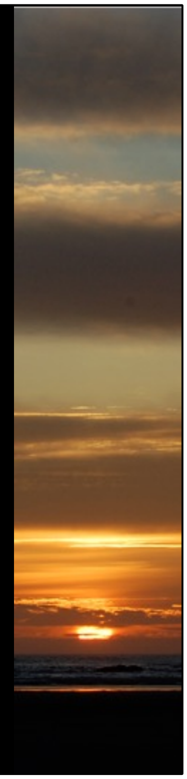
2026 International Summer Course on Environmental and Ecological System Engineering

Part A: Environmental Accounting and Systems Thinking (EAST)

Lecture 2:

Emergy Introduction



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Organization...

Introduction to the theory and principles of emergy

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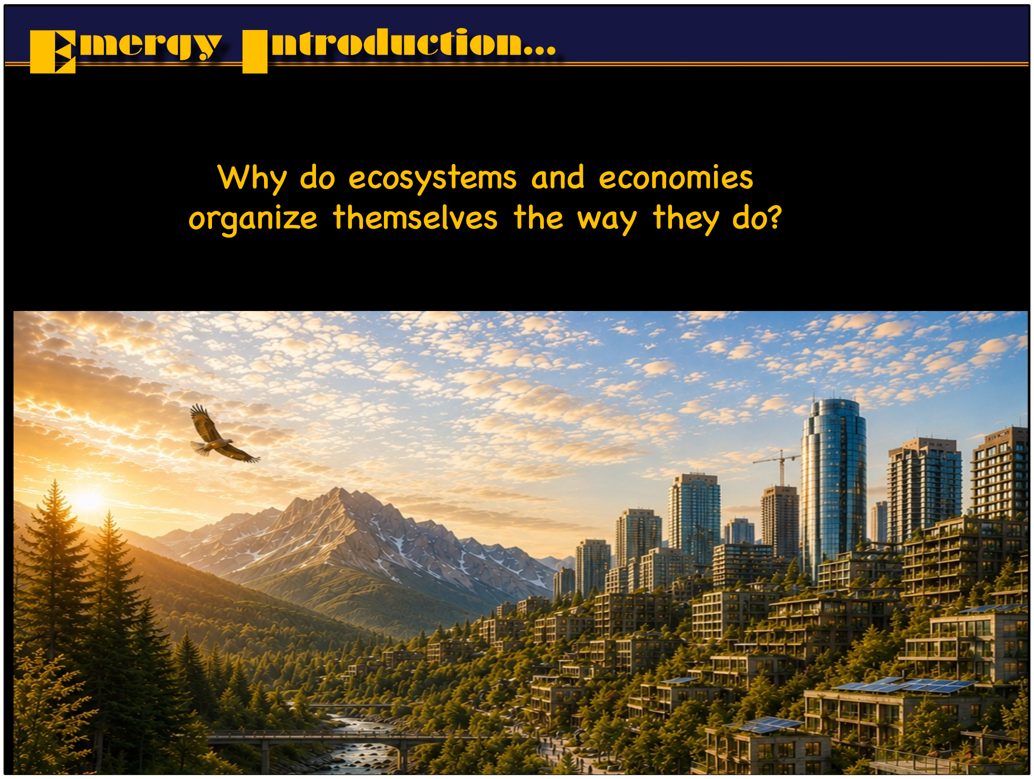


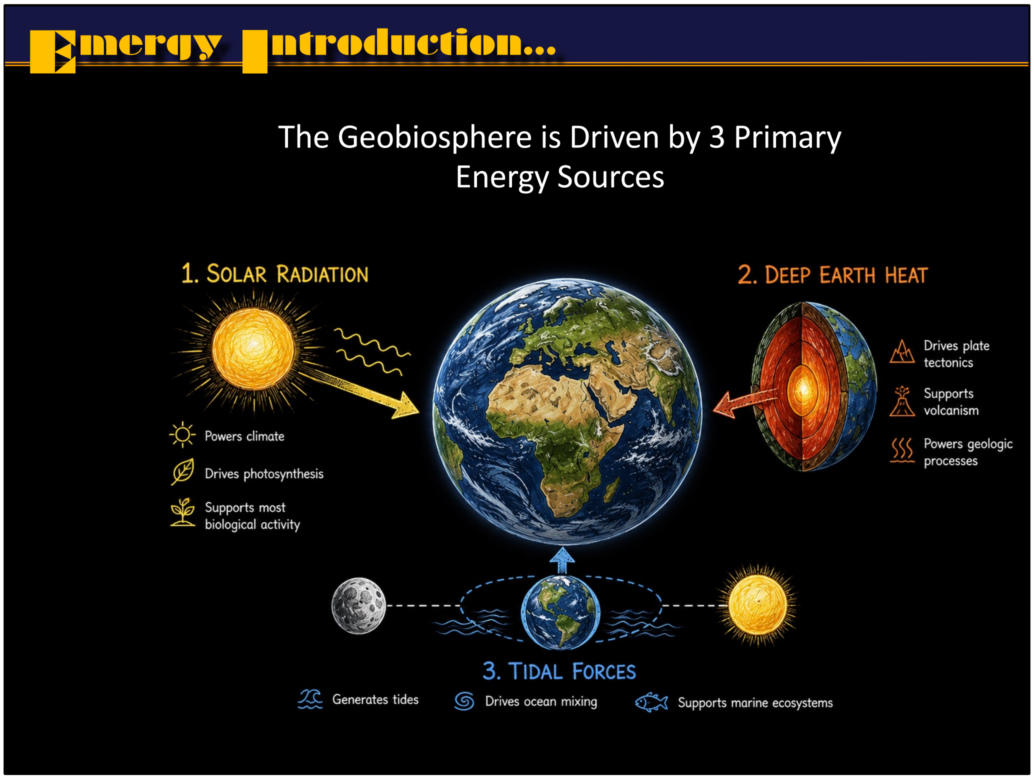
Today I'd like to begin with a simple observation: everything we value depends on energy.

Ecosystems, cities, economies, and societies all require continuous inputs of energy to exist and function.

But these systems are not organized randomly. They develop recognizable patterns, hierarchies, and networks. Forests have structure. River basins have structure. Economies have structure.

So a fundamental question is: Why do ecosystems and economies organize themselves the way they do?

The answer begins with the flows of energy that support them. To understand those flows, we first need to look at the primary energy sources that drive the Earth system.



Today, we need to step back and look at what powers the Earth system itself.

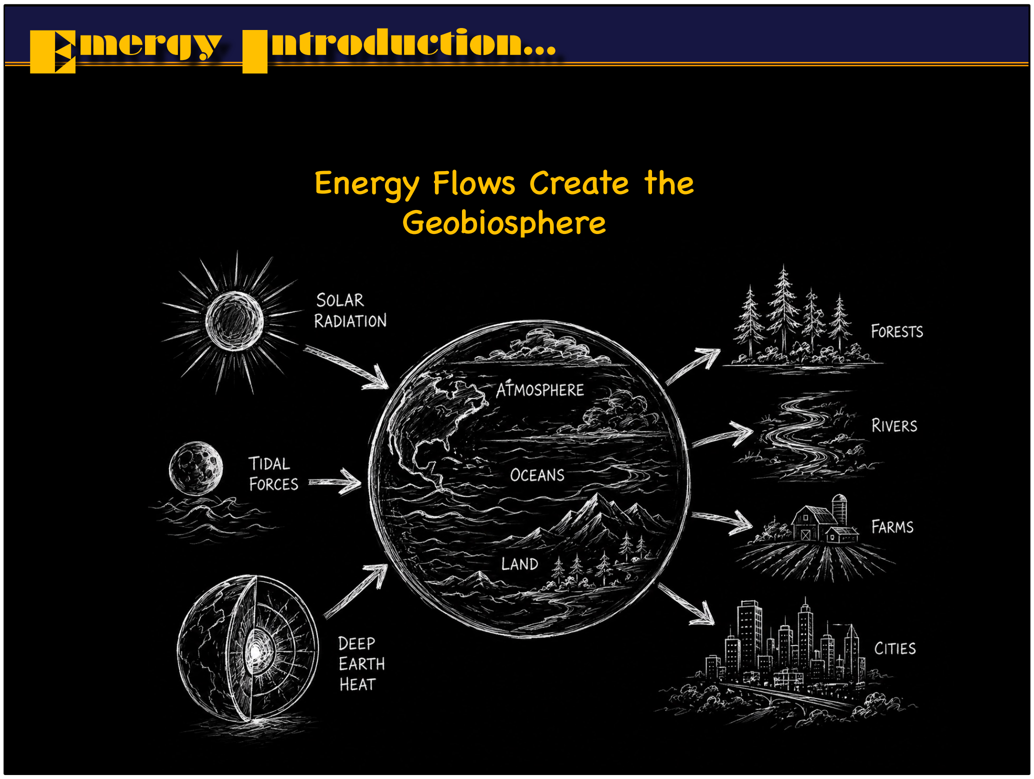
The Earth is an open system maintained by continuous inputs of energy. Three primary sources provide the energy that drives geobiospheric processes.

