BETHEL UNIVERSITY, VERMONT

"Evolutionary Thermodynamics"

- Justin Lancaster

- March 26, 2022

Thermodynamics is a branch of physics that deals with heat, work, and temperature, and their relation to energy, entropy, and the physical properties of matter and radiation.

THERMO DYNAMICS

- *THERMAL* = related to **heat**
- *THERMOMETER* **=** measures **temperature (T)**
- *THERMOSTAT* **=** regulates **T**

- *DYNAMO* = a machine that generates electricity from **energy** (work)
- *DYNAMIC* = characterized by constant **change**; full of **energy**
- *DYNE* = **force** which, acting for one second, will produce a change of velocity of one centimeter per second in a mass of one gram

Evolutionary Thermodynamics is the science that studies the evolution of energetic systems in Nature.

Research in this field involves such broad questions as:

- What is life?
- Is energy itself alive?
- Are all energetic systems alive?
- Are human organizations following a fundamental principle?
- Is global environmental change inevitable?
- Can humans prevent global climate change?

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Evolutionary Thermodynamics: 21st Century Research Questions

- How do **patterns of energy-flow** change within subsystems of human society? (Geographically mapped storage? Transport? Through-flow? Use?)

- What **patterns of growth and/or stability** can be seen in differing subsystems?

- Assuming subsystem flows can be modified, what instabilities in the
- **energy through-flow in a subsystem** are introduced by such modifications?

- What **leverage points** in which subsystems can present the most responsive and stable ongoing control?

- Given instabilities or other difficulties created by converting energy sources for particular subsystem flows, **how do these effects cascade** through other subsystems?

1600s: FORCE as a function of mass, distance and time

Isaac Newton described FORCE as mass times acceleration (F = m*a), or mass times **speed** per time.

Thus, 1 **Newton** (**N**) force = 1 kg * (**m/s**)/s.

Eventually, the **dyne** was defined as the force that would give a mass of one gram an acceleration of one centimeter per second per second, so that

1 **dyn** force = g * (**cm/s**)/s
= (10^-3)kg * ((10^-2)m/s)/s
= 10^-5 **N**

1800s: ENERGY as a function of FORCE, distance, mass and time

1860-75: Clausius proposed the word “ergon” (Greek: ἔργον) as a unit of energy, work and heat, while Maxwell and Thomson chose centimeter, gram and second as fundamental units of distance, mass and time. (CGS system of units).

An **ERG** was defined as the work done by a **DYNE** force over a centimeter distance, such that

1 **erg** = 1 **dyn** * cm = [**g * (cm/s)/s**] * cm = g * (cm*cm)/(s * s) = g *(**cm/sec**)^2

An erg is approximately the amount of work done (or energy consumed) by one common house fly performing one "push up", the leg-bending dip that brings its mouth to the surface on which it stands and back up.[2]

- - - - -

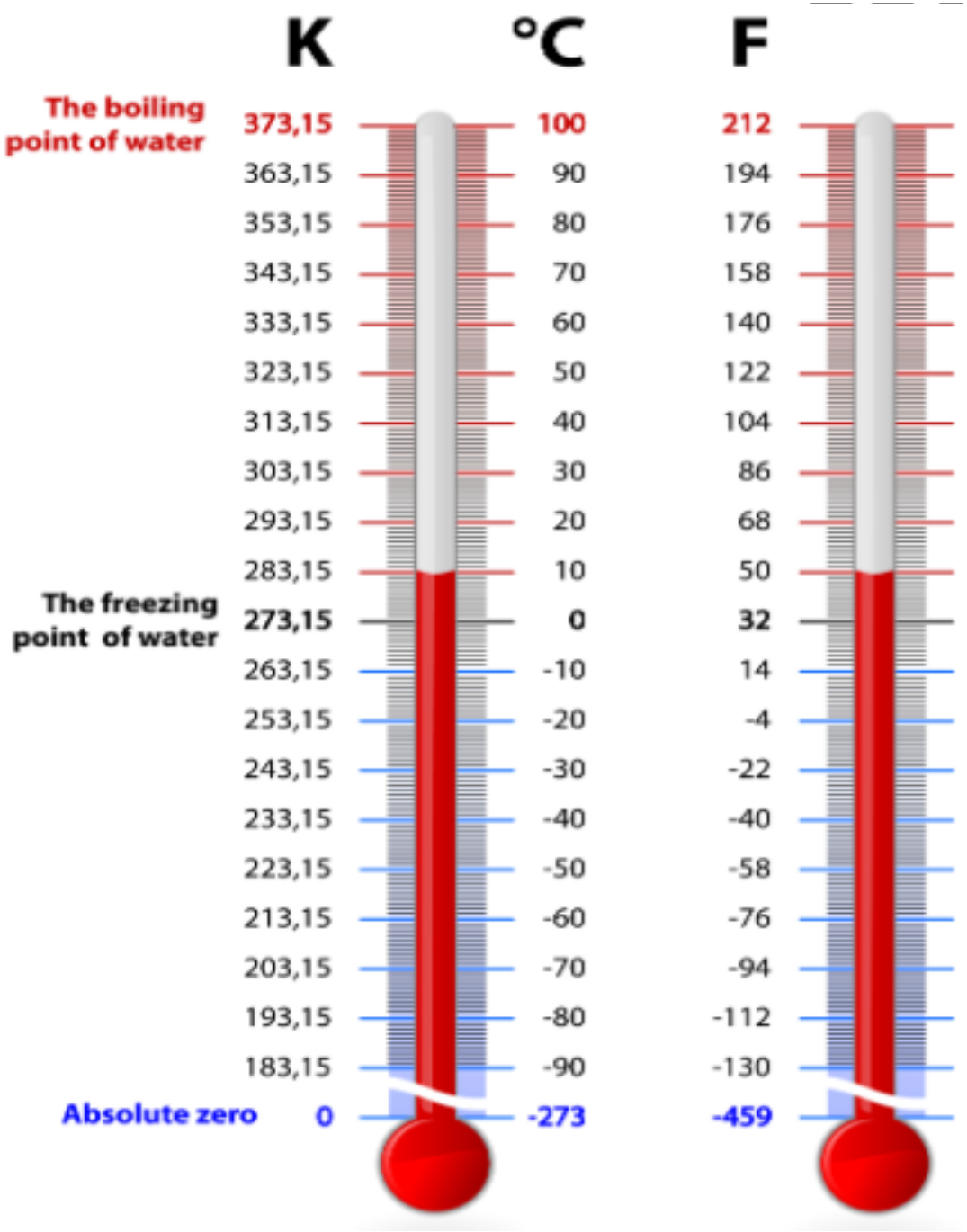
1 **joule** = 1 **Newton** * meter = kg * (m/s) ^2 = 10^7 ergs

Notice that we have Energy = mass * (**speed** squared). This equivalence was made more profound when Einstein realized that the speed squared was a constant of proportionality that told us how much energy was contained in mass, and that the speed to use for this conversion was the speed of light, c. Thus, **E** = m *c^2.

TEMPERATURE

KELVIN (K)
CELSIUS (C)

FAHRENHEIT (F)



zeroth law of thermodynamics states that

if two bodies are each in thermal equilibrium with some third body, then they are also in equilibrium with each other.

PRESSURE (p) is Force per Area (Pascal; atmosphere; PSI; bar)

Pound per square inch (PSI). Soccer balls are pumped to about 6 PSI (gauge pressure), while auto tires are often at 30 gauge PSI and road bicycle tires can be at 90 gauge PSI. For absolute pressure, add to the gauge pressure the standard atmospheric pressure at the ground, caused by the weight of the air column above.

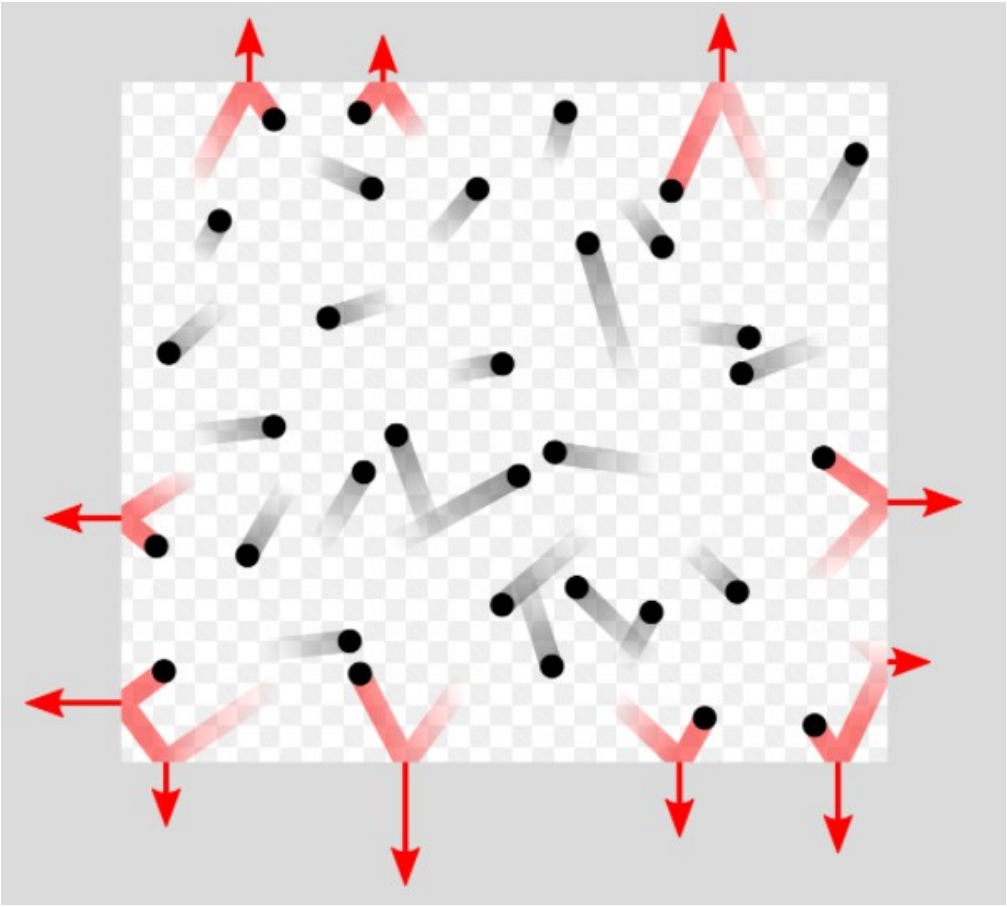
Atmosphere (atm). Atmospheric pressure is taken as 14.7 PSI, or about 101,325 **Pa** (101.325 kPa).

Pascal (Pa) in Standard International units is kilogram per meter squared.
Pa = kg·m−1·s−2. (1 Pa = 9.86923×10−6 atm)

bar. 1 bar = 1 atmosphere. Change from 1000 millibar is often used by meteorologists describing oncoming storms (low pressure systems).

PRESSURE of air molecules (O2, N2, CO2, CH4, O3, etc.) pushing against a surface will depend on the speed of those molecules colliding with that surface. KINETIC ENERGY of the gas molecules increases as more HEAT is put into the system. As TEMPERATURE of the gas increases, so does the product of the VOLUME and PRESSURE. Thus, the ideal gas law: pV = nRT

Unit	Abbreviation	1 atm equivalent
atmosphere	atm	1.00 atm (exact)
millimeters of mercury	mmHg	760 mmHg
torr	torr	760 torr
inches of mercury	in. Hg	29.9 in. Hg
pounds per square inch (psi)	$lb/in.^2$	14.7 $lb/in.^2$
pascal	Pa	101,325 Pa

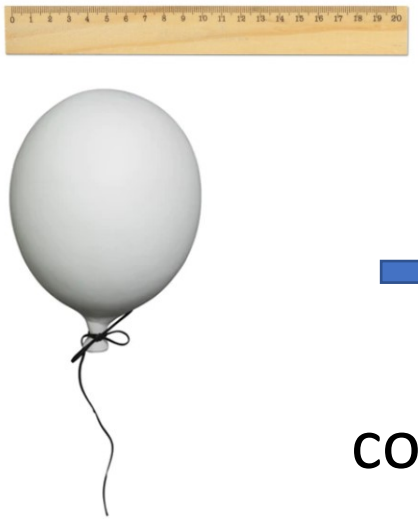


Gas Law: pV = nRT

warming

VOLUME increases;
Warmer air rises because
it is less dense than room air.

Pressure * Volume = # molecules * gas constant * Temperature



cooling

VOLUME decreases;
Cooler air sinks because
it is less dense than room air.

Force, Pressure, Energy, Work and Power

1 Newton (**FORCE**) accelerates 1000 grams at 1 meter per second, per second. Or N = $kg \cdot m/s^2$.
Gravity is a FORCE that accelerates a freely falling object by 32 feet (9.8 meters) per second per second. So, the force of gravity is 9.8 Newtons of force per kilogram of mass.

1 Pascal (**PRESSURE**) = 1 Newton per meter squared. Pressure is Force/area, such as PSI, pounds per Square Inch.

1 Joule (**WORK**) = exerting 1 N (FORCE) through 1 meter (DISTANCE)
So, 1 J = N*m = (1 kg × m/ s^2) ×m = 1 kg x (m/s)^2

Notice that (m/s)^2 is a speed squared. A mass times a speed squared we also know as **ENERGY**.
Remember E = mc^2 !!

So, ENERGY and WORK have the same units. Energy is the capacity to do work, and Work is Energy expended.

