can still be useful to review key assumptions as a sanity check on the underlying logic of the analysis. A brainstorming session also may be helpful to insure that no plausible hypothesis has been dismissed or left unaddressed. If a firm consensus has formed around an analytic line and has not been seriously questioned in some time, then a Devil's Advocacy exercise could be useful. Analysts might also use a final review to decide if they have identified a list of key indicators for future developments. This can be an important guide to include in the assessment as a way to track future developments and monitor whether the analytic judgments reached are being realized or in need of revision.

Graham Allison, *Essence of Decision*: *Explaining the Cuban Missile Crisis*: Examines the Kennedy Administration's decisionmaking style from alternative perspectives of the "rational actor," "organizational actor," and "bureaucratic politics" models.

Max Bazerman and Michael D. Watkins, *Predictable Surprises: The Disasters You Should Have Seen Coming and How To Prevent Them*. Examines the cognitive, organizational and political causes of some predictable surprises and outlines steps to overcome them.

Richard Betts, *Surprise Attack: Lessons for Defense Planning*. Explains why surprise attacks historically have succeeded and argues that the US needs strategies for avoiding surprise or at least reducing their consequences. Uses examples from World War II, Korea, and the Middle East.

Josh Epstein and Rob Axtell, *Sugarscape: Creating Artificial Societies from the Ground Up*. Develops a very simple agent-based model of a silicon-based society and then does simulations of various social, economic and political phenomena, including conflict.

Malcolm Gladwell, *The Tipping Point: How Little Things Can Make a Big Difference*. Examines how social trends, ideas, and products emerge from nowhere and take hold.

Cynthia M. Grabo, *Anticipating Surprises: Analysis for Strategic Warning.* Examines distinctive ingredients of the analytical method of intelligence and suggests ways of improving warning assessments.

Richards J. Heuer, Jr., *The Psychology of Intelligence Analysis*. Examines the impediments to good analysis and provides techniques for overcoming mind-sets and cognitive biases.

Barry Hughes, *International Futures*. Develops scenarios for international relations using a simulation tool contained in a CD ROM in the back jacket.

Robert Jervis, *Perception and Misperception in International Politics*. Examines how policymakers learn from history, perceive complexity, and form and change their beliefs.

Gary Klein, *Intuition At Work*. Shows how developing one's intuition can improve your analytic skills and that it is a "learnable" technique.

Richard E. Neustadt and Ernest R. May, *Thinking in Time: The Uses of History for Decisionmakers*. Uses case study methods to identify the perils of historical analogies and recommends identifying what is "known, unclear and presumed."

Peter Schwartz, *The Art of the Long View: Planning for the Future in an Uncertain World*. Explains the "scenaric" approach pioneered at Royal Dutch Shell and argues for making strategic decisions that will be sound for "all plausible futures."

James Surowiecki, *The Wisdom of Crowds*. Argues that diversity and independence of even non-expert individuals in groups, properly organized, can reach more accurate forecasts than individual experts.

M. Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Disorder and Chaos*. Introduces the literature of complex systems and suggests why forecasting anything complicated is so difficult.