The first is solar radiation. Solar energy powers climate, photosynthesis, and most biological activity on Earth.

The second is heat from the Earth's interior, which drives tectonic activity and many geologic processes.

The third is the gravitational attraction among the Earth, Moon, and Sun, which produces tides and helps drive ocean circulation.

Together, these three energy sources power the processes that shape the Earth and support life.

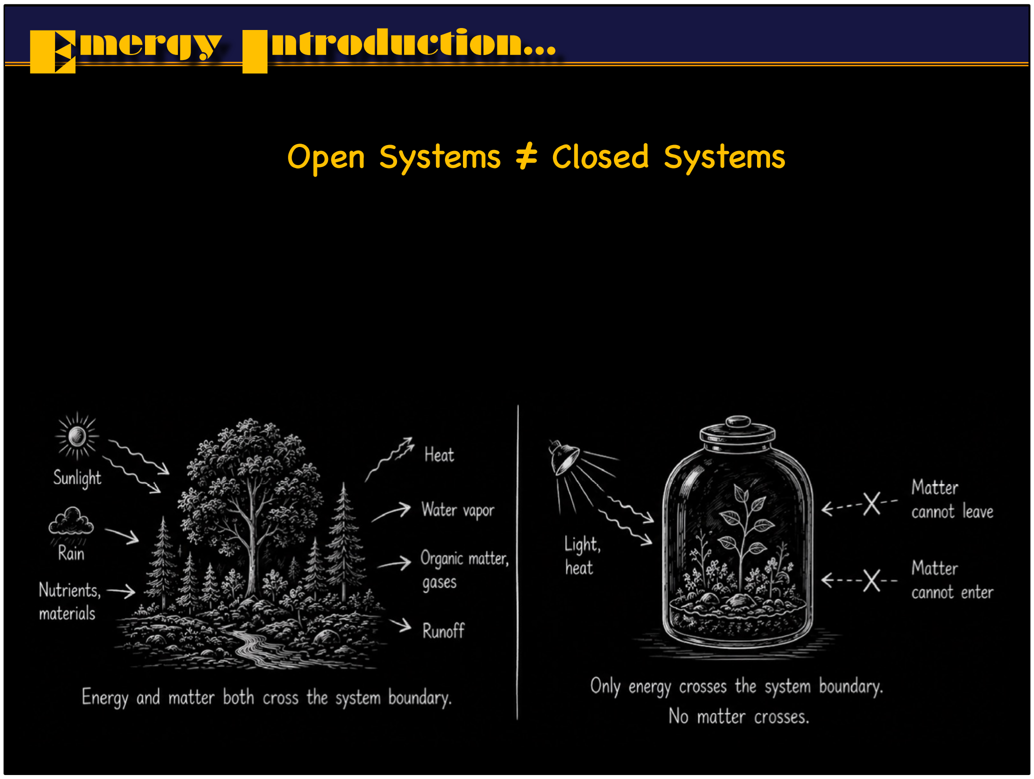


The three primary energy sources do not act independently.

Solar radiation, tidal forces, and heat from the Earth's interior interact to drive atmospheric circulation, ocean currents, the hydrologic cycle, and geologic processes.

Together, these processes create and maintain what we call the geobiosphere—the integrated system of atmosphere, oceans, land, and living organisms.

Everything we see around us is a product of these interacting energy flows. Forests, rivers, wetlands, agricultural systems, and even human settlements all depend on the continuous movement and transformation of energy through the Earth system.



Everything shown on the previous slide shares one important characteristic: it is an open system.

An open system exchanges energy and materials with its surroundings. Ecosystems, cities, economies, and even individual organisms are all open systems.

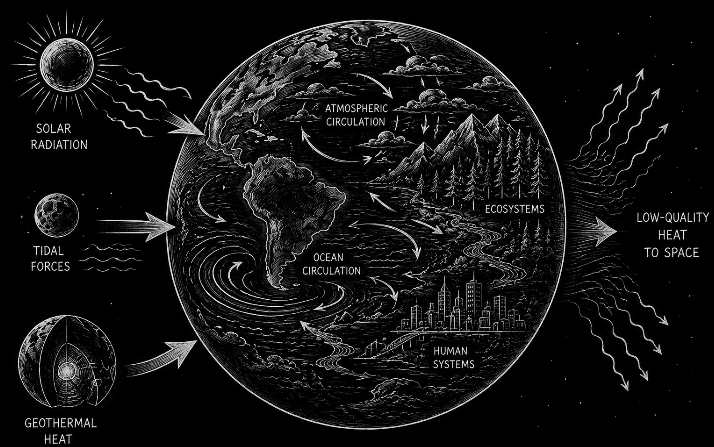
They maintain their structure and function through continuous exchanges with their environment.

As long as energy and materials continue to flow through them, open systems can maintain organization, grow, reproduce, and evolve.

Life itself is possible only because living systems are open systems.

Emergy Introduction...

Why doesn't the Earth run down?



The Earth has maintained organized structures for billions of years. Forests grow, rivers organize into drainage networks, and life persists.

Yet the Second Law of Thermodynamics tells us that systems tend toward disorder.

So why doesn't the Earth simply run down?

The answer is that the Earth is not a closed system. It receives a continuous input of high-quality energy from the sun and continuously exports degraded heat to space.

Those energy flows make it possible for order and organization to develop and persist.

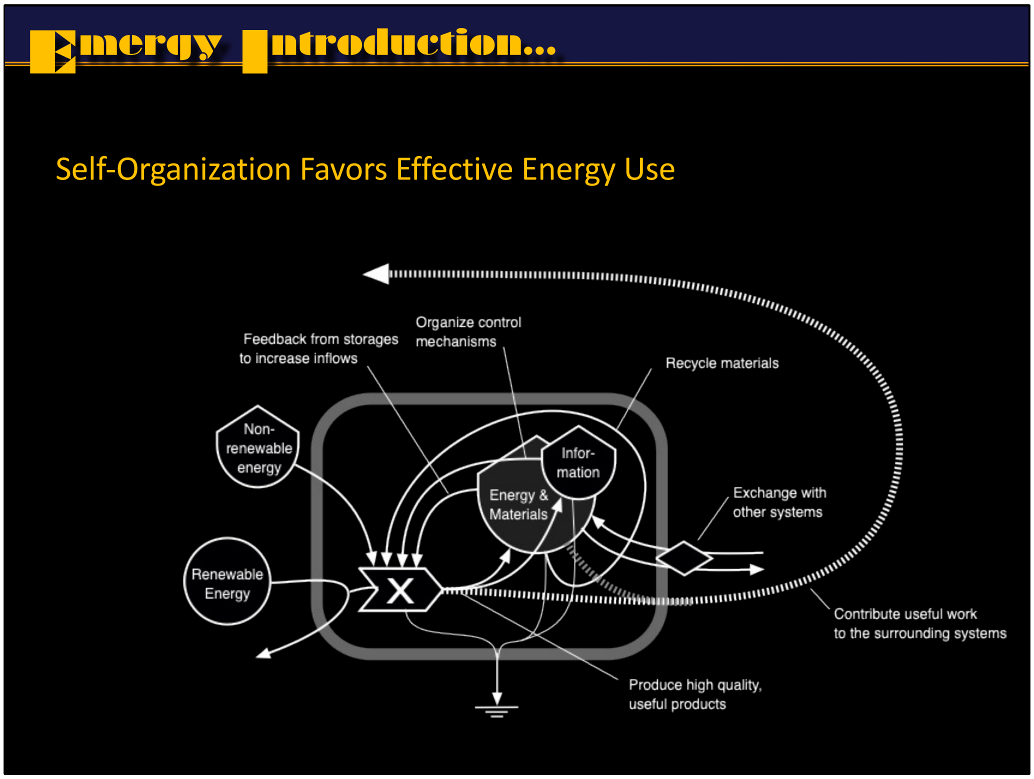
The development of order and organization in open systems is called self-organization.