1 Watt (**POWER**) = 1 Joule per second. Power is the rate of doing Work.

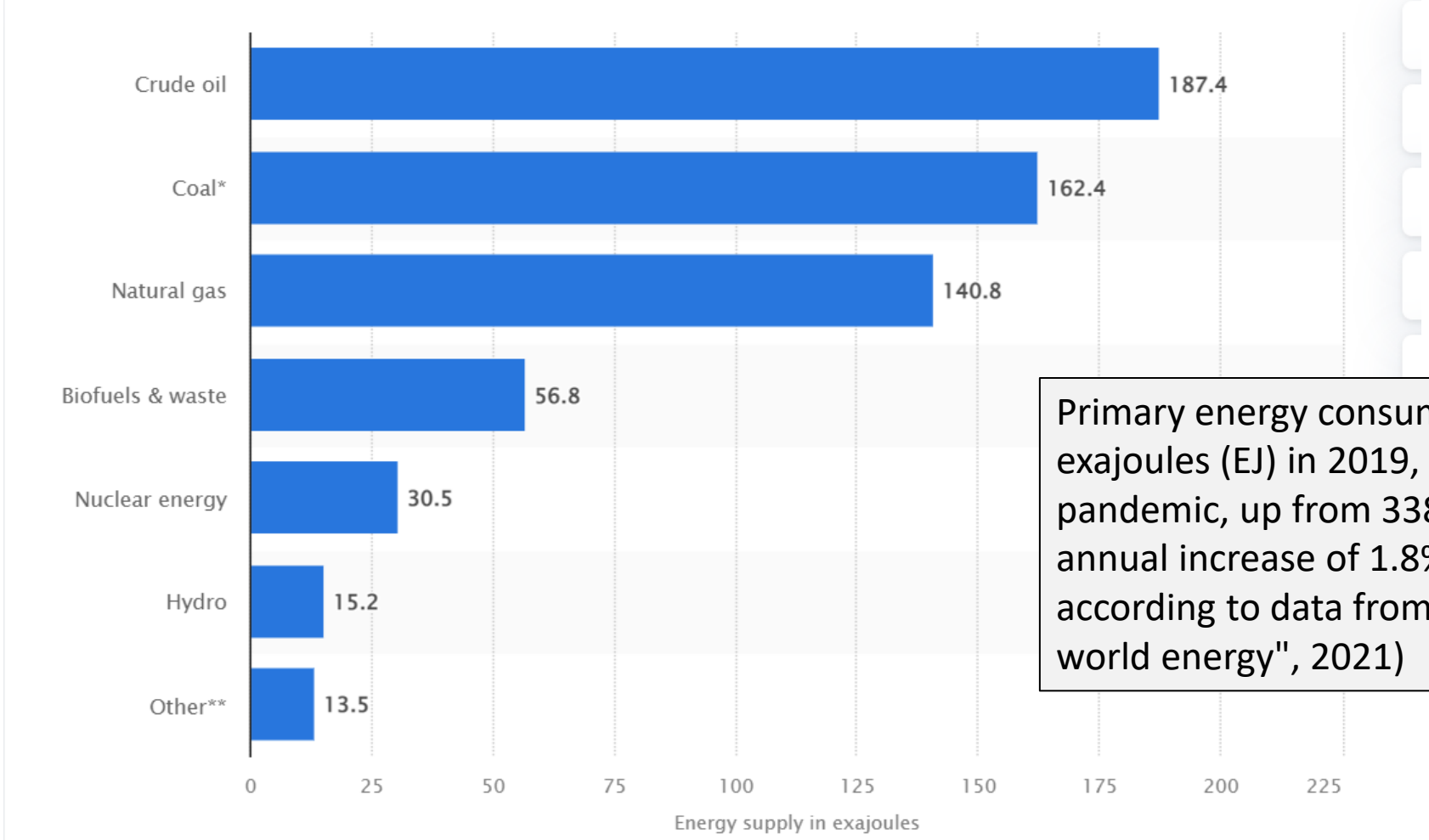
Compare pressure, current, power and resistance in electrical energy (Volts, Amps, Watts and Ohms). In a sense Pressure is the potential to push current against a resistance, similar to Energy being the potential to move a mass against inertia. So electron Volts are energy. Energy is a potential pressure, in a sense.

Total primary energy supply worldwide in 2019, by source

(in exajoules)

TOTAL = 606 exajoules

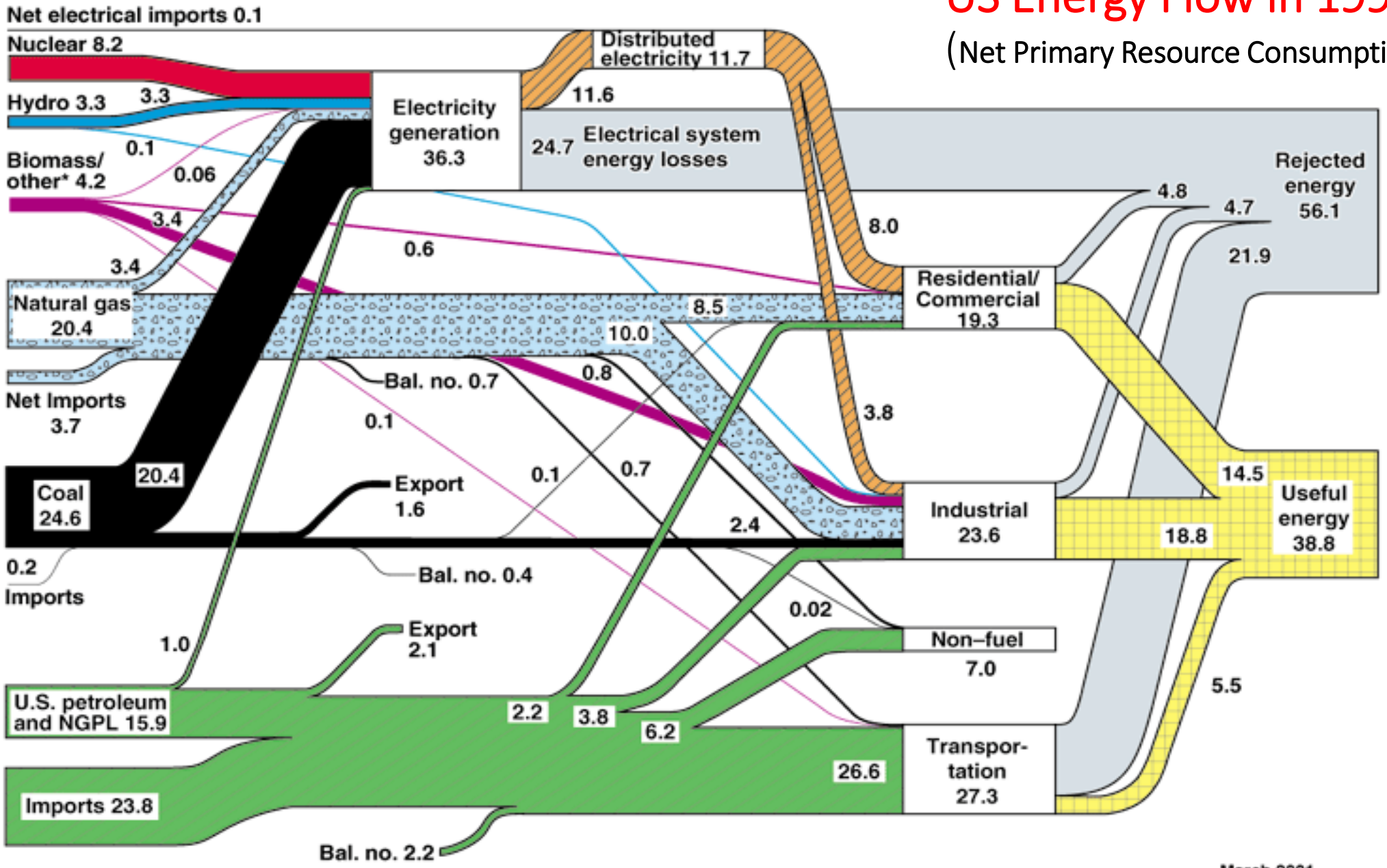
1 Gigaton of oil equivalent
= ~ 42 exajoules



Primary energy consumption climbed to 582 exajoules (EJ) in 2019, the last year before the pandemic, up from 338 EJ in 1989, a compound annual increase of 1.8% over three decades, according to data from BP ("Statistical review of world energy", 2021)

US Energy Flow in 1999

(Net Primary Resource Consumption 102 Exajoules (EJ))



EJ = ExaJoule
= 10^18 Joules
= Quintillion J

kilowatt-hour
3.6 MegaJoules

House, annual,
~ 30 GigaJoules

Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 1999*
*Biomass/other includes wood and waste, geothermal, solar, and wind.

March 2001
Lawrence Livermore
National Laboratory

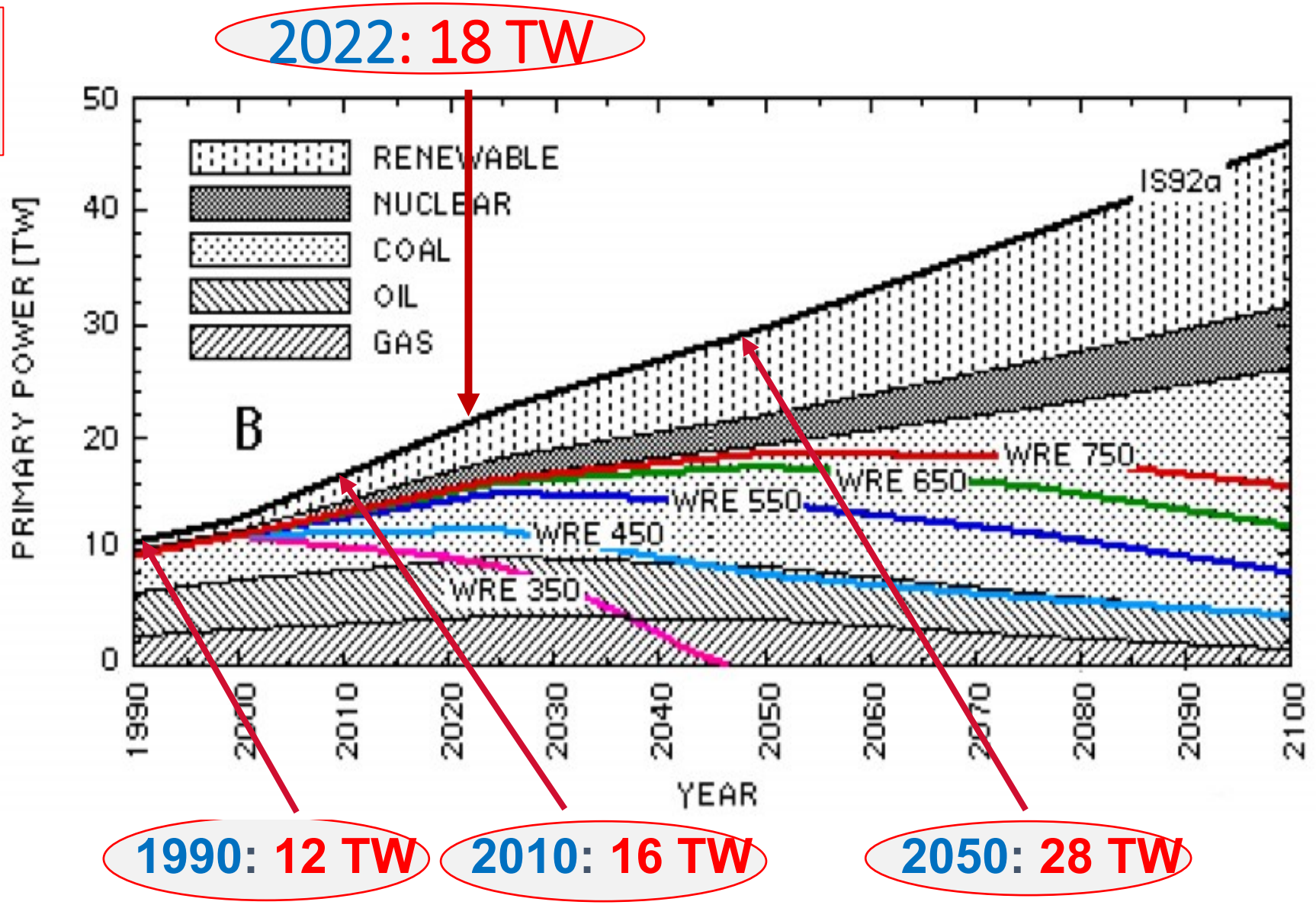
Power

POWER is the ability to do WORK (apply ENERGY) in a period of time.

- Power = Energy/*time*
- Watt *= 1 joule of work (energy expended) per second*
- *Light bulb, 100 W*
- *Kilowatt (1000 W)*
- *Megawatt (10^6 W)*
- *Gigawatt (10^9 W)*
- *Terawatt (10^12 W)*

Total Primary Power, Global

TW = TeraWatt
= 10^12 Watts
= Trillion Watts



Nuclear plant,
GigaWatt

Locomotive,
MegaWatt

Source: Lewis, CalTech

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Ecological Economics and Power

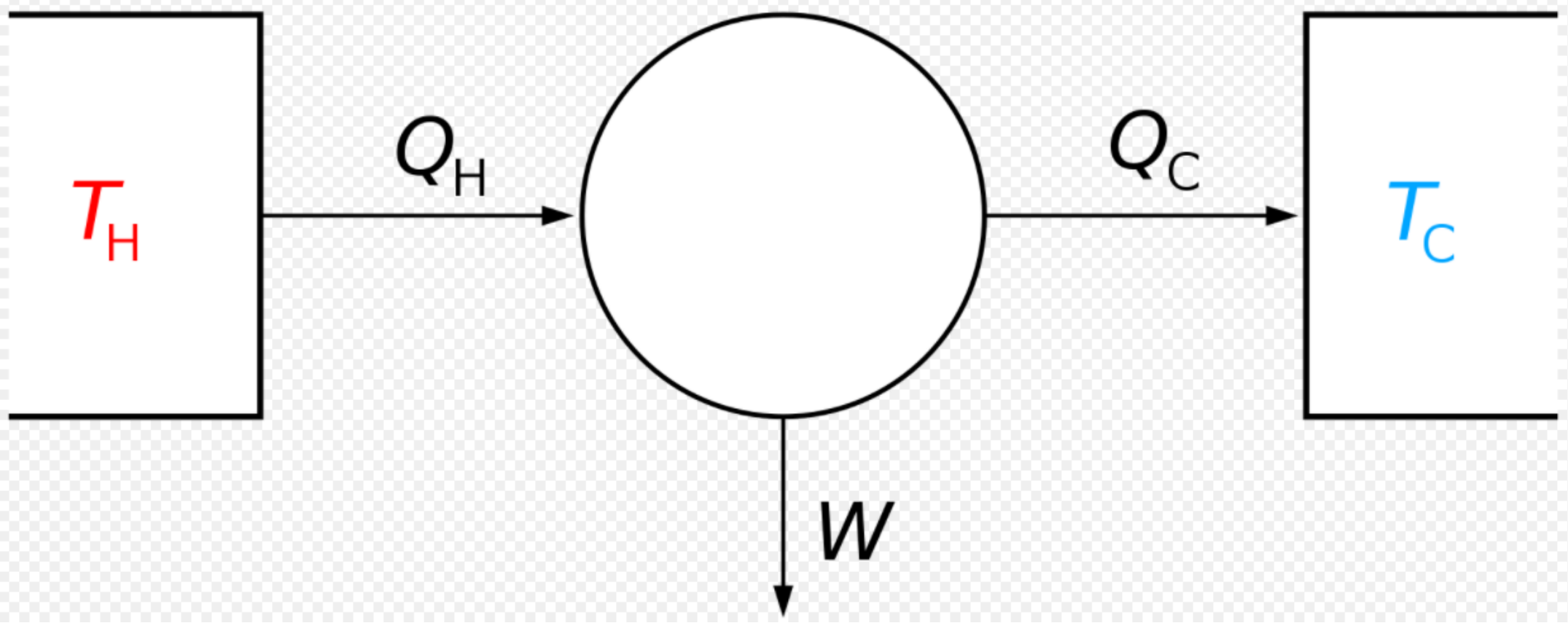
Lotka (1922):

> ". . . man has been unconsciously fulfilling a law of nature, according to which [energy per unit time] in the system tends toward a maximum."

Carnot engine:

HEAT (Q) = Energy
TEMPERATURE (T) = Measure of Heat
WORK (W) = Energy expended by exerting Force through a distance

HEAT **Q**H flows from a high temperature **T**H **source** through a working chamber or substance and the remaining HEAT **Q**C flows into the **cold sink T**C, thus forcing the working substance to do mechanical WORK **W** on the surroundings, via cycles of contractions and expansions.



Energy, E

Heat, Q

Internal system energy, U

Work done on system, W

A basic thermodynamic law states that energy is conserved. The total energy of a system, E, will be a combination of its kinetic and potential energy, and its internal energy, U. The change in a system's internal energy, ΔU, will be equal to the heat entering the system ΔQ, and the work done on the system, ΔW:

$$\Delta U = \Delta Q + \Delta W. \tag{1}$$

First Law of Thermodynamics

$$\Delta (E) = Q - W$$

THERMAL ENTROPY, dS

Entropy is the measure of a system's **thermal energy per unit temperature** that is unavailable for doing useful work. Because work is obtained from ordered molecular motion, the amount of entropy is also a measure of the molecular disorder, or randomness, of a system

To describe what happens as heat flows into a system, Clausius established a quantity called entropy (Greek: evolution), such that the change in entropy equals the change in heat content of the system per absolute temperature, T, for a reversible change.

$$dS = \frac{dQ}{T}. \qquad (2)$$

The thermodynamic entropy, S, describes the state of the system in Joules per degree Kelvin (J/°K).

$$\frac{\delta Q}{T} \leq dS$$

STATISTICAL ENTROPY, S

The statistical entropy, S, is defined as the measurement of degree of randomness. It is the increase in the disorganization within a system.

$$S = k_b \ln \Omega$$

S = entropy

k_b = Boltzmann constant

ln = natural logarithm

Ω = number of microscopic configurations

A statistical entropy was then identified with the thermodynamic entropy. The absorption of kinetic energy is associated with knowing less about the exact quantum configuration, as the system accesses a greater number of quantum states. A quantum state here, is a specific mix of electronic, vibrational, rotational and translational aspects of the kinetic energy. Where k is a positive constant and P_i is the probability of the system being in any one quantum state i, we can write for the statistical entropy

$$S = -k \sum P_i \ln P_i. \qquad (3)$$

Entropy quantifies how dispersed the energy is among the particles in a system, and how diffuse those particles are throughout space. It increases as a simple matter of probability: **There are more ways for energy to be spread out than for it to be concentrated**.

The **second law of thermodynamics** states that "**as one goes forward in time, the net entropy (degree of disorder) of any isolated or closed system will always increase (or at least stay the same)**

ENTHALPY, H

ENTHALPY is the **total heat content of a system**. It is equal to the internal energy of the system, U, plus the product of pressure, p, and volume, V.

$$H = U + pV$$

Gibbs energy, G

$$\Delta G = \Delta H - T\Delta S$$

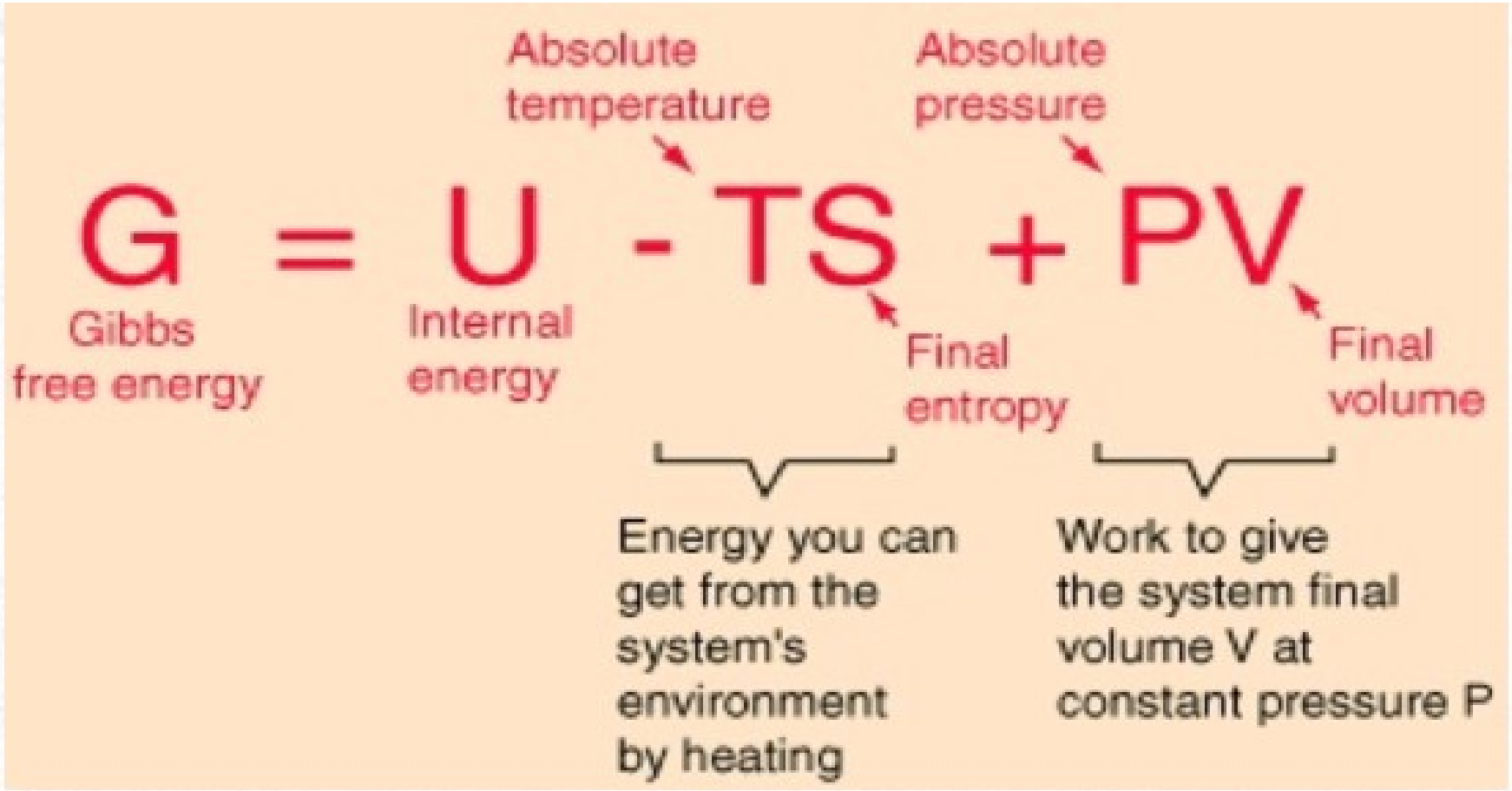
The Gibbs free energy is a thermodynamic potential that can be used to calculate the maximum reversible work that may be performed by a thermodynamic system at a constant temperature and pressure.

When a system transforms reversibly from an initial state to a final state, the decrease in Gibbs free energy equals the work done by the system to its surroundings, minus the work of the pressure forces.
The change in the Gibbs energy is equal to the change in enthalpy less the product of Temperature and the change in entropy (which is delta-Q)

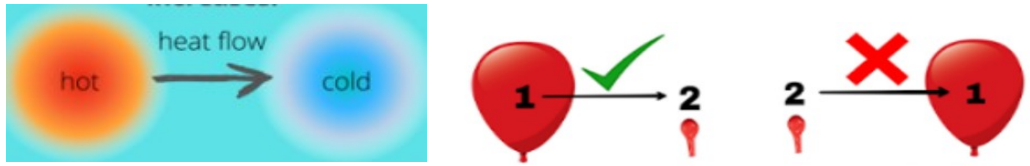
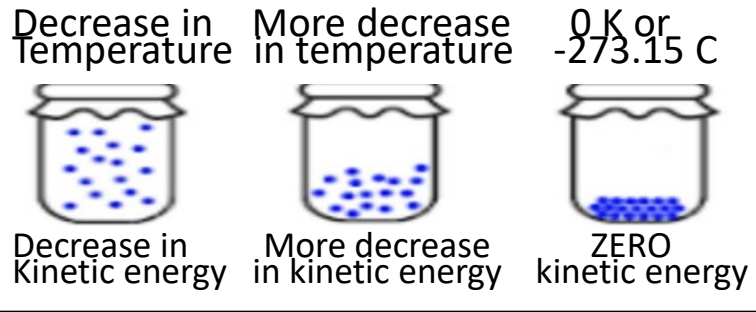
$$\Delta G = \Delta H - T \cdot \Delta S$$

ΔG = Gibbs free energy
ΔH = Change in enthalpy
ΔS = Change in entropy
T = Temperature in K

The Gibbs Free Energy can also be defined by the below equation, where the Enthalpy, H, is replaced by U + pV



LAWS OF THERMODYNAMICS

0th	**Thermal equilibrium is transitive**		**If two bodies A and B are in thermal equilibrium with third body C, then body A and B are also in thermal equilibrium with each other"**
1st	**Energy is conserved**	$\Delta E = Q - W$	**"The net change in total energy of a system (ΔE) is equal to the heat added to the system (Q) minus work done by the system (W)"**
2nd	**Entropy increases overall**	$\Delta S_{TOTAL} = \Delta S_{system} + \Delta S_{surroundings} > 0$ 	**"In all the spontaneous processes, the entropy of the universe increases"**
3rd	**Entropy constant at 0 K**		**"The value of entropy of a completely pure crystalline substance is zero at absolute zero temperature"**

Evolutionary Thermodynamics is concerned with open systems, often called non-equilibrium systems. This includes work in non-equilibrium thermodynamics.

Evolving natural systems grow through a successive self-organization from the microworld to the macroworld.

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What is growth?

Growth in an energetic system is radially outward (like an expanding balloon) driven by a positive feedback between energy capture (acquisition) and development of methods to hold, move and convert that captured energy into structure (including dynamic structure). Test idea at:

-- ATOMIC SCALE: Accretion of energy spherically: H, He, Li, Be, B, C, N, O, F, Ne. These little storms get bigger radially, with an interplay of an orthogonal field oscillation between two manifestations of the electromagnetic field.

-- MOLECULAR SCALE: H gets with O, and with C → start making stuff, H_x0_y, C_xH_y, $C_xH_yO_z$, etc., adding N, etc. (see Stanley Miller, UCSD).

-- EARLY BIOLOGY SCALE: Then H, C, N and O figured out how to embrace (use) bigger tools, such as Na, Mg, P, S, Cl and K, Ca, Mn, creating technologies like chlorophyll and hemoglobin, which are atomic-molecular systems that can capture light and oxygen (i.e., energy) and assist in storage/transport, delivering to site of conversion and consumption. (S. Miller; and others).

An important portion of captured energy is directed, through know-how, toward increasing energy capture by the energetic system. Know-how is technology.