Self-organization occurs when structure emerges from the interactions among system components without external design or centralized control.

In other words, no one designs a forest, a river network, or a hurricane. Their structure emerges naturally from the way energy and materials flow through the system.

Many systems exhibit self-organization, including ecosystems, river basins, hurricanes, cities, and economies.

Most importantly, self-organization requires continuous flows of energy. Without energy flow, organized structures cannot be maintained.



Self-organization does not produce random structures. Many possible arrangements are possible, but some persist while others disappear.

Open systems persist by evolving designs that make the most of available energy.

This tendency, observed in ecosystems, economies, and physical systems alike, underlies what H.T. Odum called the Maximum Power Principle.

Systems that capture, transform, and use energy in ways that reinforce their own operation out-compete alternatives.

The result is not random complexity, but organized structure shaped by energetic advantage.

Emergy Introduction...

The Maximum Power Principle

In the competition among self-organizing systems, those that develop designs that maximize both the rate and quality of energy transformation, prevail.

"Notice that this statement contains two ideas: rate and quality. We are familiar with rate. The idea of quality is less familiar, and it is the key to understanding emergy."

We have seen that open systems self-organize. But self-organization alone does not explain which designs persist and which disappear.

According to the Maximum Power Principle, systems compete for available energy. Over time, those designs that capture and use energy more effectively tend to prevail.

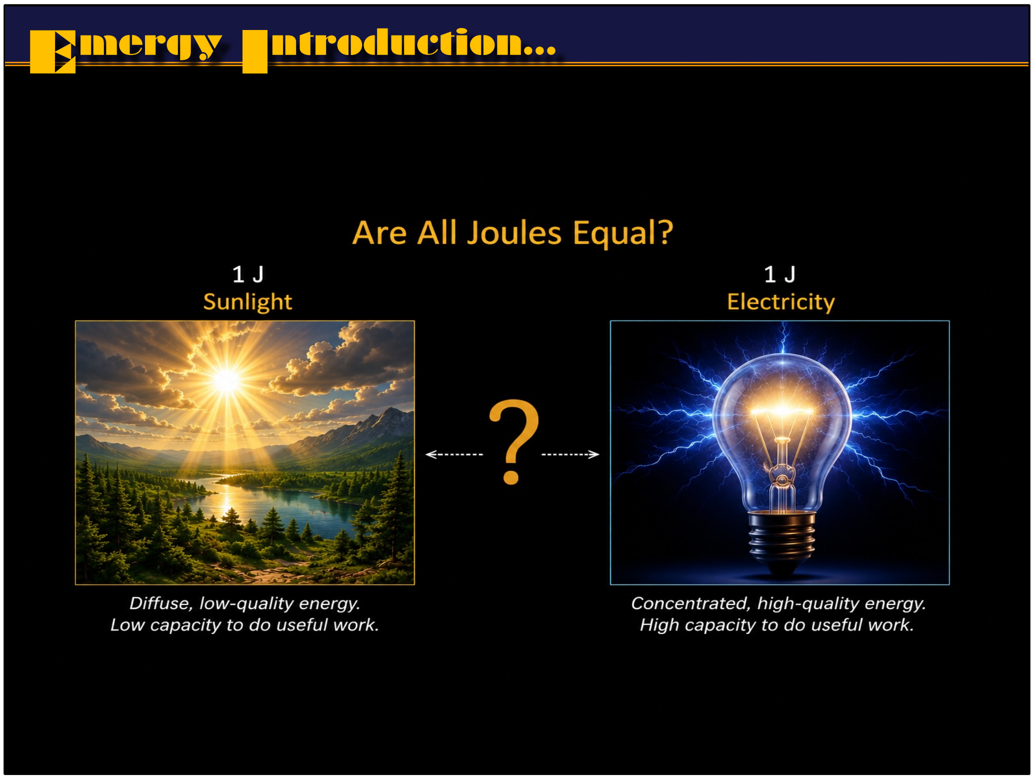
Power is the rate at which energy flows through a system. At first glance, we might think that systems simply maximize the amount of energy they process.

But natural systems do something more interesting. They do not merely maximize the quantity of energy transformed. They also develop pathways that increase the quality of energy available for useful work.

Forests, ecosystems, economies, and cities all evolve structures that concentrate energy into increasingly useful forms.

This idea leads directly to an important question:

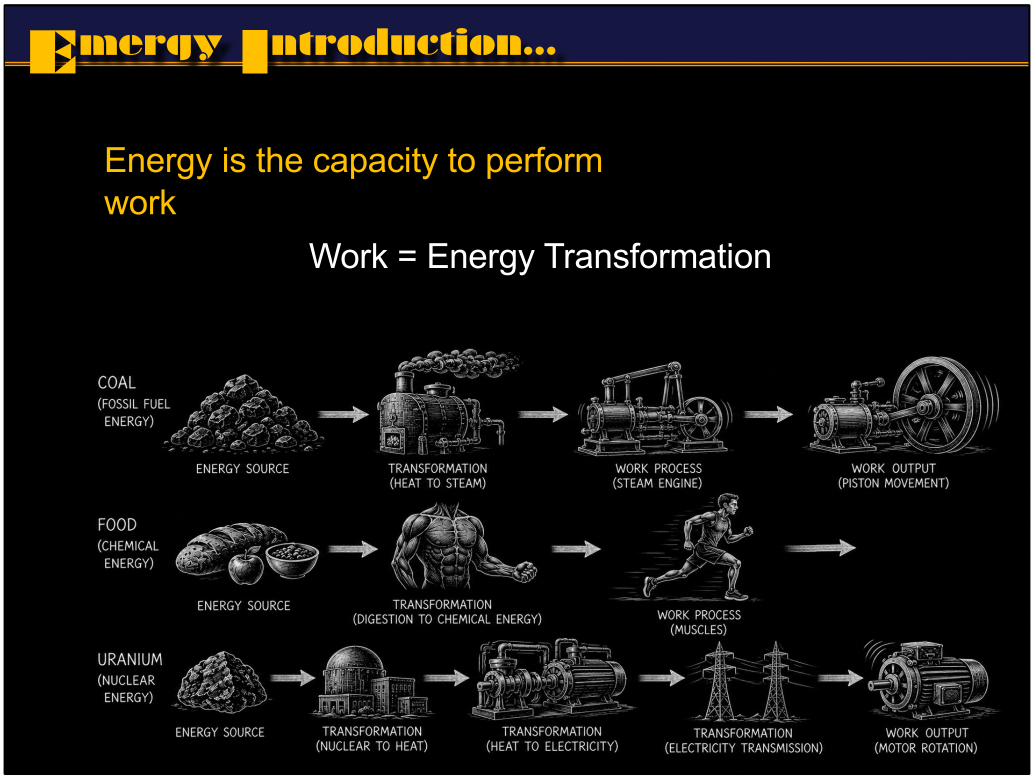
Are all forms of energy equally useful?



if systems are maximizing both the rate and quality of energy transformation, then we need to understand what we mean by quality.

A joule is a unit of energy, but not all joules have the same ability to produce useful work.

To understand emergy, we must first understand why some forms of energy are more useful than others.



We've seen that energy is essential for self-organization. But what exactly do we mean by energy?

Energy is often defined as the capacity to perform work.

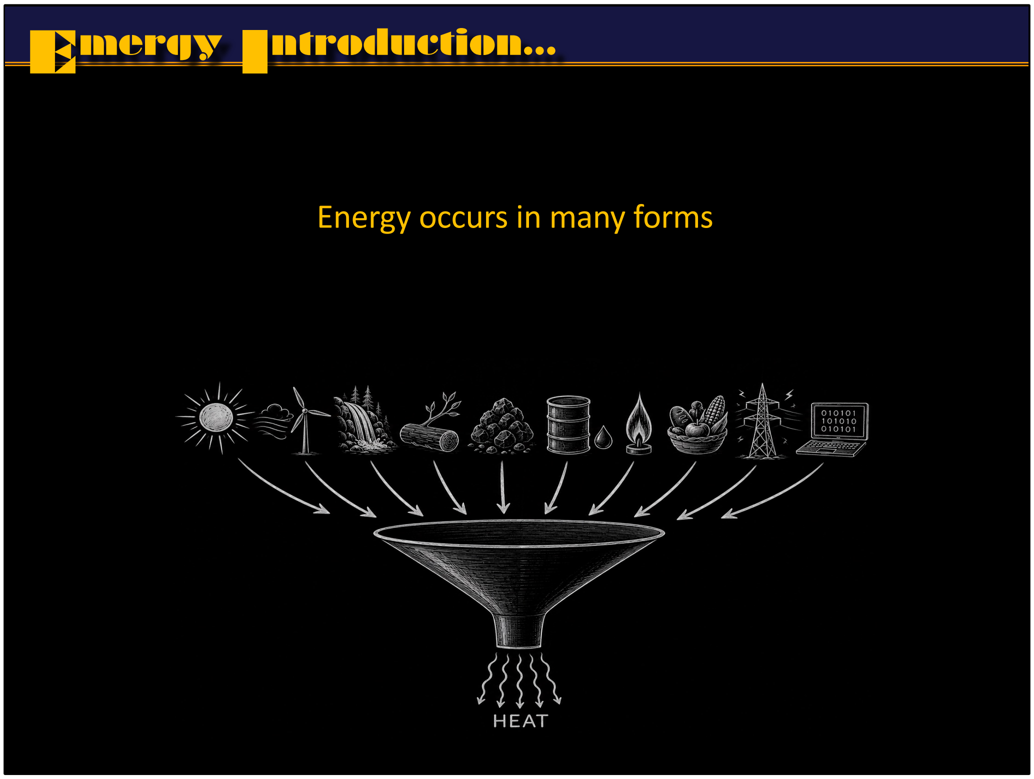
In energy systems theory, we think of work more broadly as a useful energy transformation—one that produces change or helps maintain structure and organization.

Of course, we rarely observe energy directly. Instead, we observe its effects.

Coal powers steam engines. Food powers muscles. Uranium generates electricity. In each case, energy is transformed into processes that produce change in the world around us.

The figure on this slide shows three different forms of energy. All can perform work, but they are not necessarily equivalent in their ability to do so.

That observation leads to one of the central ideas of this lecture: energy quality.



We've seen that energy exists in many different forms. Sunlight, wind, fuels, food, electricity, and information all represent different ways that energy is organized and expressed.

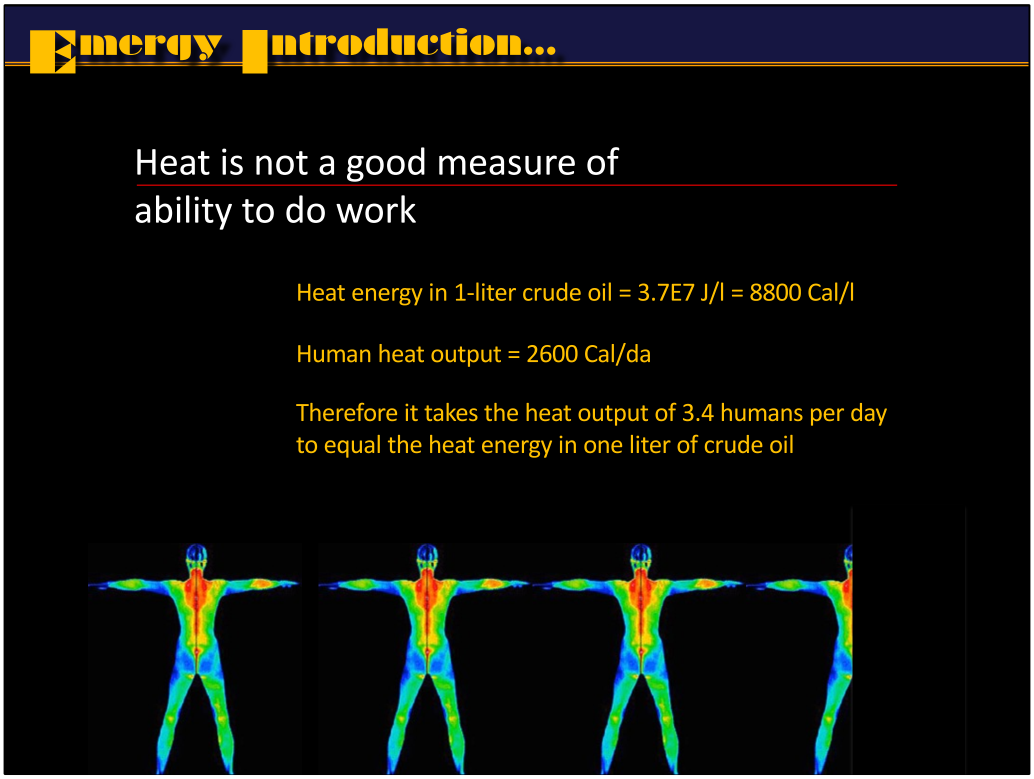
Because all forms of energy can ultimately be converted to heat, it has been convenient to measure energy using common units such as joules, calories, or BTUs.
At first glance, that seems reasonable. A joule is a joule.

But there is a problem.

Equal quantities of energy are not necessarily equal in their ability to perform useful work.

A joule of sunlight, a joule of food, and a joule of electricity may contain the same amount of heat energy, yet they differ greatly in what they can accomplish.

This brings us to the problem of energy quality.



The problem becomes clearer with a simple comparison.

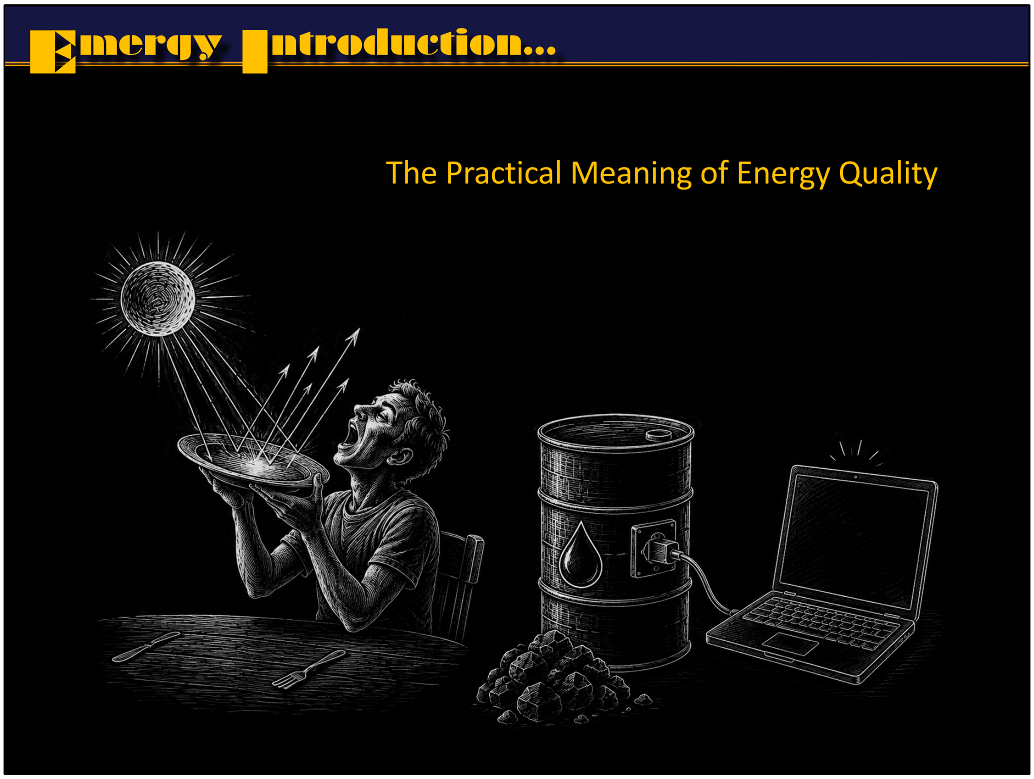
One liter of crude oil contains approximately the same amount of heat energy as the daily heat output of about 3.4 humans.