Growth is an energy-technology feedback (ETF)

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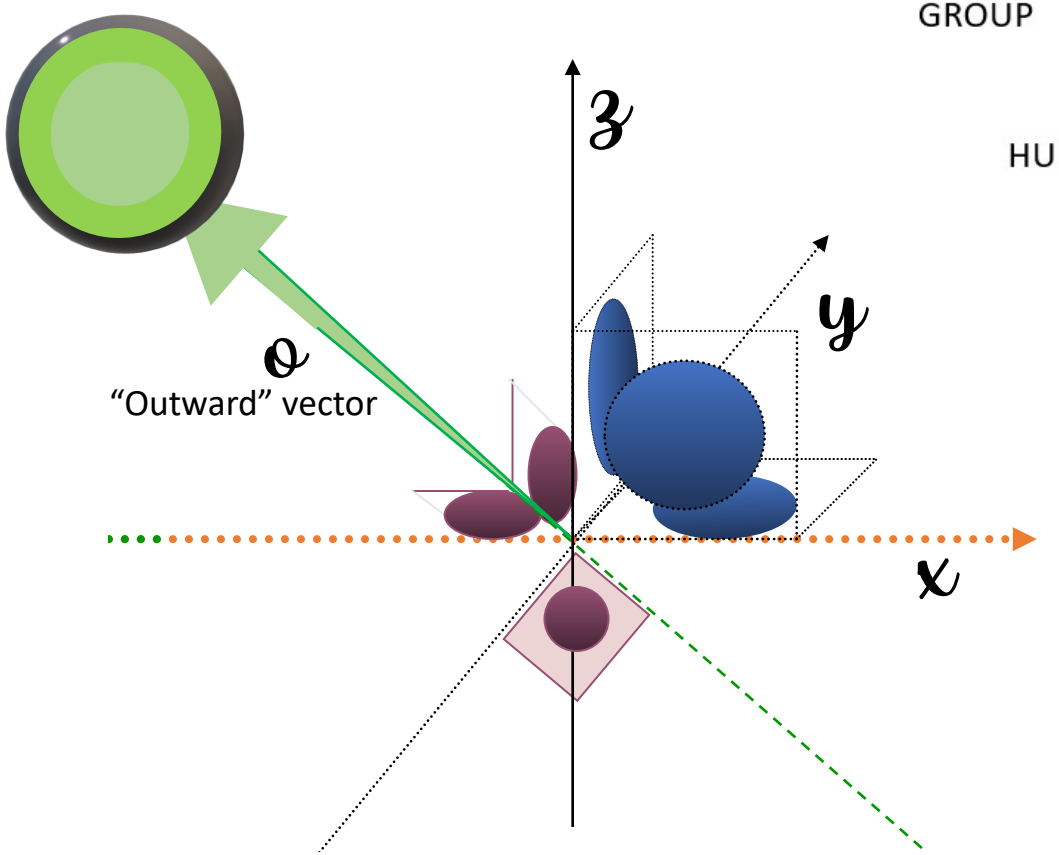
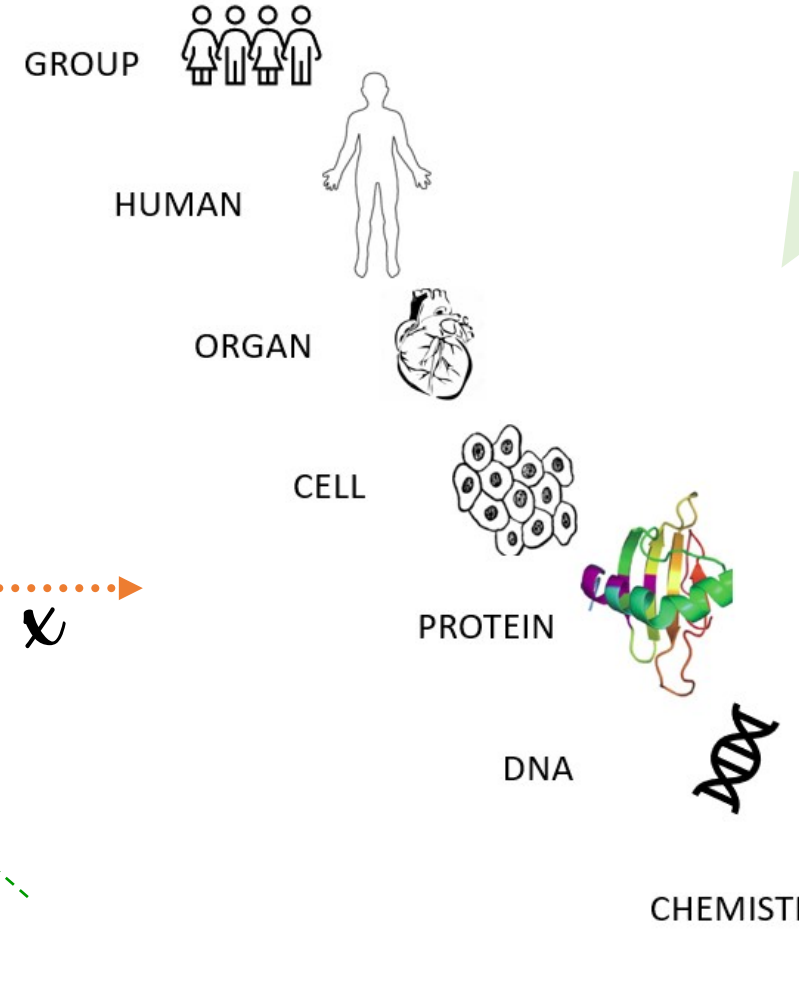
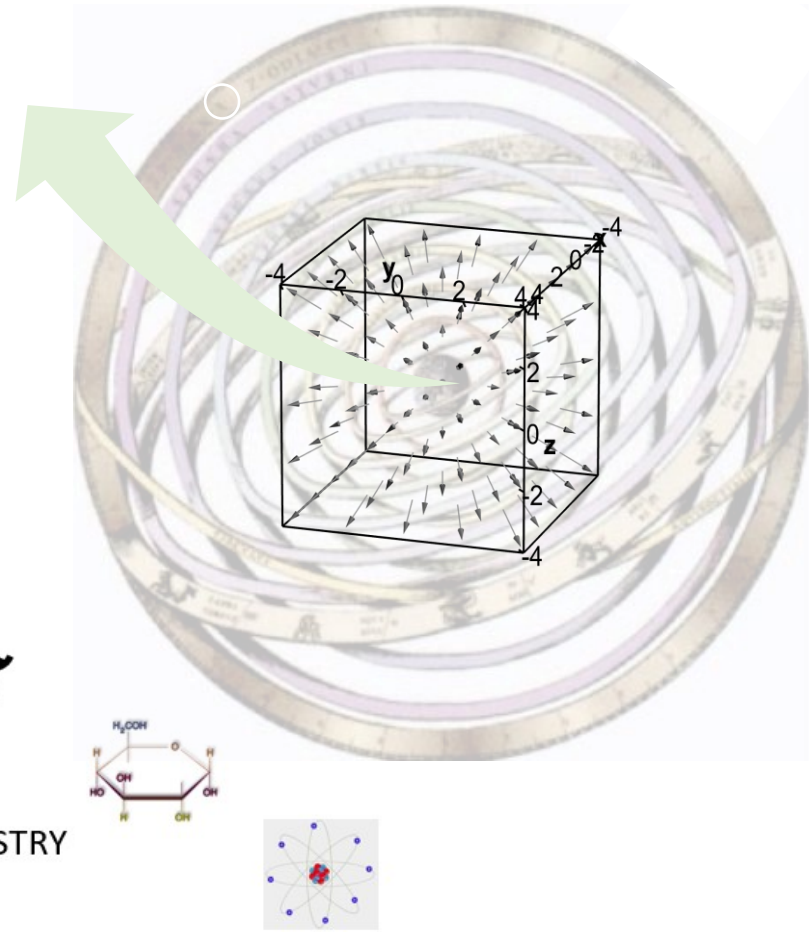


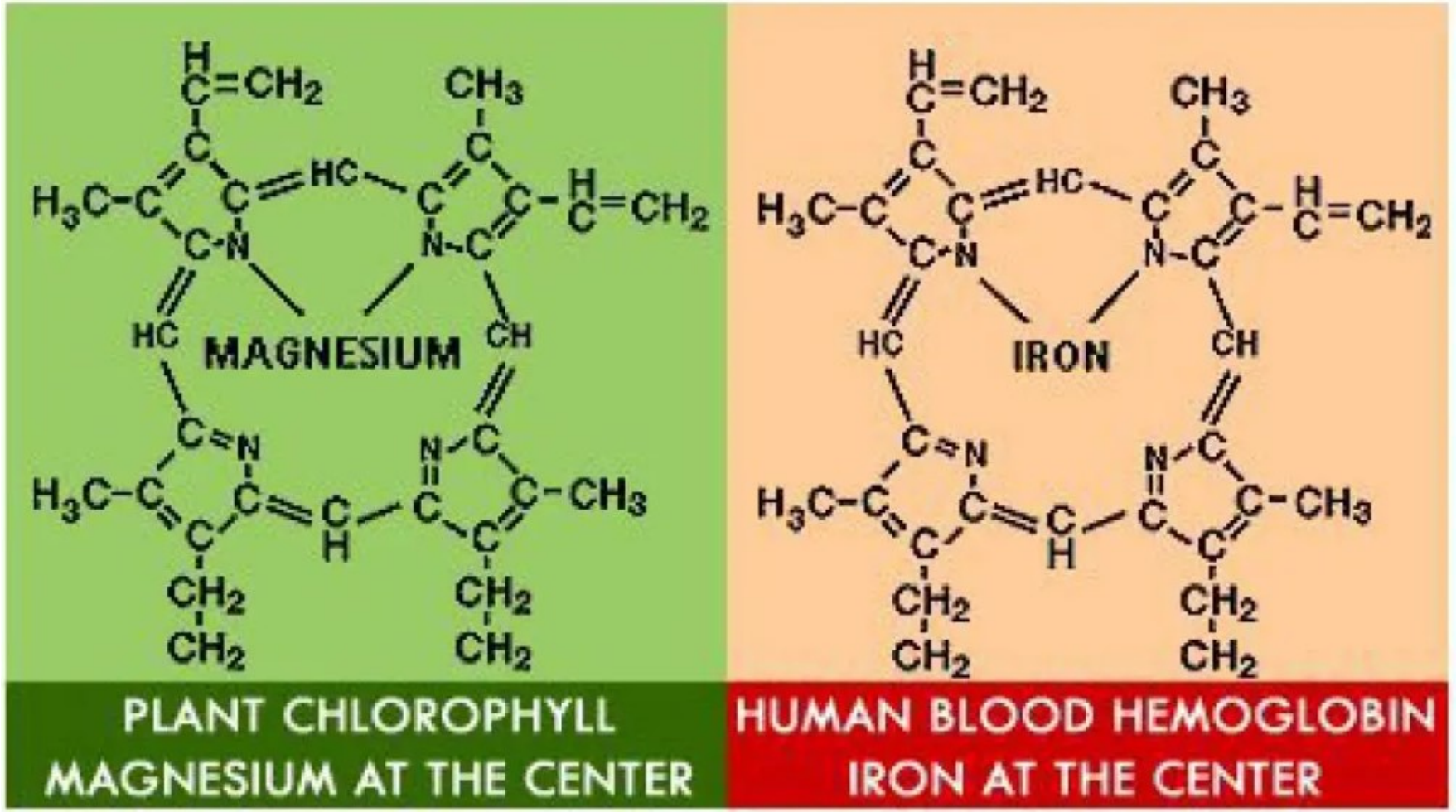




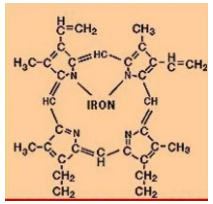
The progressive and successive growth of energetic systems can be described as proceeding along an "Outward" radial vector (O) that diverges from all infinitesimally small points in 3-dimensional space (R-3). This divergence can be related to the expansion of our 3-dimensional space.

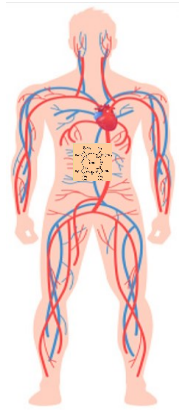
What is TECHNOLOGY? Method = Technique = Technology

Early molecular wheelbarrows created as METHODS to hold and move ENERGY within the plant and within the animal:

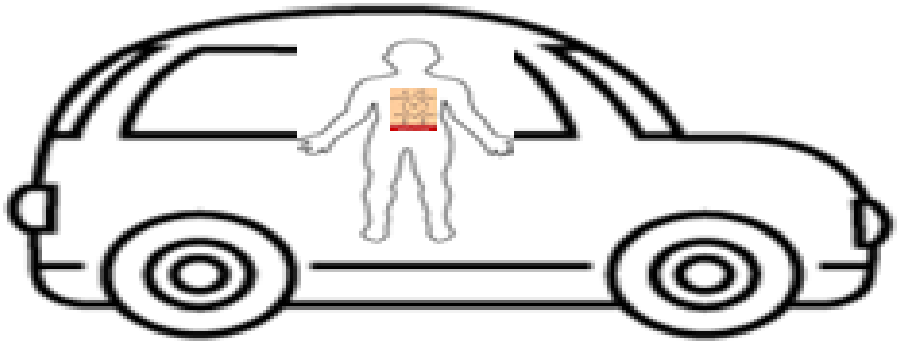


TECHNOLOGY EVOLVING:





Iron inside hemoglobin,
circulating through blood vessels the human.



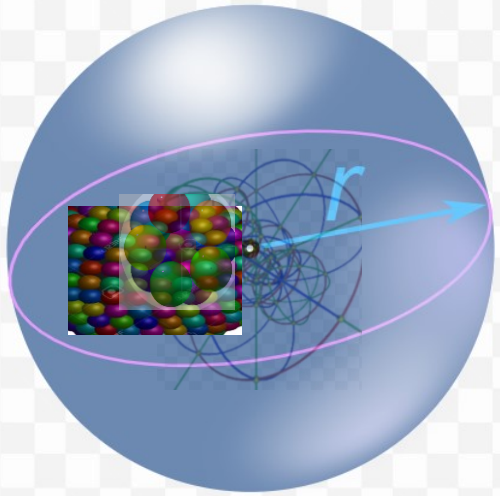
The human inside an iron car,
circulating through streets of the city.

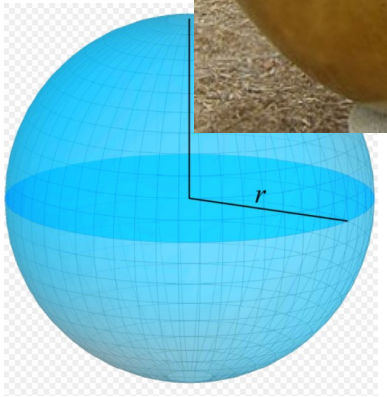
As above, so below …

The **Theory of Radially Evolving Energy (TREE)**

(from a Restatement of Evolutionary Thermodynamics made in 1989)

The evolution of energy proceeds radially from and into energetic structure. Energetic structure disorganizes into energy, and the unbound energy diffuses radially, moving from a volume of higher energetic density to lower. Energy self-organizes into energetic structure, and the bound energy aggregates radially.





An *Energetic Structure* is an organizational process, O_{r_i}, for which there exists an organizational radius, r_i. An energetic structure may be an energetic system.

An *Energetic System* is characterized by an organizational radius, $r_{i=n}$, and is an assemblage of energetic structures within an observed boundary, which structures are characterized by organizational radii $r_{i<n}$.