Yet no one would argue that three people can replace a liter of fuel in powering a vehicle.

The two quantities contain roughly the same amount of heat energy, but they clearly differ in their ability to perform useful work.

No matter how hard they pedal, three people are not going to replace a liter of diesel fuel in a tractor, truck, or automobile.

The form of energy matters.



If all forms of energy were equivalent in their ability to perform work, then a person could simply sit in the sun instead of eating food, or a computer could be powered directly by a barrel of oil.

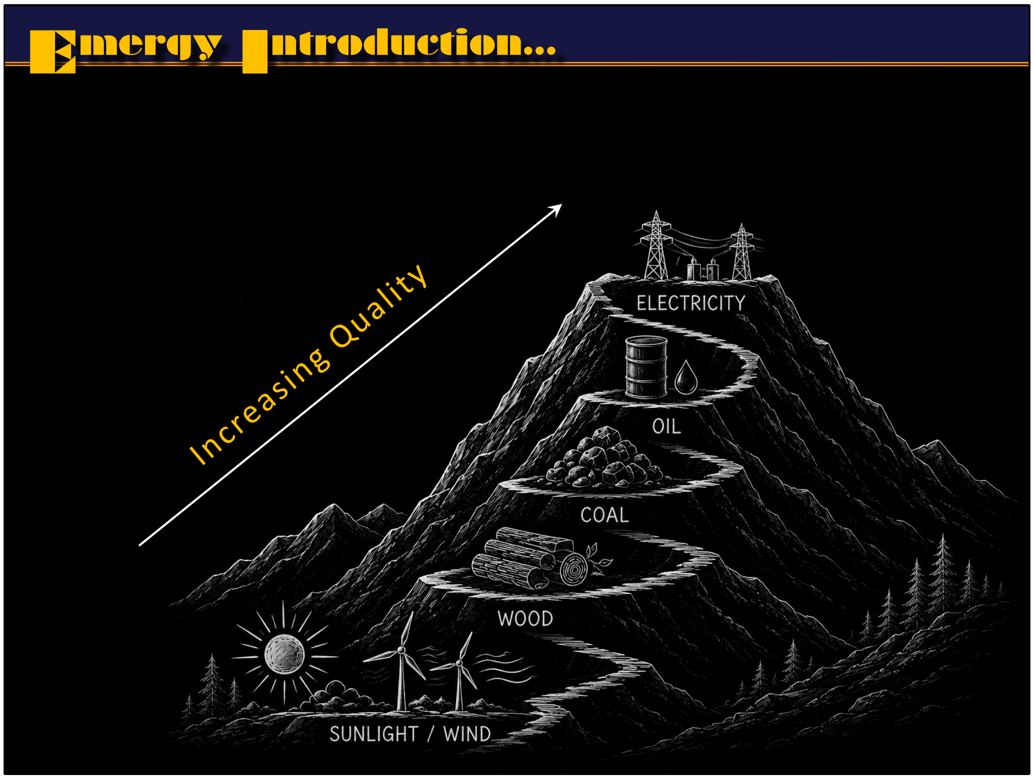
But that is not how systems work.

The form of energy matters.

Food energy is organized in a way that can be used by metabolism. Electricity is organized in a way that can power electronic devices. Oil contains energy, but it must pass through a series of transformations before it can run a computer.

Different forms of energy are useful because of the way they are organized and the transformations they can support.

This is the practical meaning of energy quality.



We can now define energy quality more precisely.

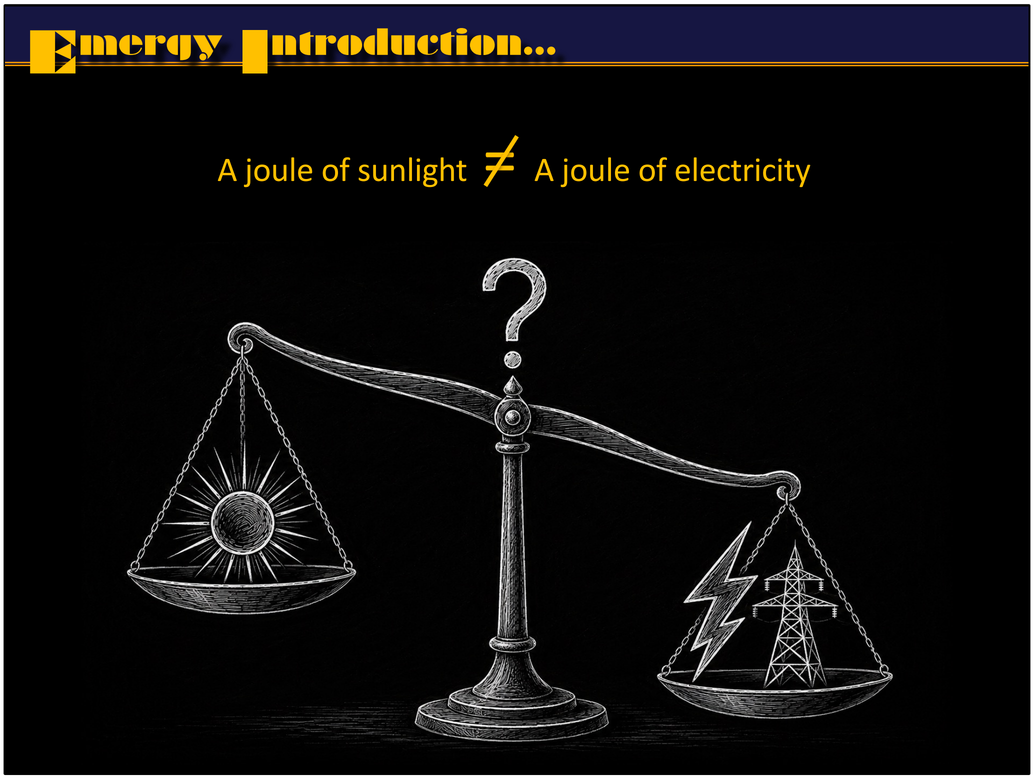
Energy quality is the relative ability of a form of energy to perform useful work.

In general, higher-quality forms of energy are more concentrated, more flexible, easier to transport, and more readily converted into other forms.

This is why equal quantities of energy may differ greatly in their ability to support work and organization.

For example, electricity and liquid fuels can be applied to a wide variety of tasks. More dispersed forms of energy, such as sunlight and wind, are often more difficult to direct toward specific purposes.

The figure illustrates this idea as a hierarchy of increasing energy quality. As we move upward through the hierarchy, energy becomes more concentrated and capable of supporting increasingly specialized forms of work.



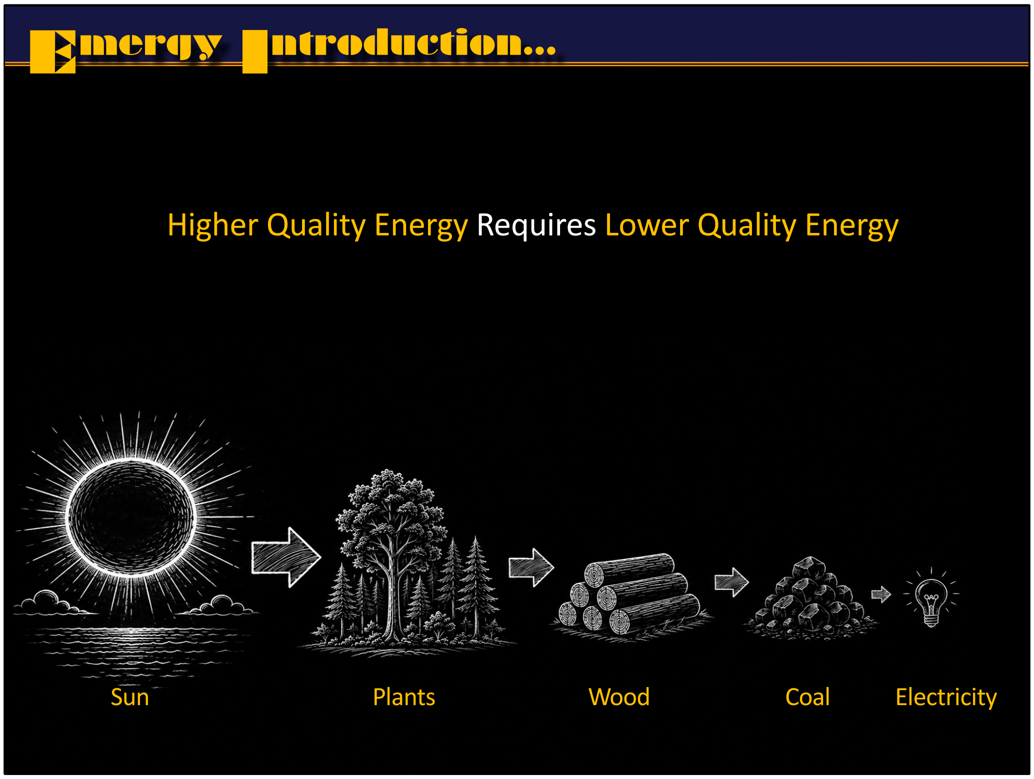
Recognizing that different forms of energy have different qualities creates a fundamental problem.

If a joule of sunlight is not equivalent to a joule of electricity, how can we compare them?

Both can be measured in joules, but the joule tells us nothing about the amount of environmental work required to produce them.

What we need is a way to account for differences in energy quality while placing all forms of energy on a common basis.

This challenge led to the development of emergy.



Higher-quality forms of energy do not appear spontaneously. They are produced through a series of energy transformations.

Sunlight supports photosynthesis. Biomass may become fossil fuels. Fossil fuels can be transformed into electricity.

At each step, large quantities of lower-quality energy are required to produce smaller quantities of higher-quality energy.

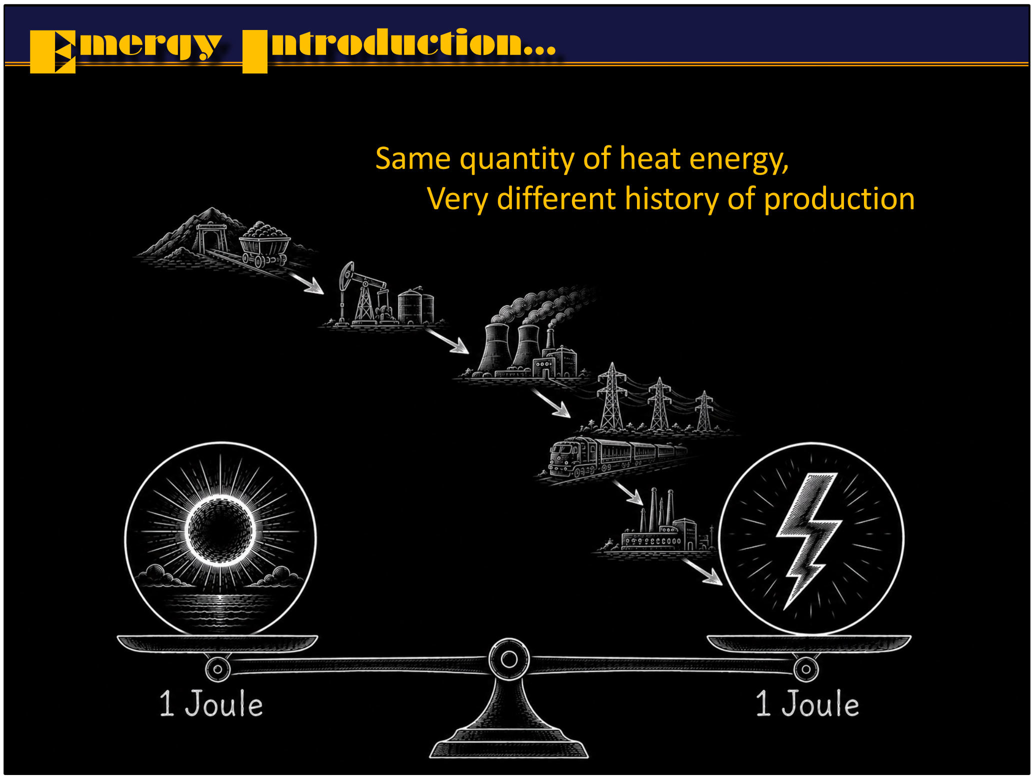
Why does this happen?

Each transformation concentrates the ability to perform useful work into a smaller quantity of output. As a result, the output is often capable of supporting a wider range of useful transformations than the energy from which it was derived.

In general, forms of energy that require more supporting work to produce are capable of performing more useful work.

This relationship between the work required to produce a resource and its ability to support useful work is the foundation of emergy theory.

The electricity shown here is only a small fraction of the original solar energy, but it embodies the contributions of all the transformations that came before it.



When converted to heat, a joule of sunlight and a joule of electricity release the same quantity of energy.

The two quantities shown here each contain one joule of energy.

Yet they are clearly not equivalent.

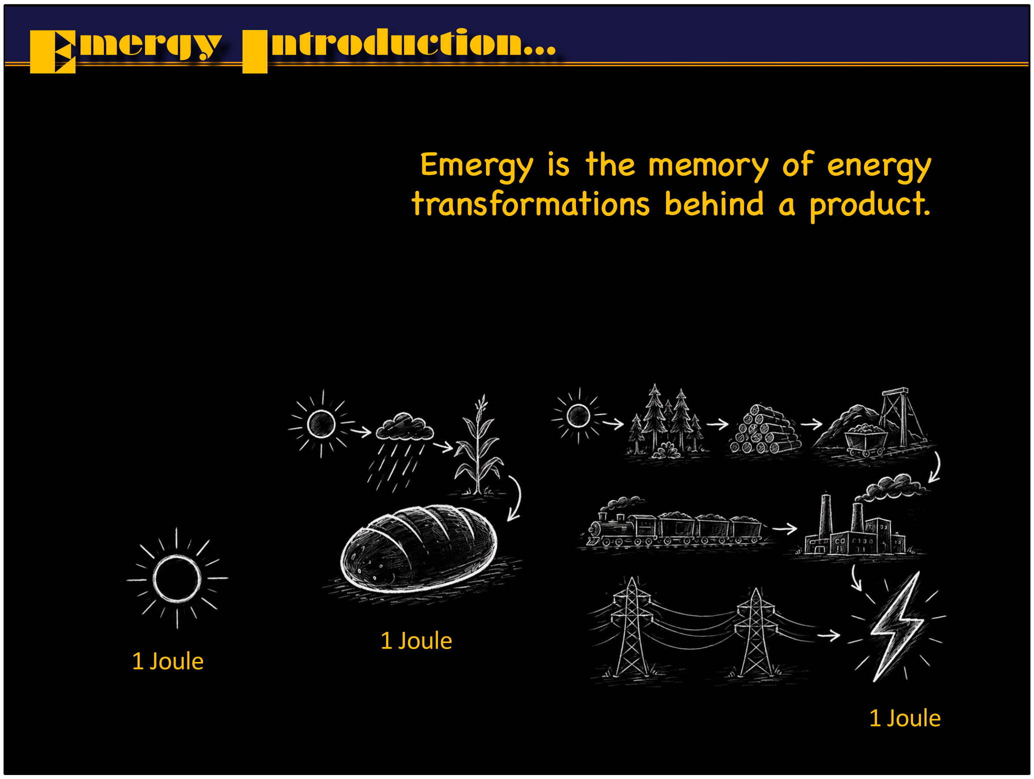
The electricity is the product of many previous transformations. Fuels were extracted, transported, processed, and converted before that electricity reached us.