The *Organizational Radius* is the scale radius, r_i, corresponding to the spherical volume, V_i, that is defined by the total energy of the system, E_i, per constant energy density, $u_s = 1\ \mathrm{J/cm^3}$, such that

$$E_i = u_s \frac{4}{3} \pi r_i^3. \tag{14}$$

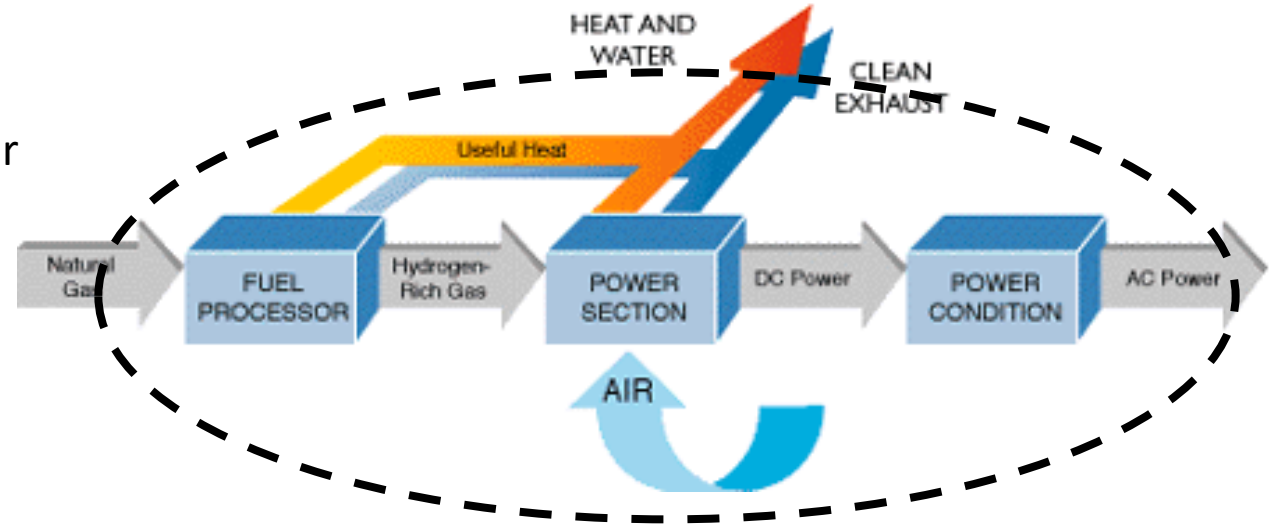
The *Observed Boundary* is the minimum spatial boundary that will circumscribe all the components of the energetic system, as defined by inter-relationships between the energetic subsystems comprising the system and by energy and material responsive to those subsystems, as determined by an observer.

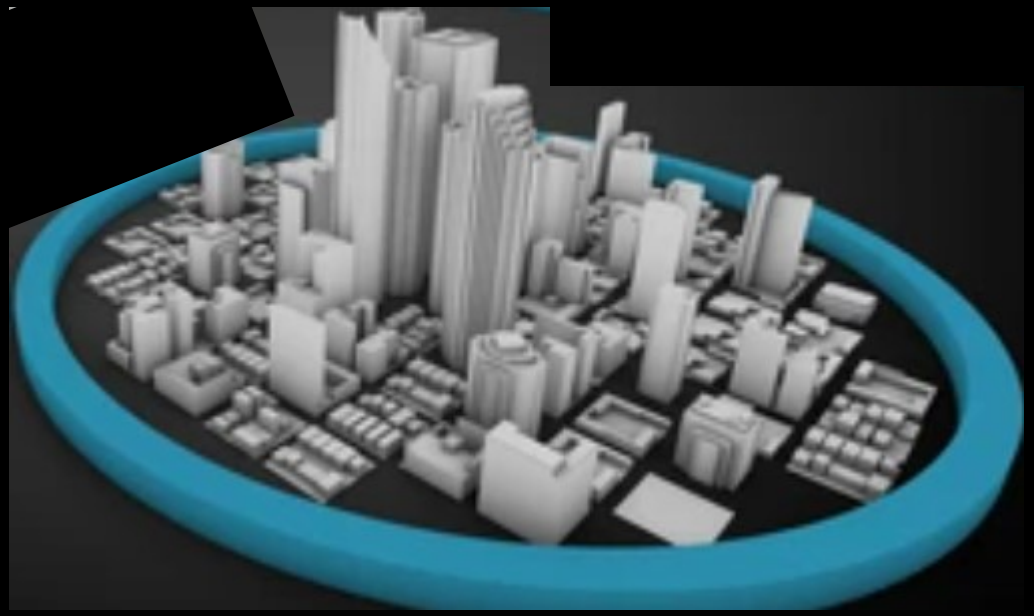
Dynamic Coordination is a process whereby kinetic energies become stored through harmonization, or non-interference.

A *Subsystem* is a subset of energetic structures within an energetic system that share a common functional relationship to the system, which relationship differs from relationship of other subsets to the system.

Setting the observed boundary around energetic systems

Observed boundary for a fuel cell system





Observed boundary for a city

RADIAL EVOLUTIONARY GROWTH FORCE

$I(b)$. The change, with respect to time, in energy contained in an evolving series of emerging structures can be modelled as the product of a radial evolutionary force, F_e, and a radial evolutionary velocity, v_e,

$$\frac{dE}{dt} = F_e v_e. \tag{17}$$

The force is the product of a pressure and surface area at radius i. The pressure is the energy density, u_s, so that the force is equivalent to the change in energy with increasing scale radius

$$F_e = u_s 4\pi r_i^2 = \frac{dE_{r_i}}{dr_i}. \tag{18}$$

From Eq. (17), with substitution from Eqs. (18) and (19), we can model the change in energy in terms of the change in organizational radius with respect to time, obtaining the differential of Eq. (14)

$$\frac{dE}{dt} = u_s 4\pi r_i^2 \frac{dr_i}{dt}. \tag{20}$$

Solving Eq. (14) for the scale radius as a function of energy, and Eq. (18) for the scale radius as a function of force, we can write an expression relating a biospheric growth force, F_{bio}, and the total biospheric energy, E_{bio},

$$r_{bio} = \left(\frac{F_{bio}}{3\lambda}\right)^{1/2} = \left(\frac{E_{bio}}{\lambda}\right)^{1/3} \tag{24}$$

where $\lambda = u_s 4\pi/3$ ($\mathrm{g\,s^{-2}\,cm^{-1}}$). Making a further substitution, $\Lambda = 3\lambda^{1/3}$, which is numerically equal to 4.836, we can write the growth force as a function of biospheric energy

$$F_{bio} = \Lambda E_{bio}^{2/3}. \tag{25}$$

TREE posits that growth is a direct function of energy

An *Energetic System* is characterized by organizational radius, r_i

$$E_i = u_s \frac{4}{3}\pi r_i^3 \quad (1)$$

constant energy density. u_s = 1 J/cm^3

$$\frac{dE}{dt} = F_e v_e \quad (2)$$

v = dr/dt (outward radial velocity is change in radius); Growth is a function of v

$$F_e = u_s 4\pi r_i^2 = \frac{dE_{r_i}}{dr_i} \quad (3)$$

Energy density is a pressure, which acts at the surface of the sphere; this pressure times the area of the sphere is a Force, F.

$$r_{sys} = \left(\frac{F_{sys}}{3\lambda}\right)^{1/2} = \left(\frac{E_{sys}}{\lambda}\right)^{1/3}$$

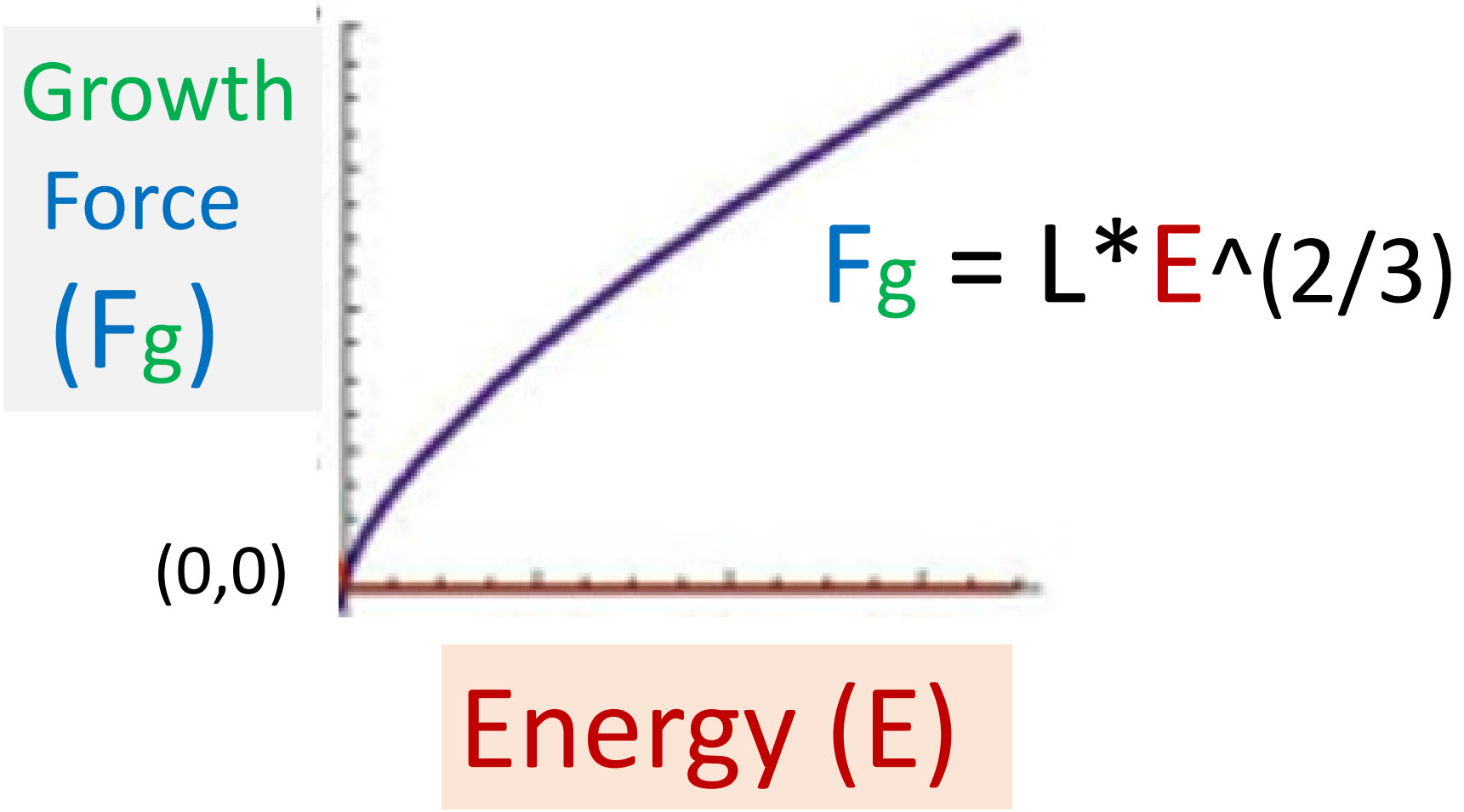
Solving Eq. (1) for the scale radius as a function of energy, and Eq. (3) for the scale radius as a function of force, we can write an expression relating a system growth force, F_{sys}, and the total system energy, E_{sys},

$$F_{sys} = \Lambda E_{sys}^{2/3}$$

Growth force is function of energy in the system

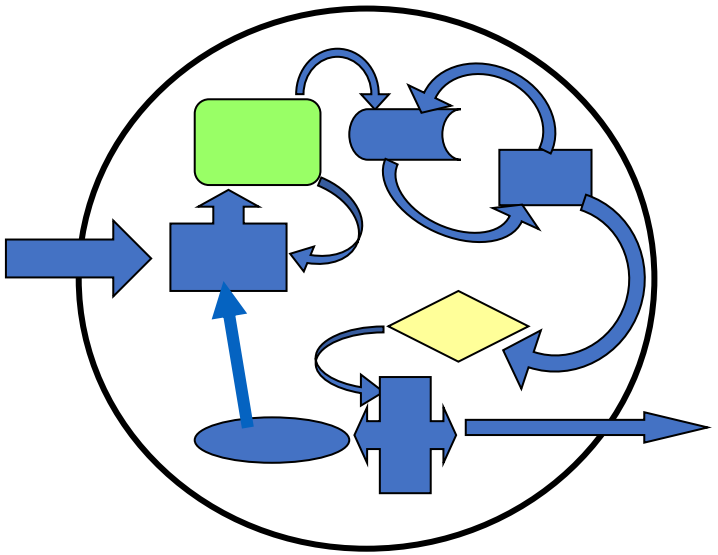
Lancaster, 1989

The growth **force (F_g)** of an energetic system equals a constant (**L**) times the quantity **Energy (E)** raised to the 2/3 power



$$F_g = L * E^{(2/3)}$$

Energetic systems have subsystems that produce non-linear feedbacks and dynamics



- **Through-flow**
- **Storage**
- **Feedbacks**
- **Information**
- **Method/Technique**
- **Switching/control**
- **Transport**
- **Metabolism**
- **Manufacture**
- **Identity/System Boundary**

Dynamic Coordination among Subsystems

II(*d*). Dynamic coordination, while enhancing the growth and stability of an emerging energetic system, reduces the degrees of freedom of component energetic structures.

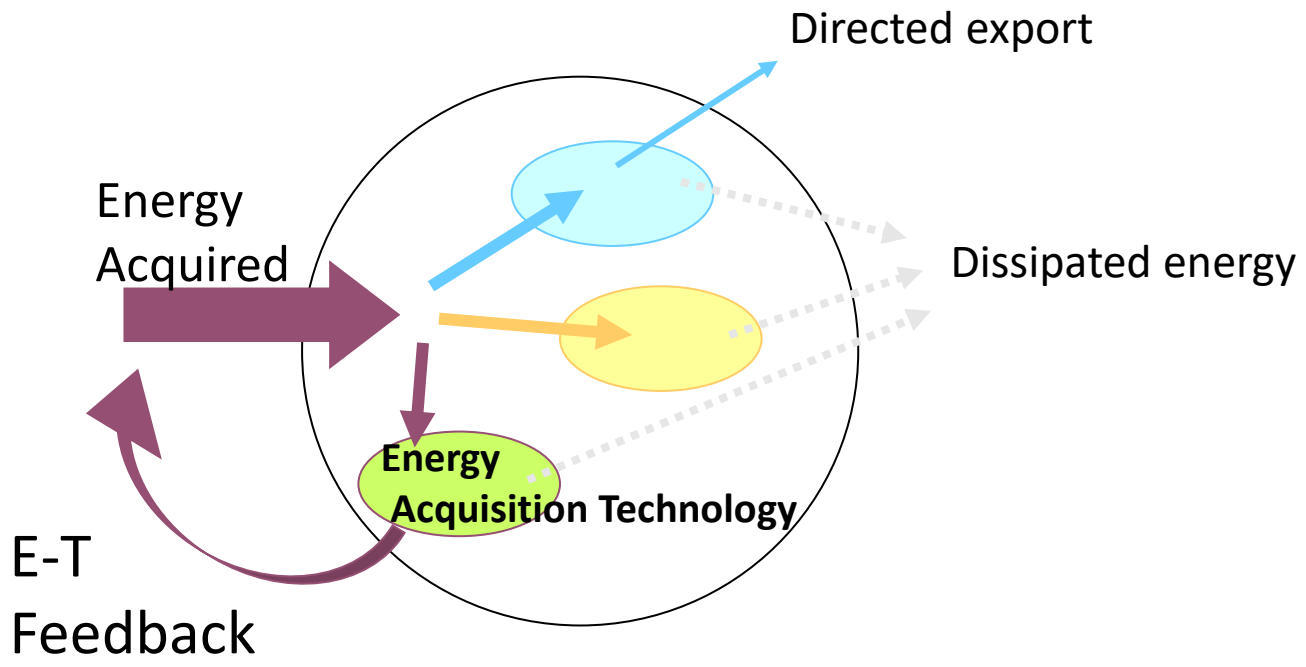
Bonding, parallel motion, and commitment to harmonic interactions are aspects of dynamic coordination that limit the independent motion of components in any system. The patterning of kinetic energy removes conflict. Conserved is the inefficient waste heat from non-harmonic collision (interference, if you prefer), allowing the maximum storage of energy, maximum structure and longevity for the system. The roles of the component energy identities become reinforced, parameterized by the emergent organizational process, to the point where the greater system will sacrifice its components in order to act with or against other high level systems. Incompatibility with the system is interference, and the flow of energy in the system will operate to damp it out. The organized system is naturally selected for.

Energy-Technology Feedback

II(*a*). System functions, or techniques, that enhance the incorporation of energy previously external to the system, will provide a positive energy feedback to the extent that the incoming energy can be used to enhance those functions. Similarly, innovative techniques that yield more efficient work create a positive feedback by making conserved energy available for greater work. Such techniques, as well as those that reduce destructive interference and minimize degenerative transformations, will enhance the stability and evolutionary competitiveness of the encompassing system.

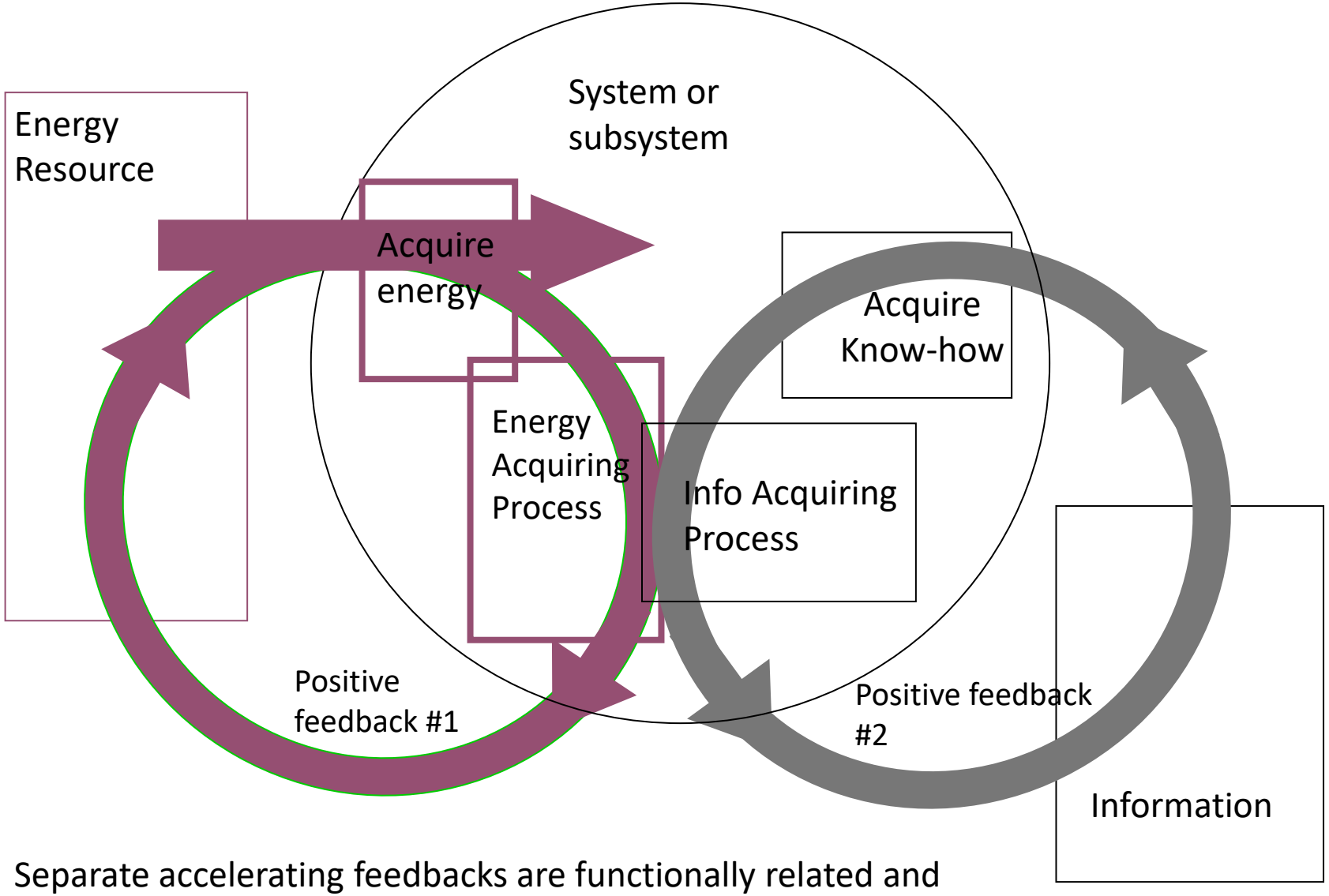
The Energy-Technology Feedback is part of the growth function in energetic systems

Positive feedback between energy acquisition and technology development for energy acquisition is a fundamental system function



(Lancaster, 1989, 1994)

The Energy-Technology Feedback



Separate accelerating feedbacks are functionally related and multiply each other.

The Energy-Technology Feedback (ETF)

The energy-technology feedback is a compound function of:

- change in know-how (ΔKH),
- change in material technology (ΔMT), and
- change in population (ΔP):

$$ETF = f(\Delta KH, \Delta MT, \Delta P)$$

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The Energy-Technology Feedback (ETF) grows

We can expect the ETF function to itself be an increasing function, becoming steadily more powerful as a process. The ETF may have a compound, exponential shape:

$$ETF = ETF_{(t=0)}\ e^{(kt)}.$$

where the exponential factor k is likely to be in the range of 0.001 to 0.04, assuming that it will be similar to the exponential growth factors seen in productivity, energy use, and population:

Growth factor, *k*	*Context*
0.0188	(EIA, 2009; 1971-2006; estimated production)
0.035	(Boden et al.; 1750-2006; estimate emissions)
0.0007	(population, P)

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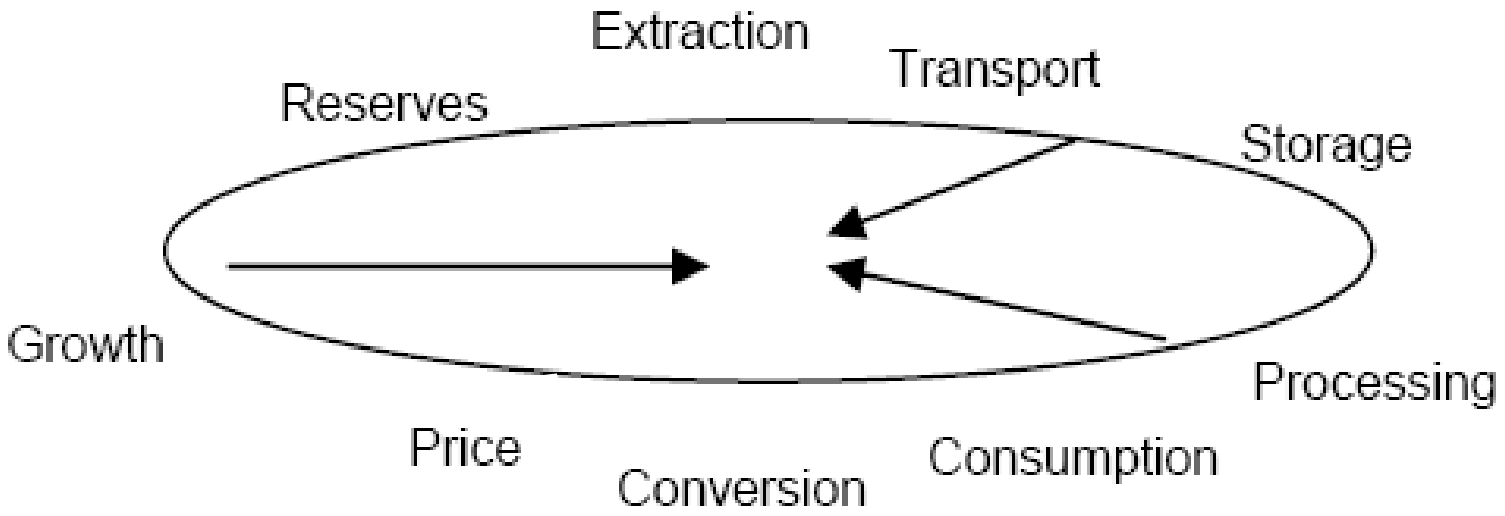
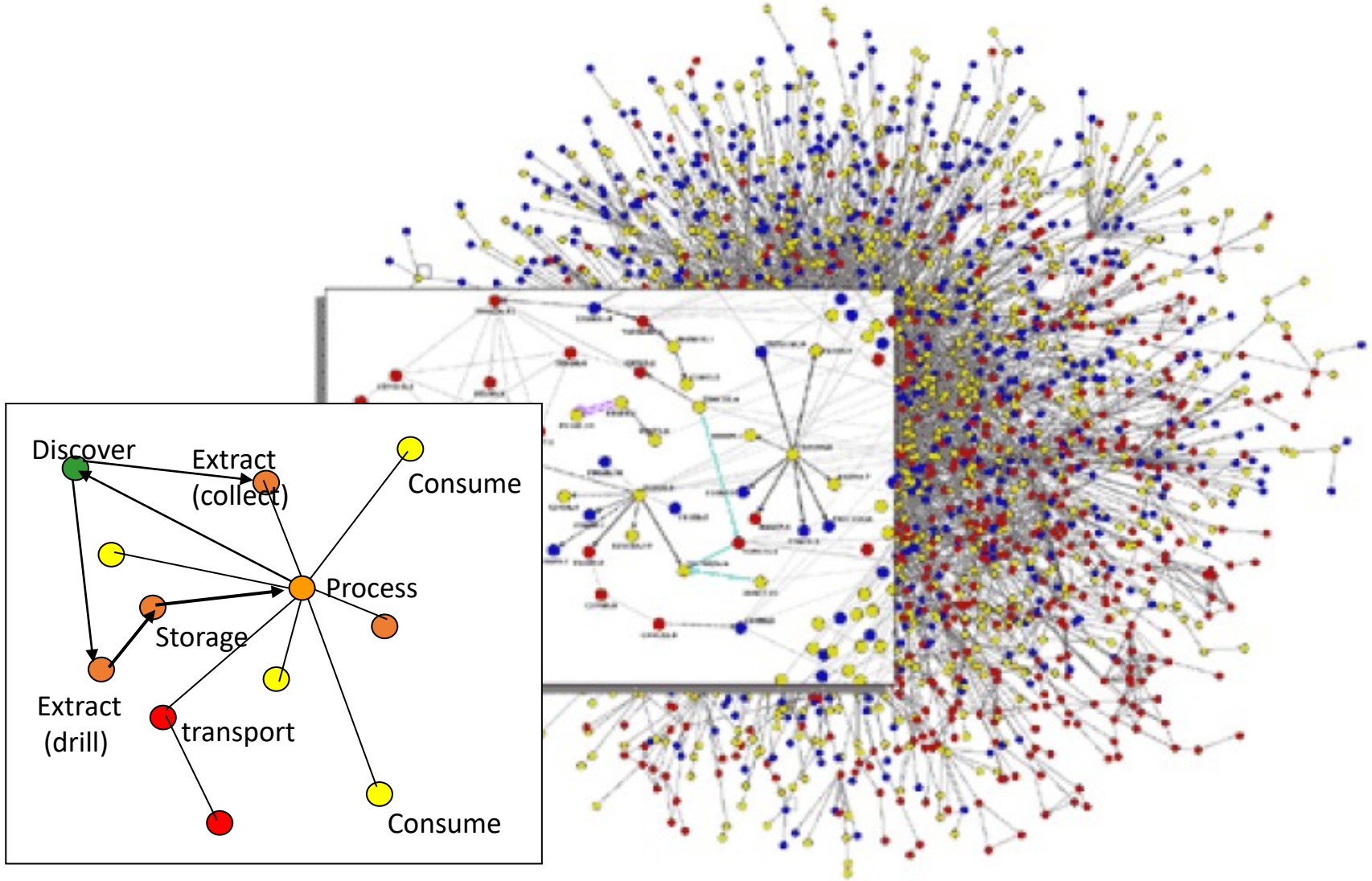
Many parameters and aspects of energy use in the human system must be modeled in a network of interactions



From Fig. 4

Network Modeling of Complex Energetic System



For an energetic system, the usefulness of energy is the extent to which it confers growth

- For growth, the ETF is useful, therefore, energy that is useful for growth is energy deployed in accelerating the ETF
- Define change in usefulness of energy, Φ_x in terms of percent increase in the ETF