The sunlight arrives directly from the sun with little prior transformation.

As a result, the electricity can support a much wider range of useful work than the sunlight, even though both contain the same quantity of energy.

Their histories are different, but more importantly, their capabilities are different.

How can we account for those differences in a systematic way?



Emergy was developed to account for differences in energy quality.

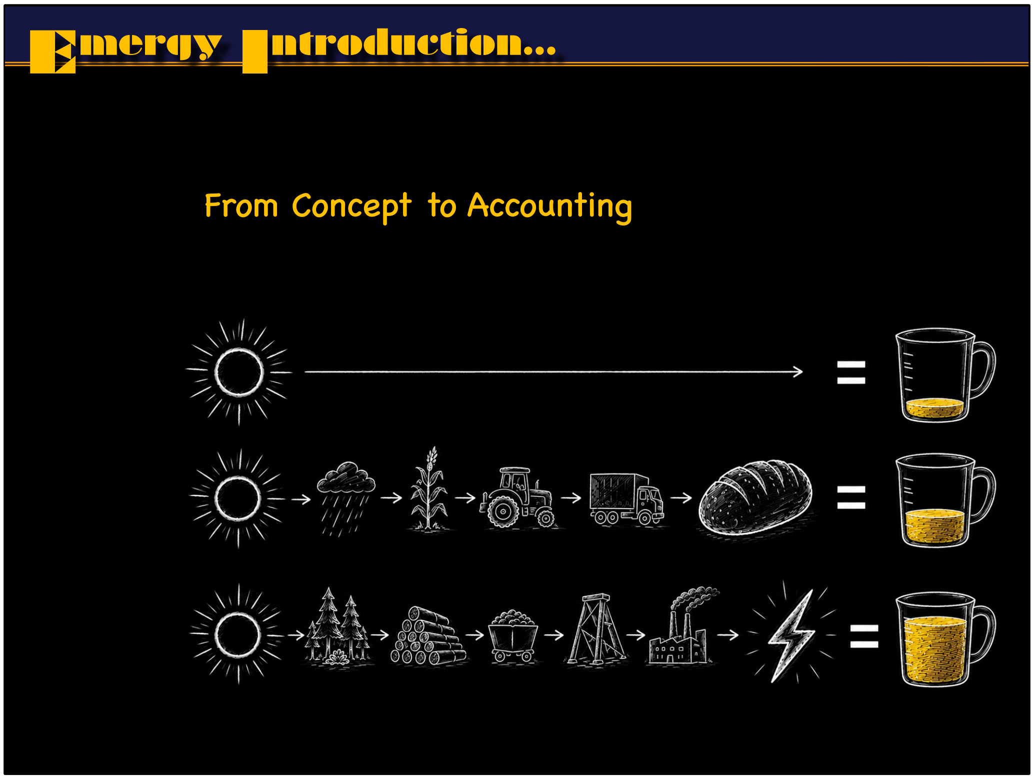
Emergy is the available energy of one kind previously required, directly and indirectly, to make a product or service.

In most emergy evaluations, all contributions are expressed on a common basis: the solar energy required to generate them.

Why is this useful?

The work required to produce a resource is reflected in its ability to support useful work and organization. Products that require more supporting work generally embody more emergy and have a greater capacity to perform useful work.

Emergy therefore provides a common basis for comparing the quality of different forms of energy, materials, products, and services.



Emergy provides a way to compare resources based on the environmental work required for their production.

Some products require only a few transformations. Others require many.

As the chain of transformations grows, the amount of environmental work embodied in the final product also grows.

Sunlight requires relatively little supporting work.

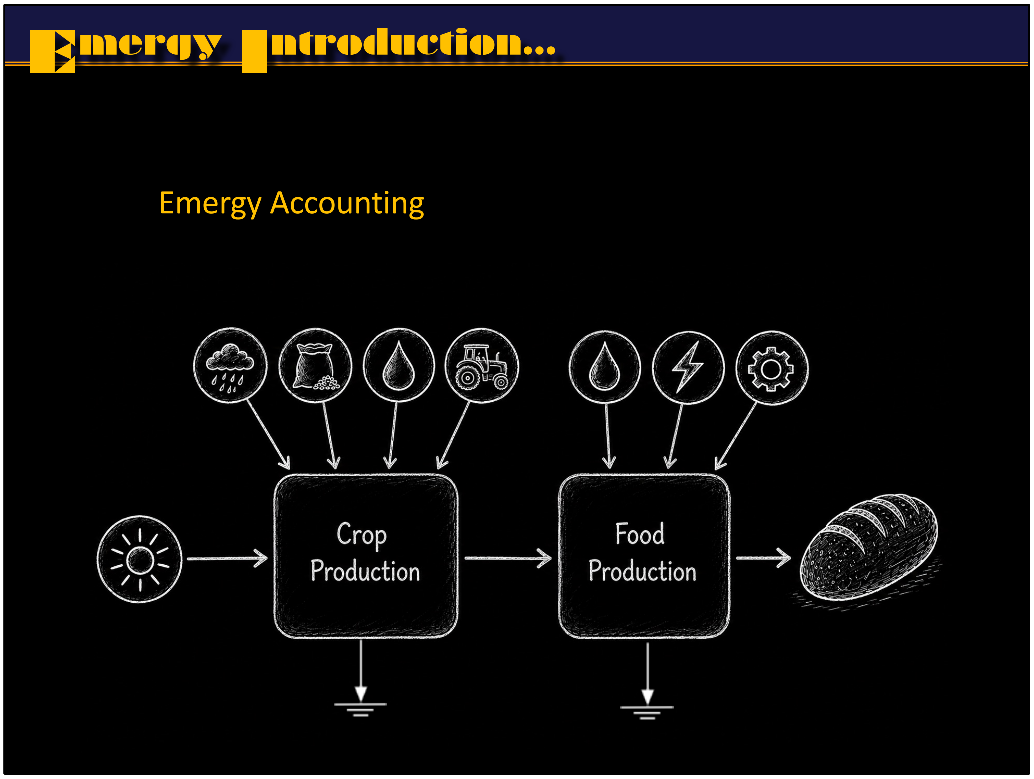
Food embodies the contributions of ecosystems, agriculture, transportation, processing, and distribution.

Electricity may embody an even longer chain of transformations involving fuel extraction, transportation, conversion, infrastructure, and maintenance.

As products embody different amounts of supporting work, they differ in their ability to support useful work and organization.

If we want to compare these differences quantitatively, we need a systematic method of accounting for all of the supporting contributions.

This is the purpose of emergy accounting.



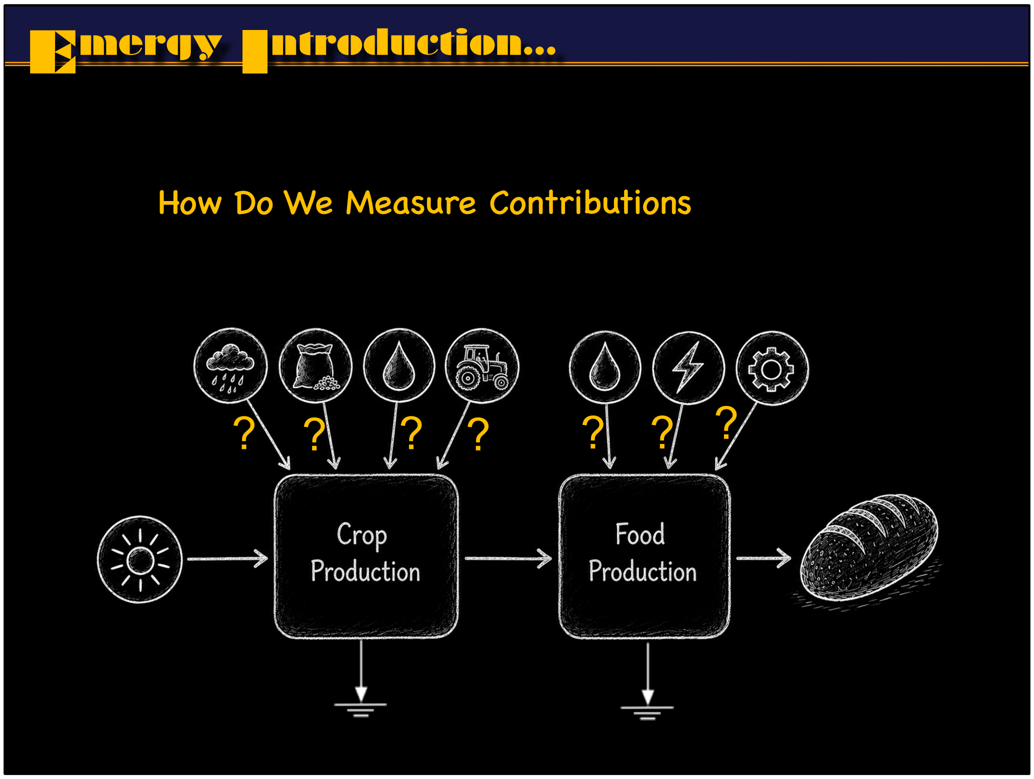
Emergy accounting begins by identifying the sources that support production.