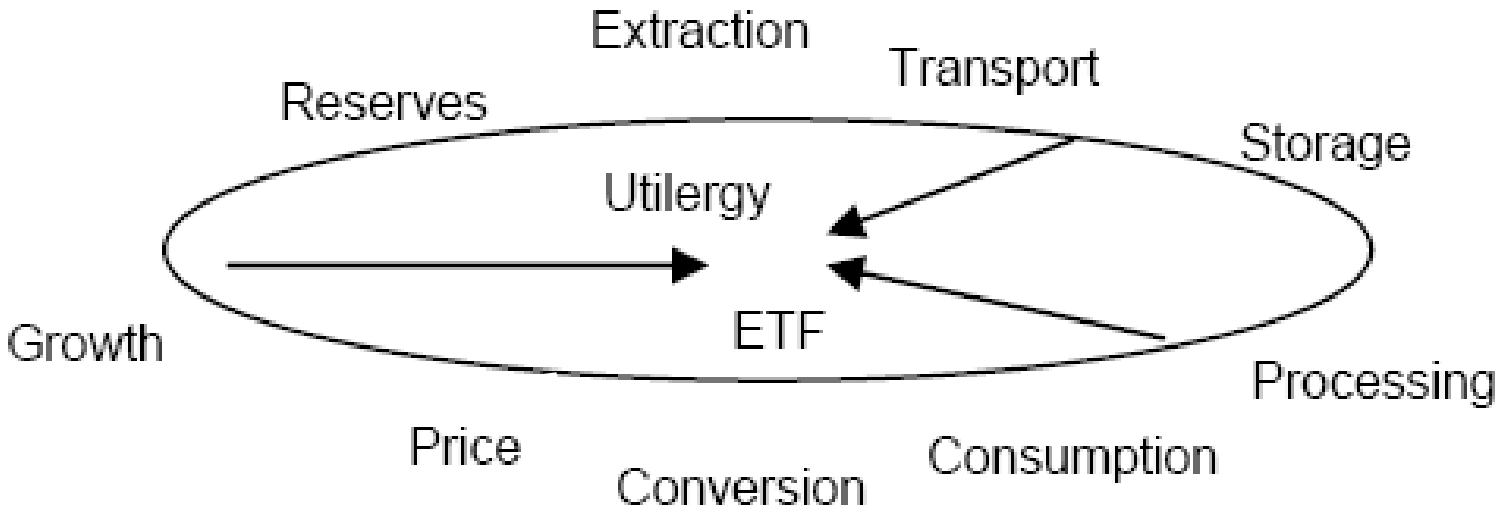
$$\Delta\Phi_x = f_2(\Delta \mathrm{ETF}_x)$$

Multiply change in usefulness of energy by the change in energy in the system being redirected toward energy acquisition:

$$\Delta E_x\ (ergs) \times \Delta\Phi_x\ (utils) = \Delta\Pi_x\ (util\text{-}ergs)$$

"**Utilergy**" becomes a new parameter for modeling

Modeling network relationships affecting growth



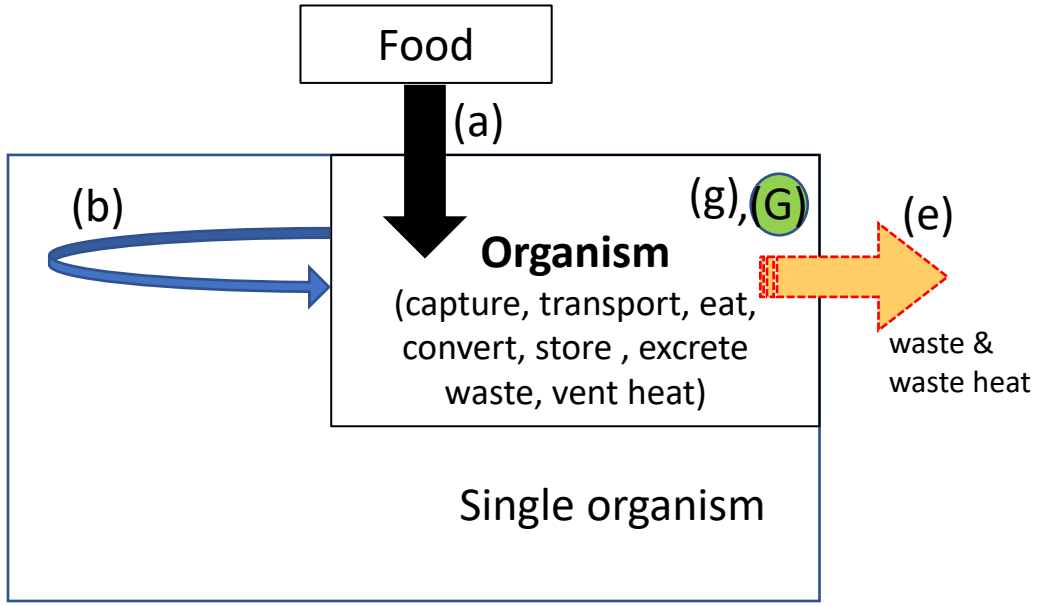
From Fig. 4

What is goal of tracking/modeling utilergy?

- Look at spatial, geographical distribution
- Look at time-development of ETF change
- Examining momentum of the ETF-related energy flows through the subsystem
- Examine “independence” of ETF-related energy pathways
- Examine potential ETF energy pathway control points and mechanisms

A Simple Model of System Growth

(a) Capture rate
(b) Direct internal use rate
()
()
(e) Waste heat rate
()
(g) Storage|growth rate
()



(G) Storage|Growth (bone, muscle, fat, teeth, eyes, ears, know-how)
()
(sb) store|grow (b)
(wb) waste (b)

$a = e + g$

$e = a - g$

$g = a - e$

$b = sb + wb = g + e$

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Adding components to growing system

(a) Capture rate

(b) Direct internal use rate

(c) Food|Energy distribution rate to children

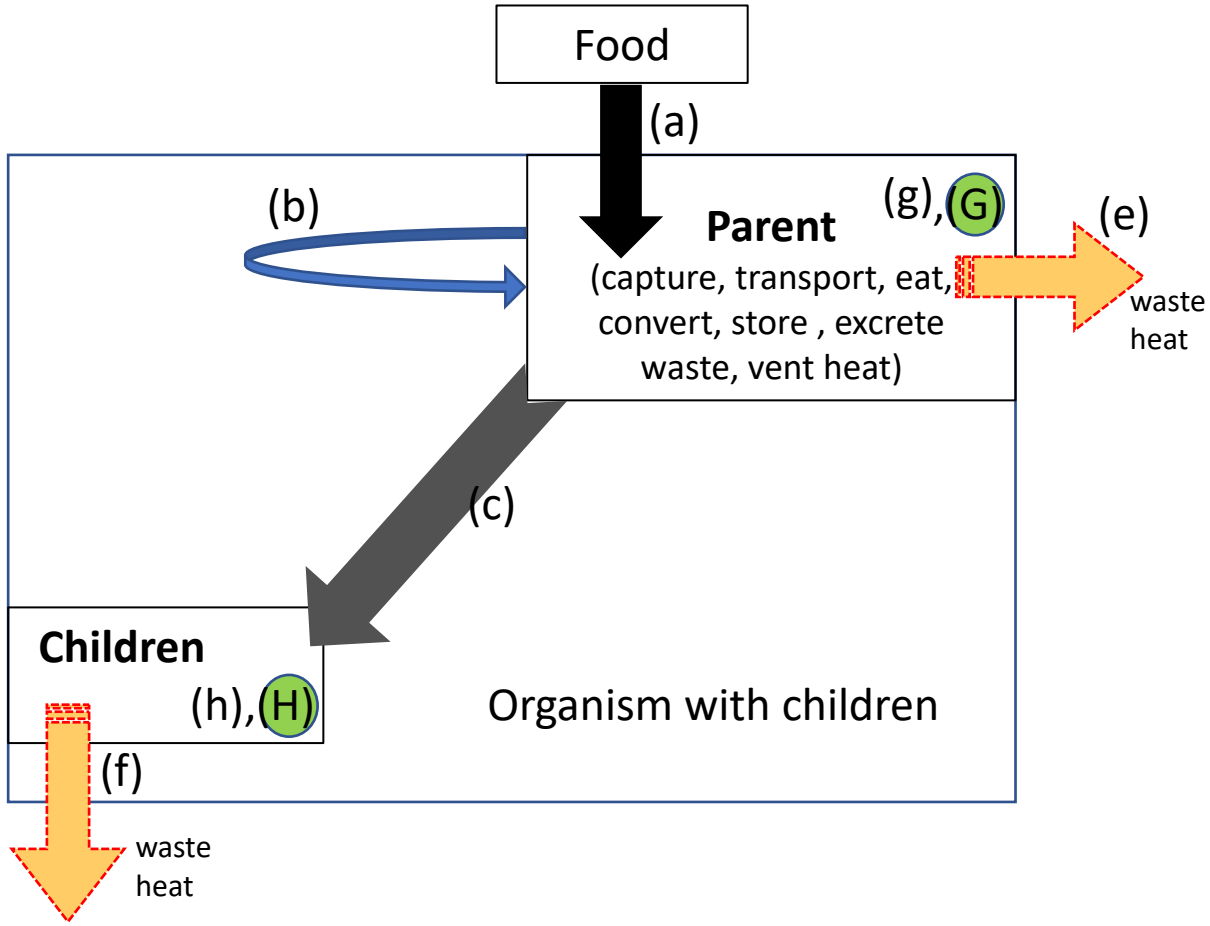
()

(e) Waste|Heat rate (Parent)

(f) Waste|Heat rate (Children)

(g) Storage|Growth rate (Parent)

(h) Storage|Growth rate (Children)



(G) Storage|Growth

(H) Storage|Growth

(sb) store|grow (b)

(wb) waste|heat (b)

$a = (e + f) + (g + h)$

$c = f + h$

$a = b + c$

$e = a - g - c$

$f = c - h$

$g = (a - c) - e$

$h = c - f$

$c = a - g - e$

$b = sb + wb = g + e$

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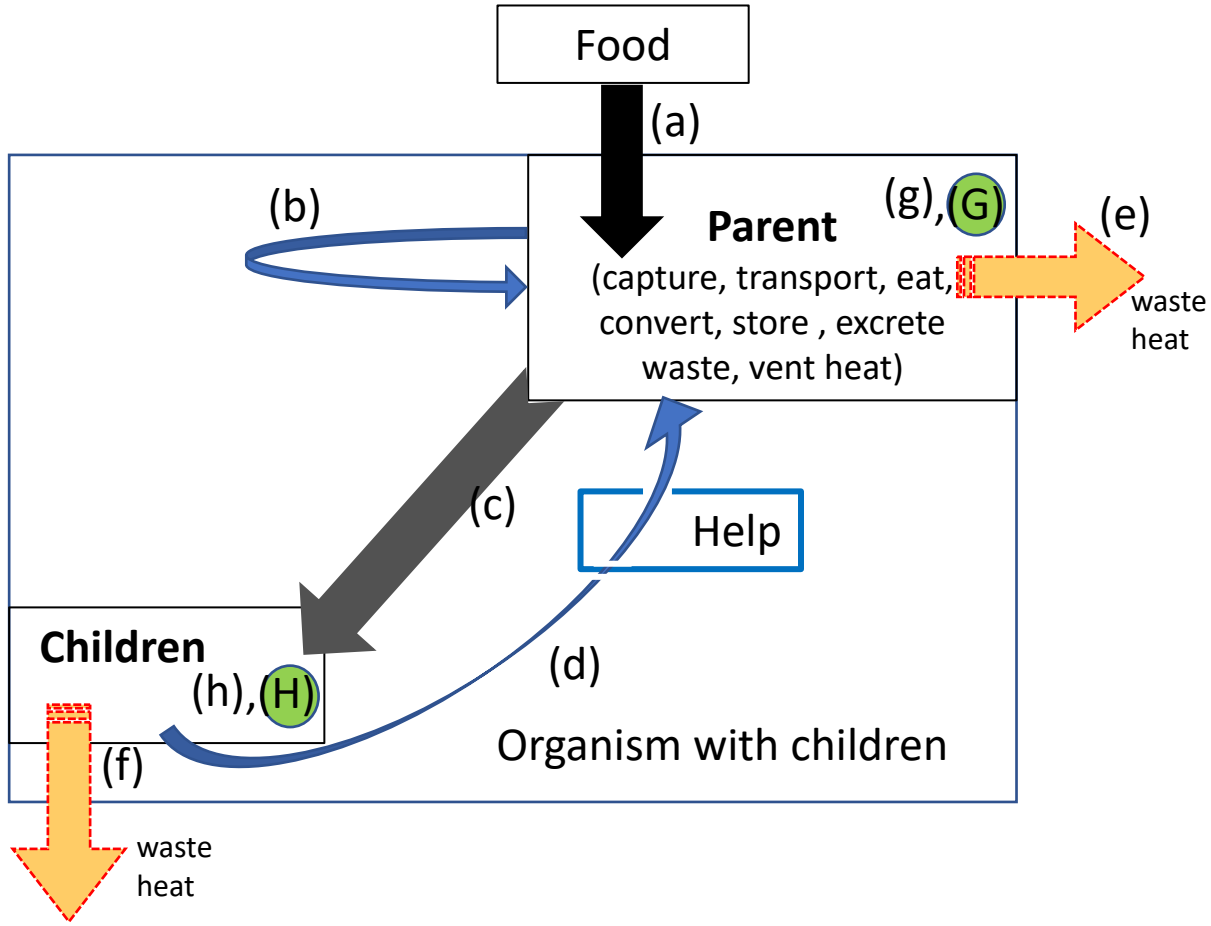
Adding component feedback in the system

(a) Capture rate
(b) Direct internal use rate
(c) Food|Energy distribution rate to children
(d) Assist parents getting food
(e) Waste|Heat rate (Parent)
(f) Waste|Heat rate (Children)
(g) Storage|Growth rate (Parent)
(h) Storage|Growth rate (Children)



(G) Storage|Growth
(H) Storage|Growth
(sb) store|grow (b)
(wb) waste|heat (b)

$a = (e + f) - (g + h)$

$c = (f + d) + h$

$d = c - f - h$

$e = a - g - c + d$

$f = c - h - d$

$g = (a - c) - e$

$h = c - f - d$

$c = a - g - e$

$b = sb + wb$

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More complex model: Add capital ($$) and "know-how"

(a) Capture rate

(b) Used/reinvested in E industry

(c) Distributed to other sectors

(d) Invest/contribute in E-ind. from other sectors

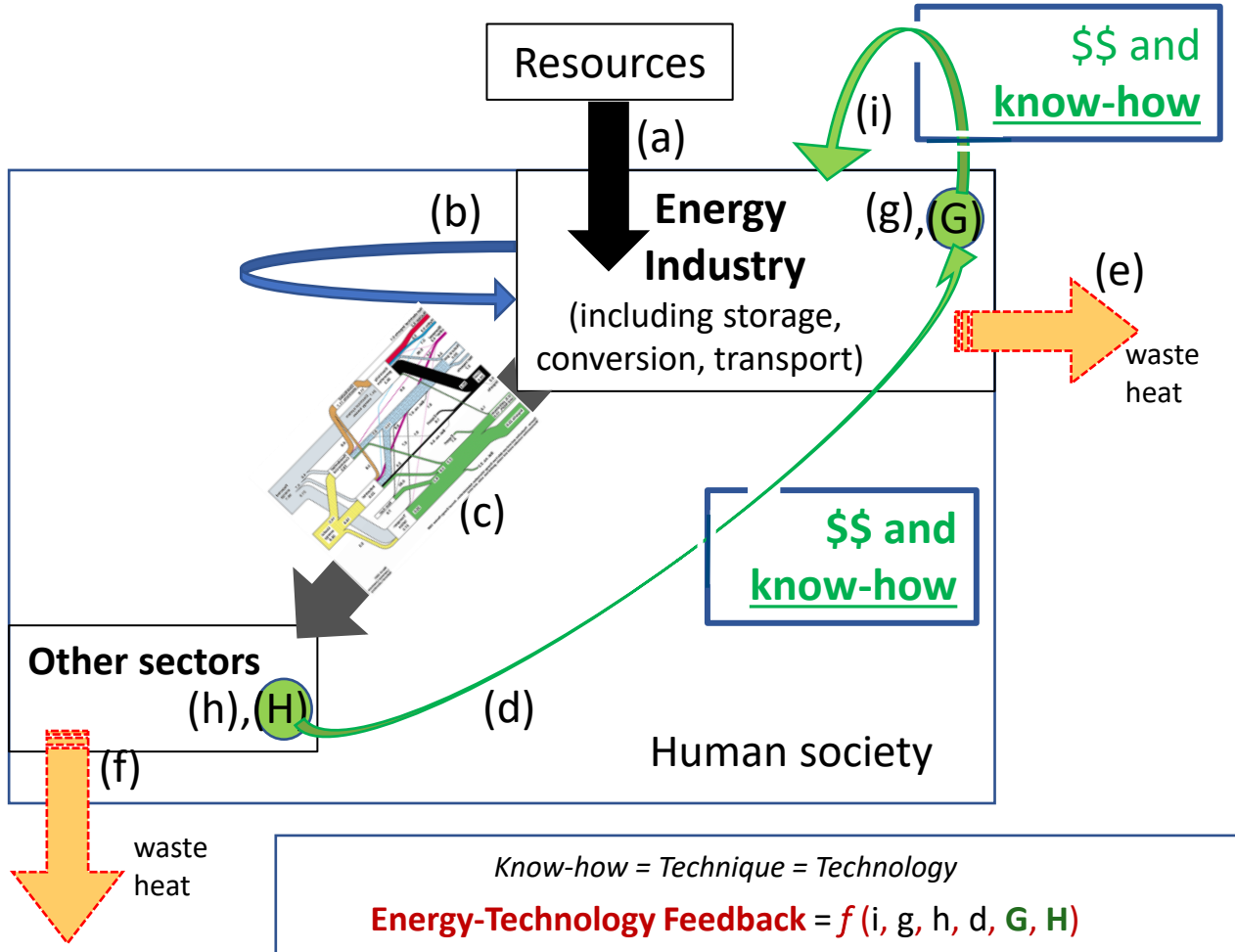
(e) Waste heat from e-ind. use

(f) Waste heat from other sector use

(g) Storage\growth in and by E industry

(h) Storage|growth in and by other sectors

(i) Leveraging capital, and know-how



Know-how = Technique = Technology

Energy-Technology Feedback = *f* (i, g, h, d, **G**, **H**)

(G) Storage

(H) Storage

(sb) stored (b)

(wb) waste (b)

$a = (e + f) - (g + h)$

$c = f + h$

$d = (\text{delta-H}) - h$

$e = a + i - g - c$

$f = c - h$

$g = a + i - c - e$

$h = c - f - d$

$c = a - b - (g - sb) - (e - wb)$

$b = sb + wb$

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Biospheric Energy Density

III(*a*). The energy density of the biosphere is increasing in three ways:

(i) the residence time of the solar throughput is increasing by lengthened pathway and structural storage;

(ii) the amount of solar energy being channeled through the biosphere is increasing;

(iii) terrestrial materials, including increasingly heavier elements, are being incorporated into the biosphere.

Energy is attracted to Energy

III(*b*). Organismic societies, and symbiotic assemblages of organisms in ecosystems, are energetic systems that have succeeded lower level biological systems. As energetic systems, they are attracted to energy in order to increase their energy density.

Human institution and societies are alive as their components

Social evolution will be understood better as this science progresses. Human societies, by virtue of being energetic systems, are as alive as their components. Societies exist within a positive feedback loop between energy acquisition and evolving technology. The extent to which they grow, gain complex self-control, and maintain stability, may be a sensitive function of energetics.

Those crafting human laws should not be ignorant of energetic laws. Humans, as components within an energetic system, may ultimately lose their ability to control social energy consumption. The energy-technology feedback, while giving us free time, is reducing human freedom by causing greater social coordination.

History offers no precedence for the increased energy flows that we have acquired within the past century, and which we may be about to acquire. Thermodynamic principles are not yet incorporated in political theory, but they should be, for they explain the most fundamental aspect of biological history, and they predict a social evolution that revolutions have been fought to avoid.

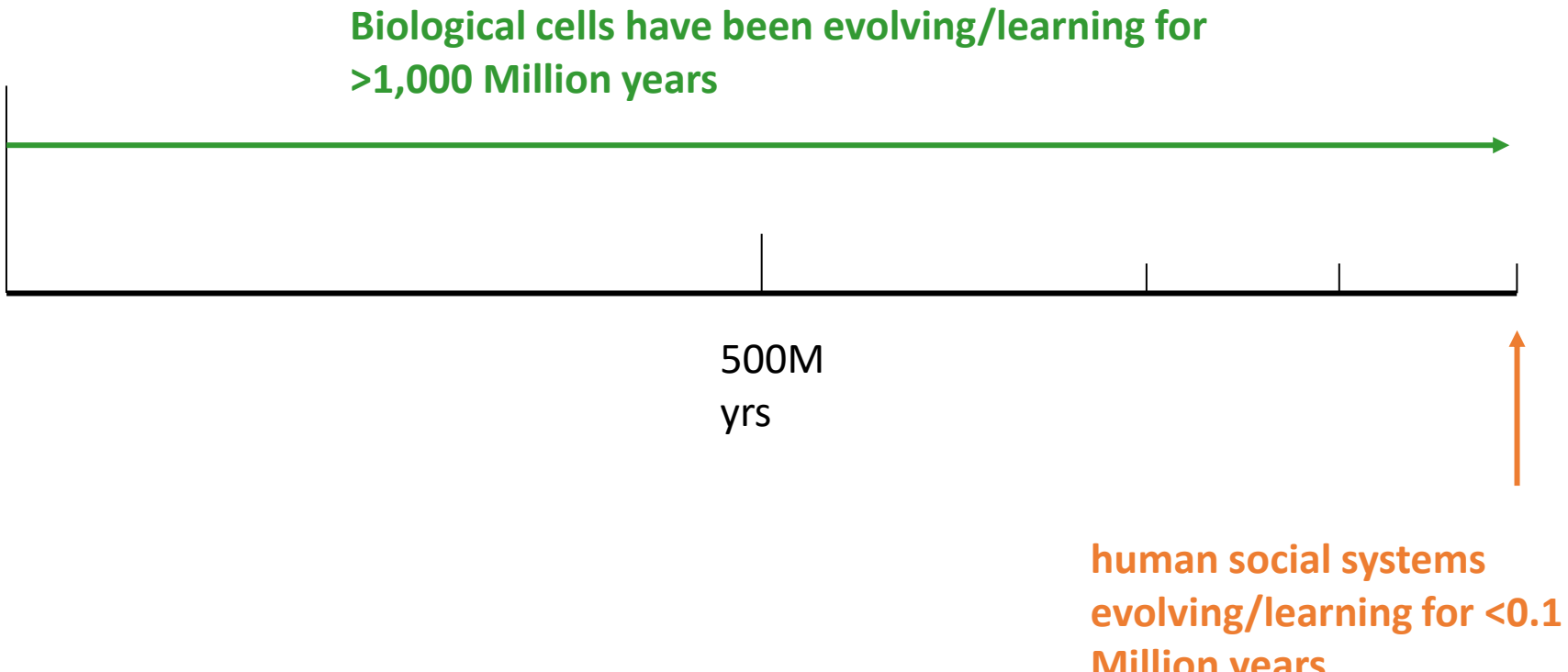
Key Questions for Climate Change concerns

1. How can we find effective control points in the human social system and various subsystems, with regard to energy resources and energy use?
2. Are human social systems doing something that is difficult for us to see, energetically?
3. Is there a basic function common to all energetic subsystems of the Earth System that, if examined through modeling, can help us to locate effective governance points (i.e., to engineer controls)?
4. Might there be a new parameter in our modeling of energetic systems that improves our view?

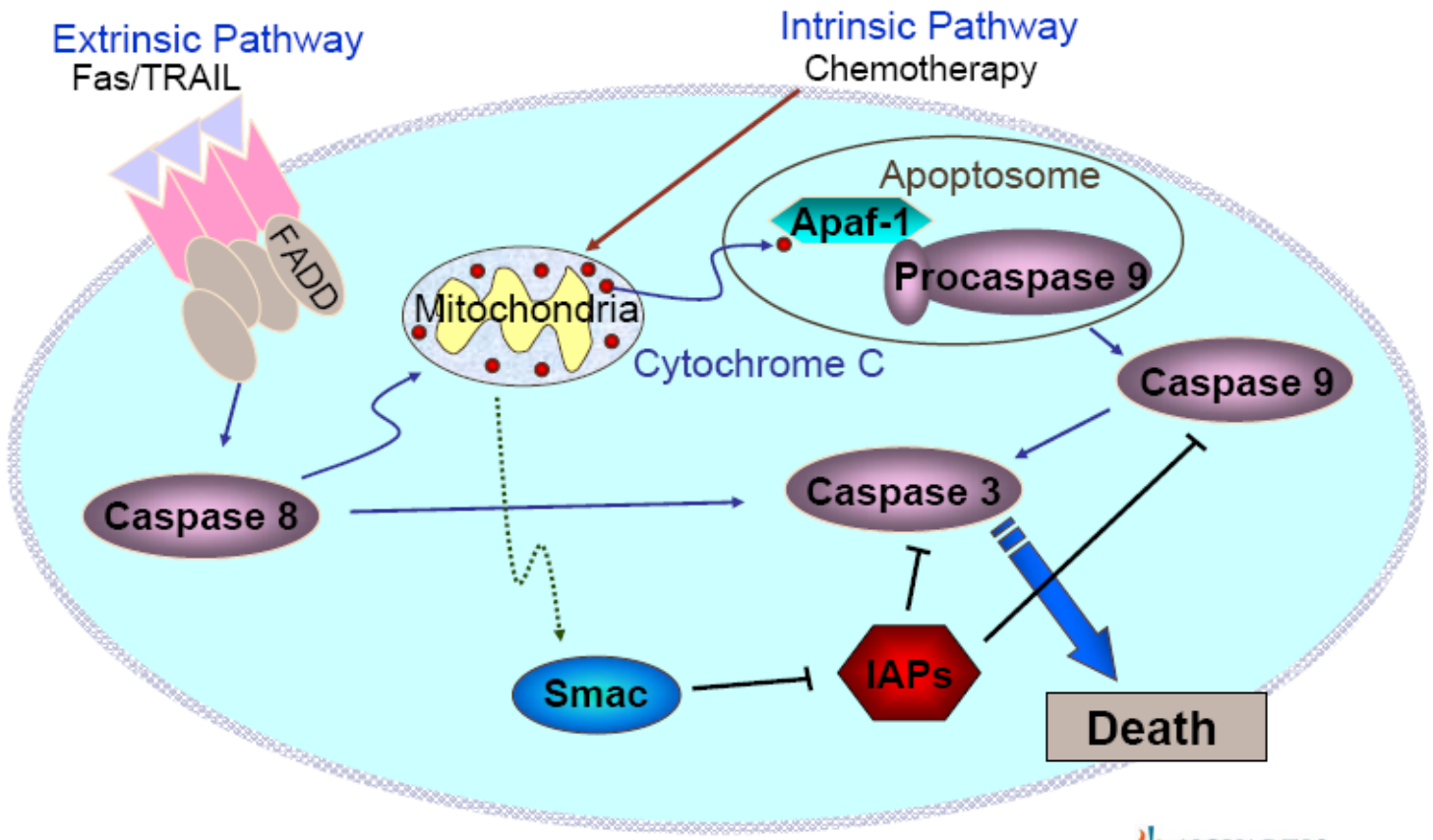
To Do: Research steps upcoming

- Assemble data (energy system accounting)
- Structure data in program accessible formats
  - XML structures; standardized
  - Ontologies & semantics (use Semantic Web approaches)
- Program auto-assembly routines
- Data analysis (R.E. and merge with knowns)
- Visualize
- Forward Simulations to test growth controls

Epilogue: Learning to control growth: biological cells have an early lead



Programmed cell death
is an internally responsive limitation on growth



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Challenge questions

1. Can a living system limit its growth to arrive at stable-state, without programmed system death?

2. Can components of an energetic system control the growth of the encompassing system?

Three Points to Take Home

- **Global warming is only a symptom**: Stabilizing T is important, but a fundamental growth principle creates a more serious underlying problem;

- **Growth and stability functions constrain options** available to decision-makers, (but may also assist);

- **The Energy-Technology Feedback (ETF) is a key** to exploring growth and stability functions: begin with a simplified, energy-flow model to picture growth, stability and the ETF.

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FURTHER READING: http://EvolutionaryThermodynamics.com

Thank you!

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