In this example, sunlight, rain, fertilizer, fuel, machinery, and labor all contribute to the production of bread.

None of these inputs alone can provide the function of the final product. Through a series of transformations, they are combined and organized into something new.

The bread is valuable not because of the individual inputs, but because it can support human metabolism and the useful work that metabolism makes possible.

Emergy accounting traces the contributions of all supporting inputs in order to evaluate the potential of the final product to support useful work.



Identifying the supporting sources is only the first step in emergy accounting.

We must also determine the contribution made by each source.

At first, this seems straightforward. We might simply measure the energy entering the system.

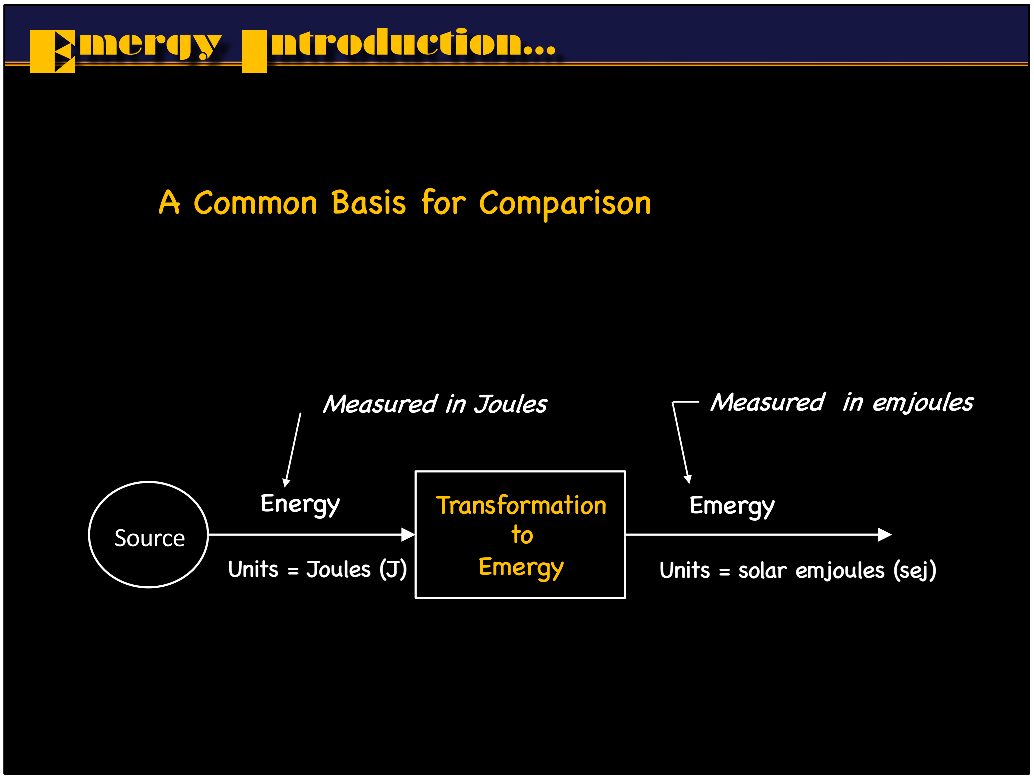
But a joule of sunlight and a joule of fuel do not contribute equally.

Both contain energy, yet they differ greatly in the amount of environmental work required for their production and in their ability to support useful work.

As a result, we cannot simply add their energies together and expect to obtain a meaningful measure of their contributions.

To compare and combine these different inputs, we need a common basis of measurement.

Emergy provides that common basis.



To compare contributions from different sources, we need a common basis of measurement.

Energy can be measured directly in joules, but emergy accounting asks a different question.

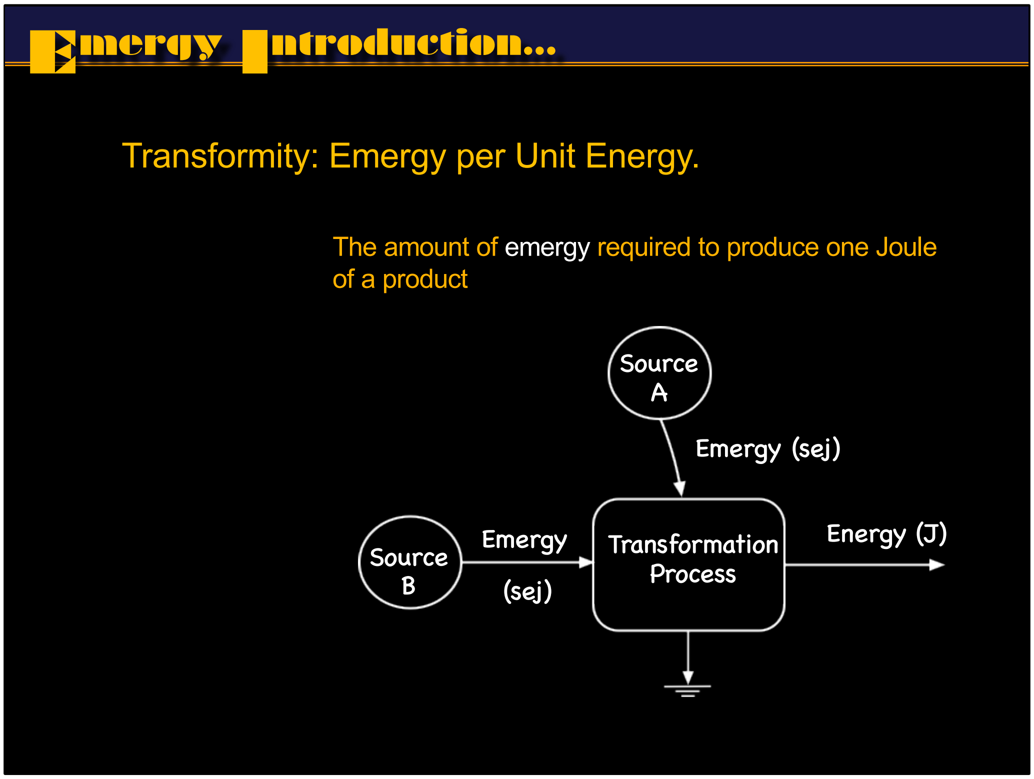
Instead of asking how much energy a resource contains, we ask how much environmental work was required to produce it.

To answer that question, all inputs are expressed on a common basis: the solar energy previously required for their production.

The resulting quantity is measured in solar emjoules, abbreviated sej.

Expressing all inputs in solar emjoules allows resources with very different origins and qualities to be compared on a common basis.

Once inputs have been converted to solar emjoules, their contributions can be evaluated and combined within a single accounting framework.



Transformity provides the link between energy and emergy.

Transformity is defined as the amount of emergy required to generate one joule of a product or resource.

In this example, two supporting sources contribute emergy to a transformation process.

Their emergy contributions are combined to produce an output containing a measurable quantity of energy.

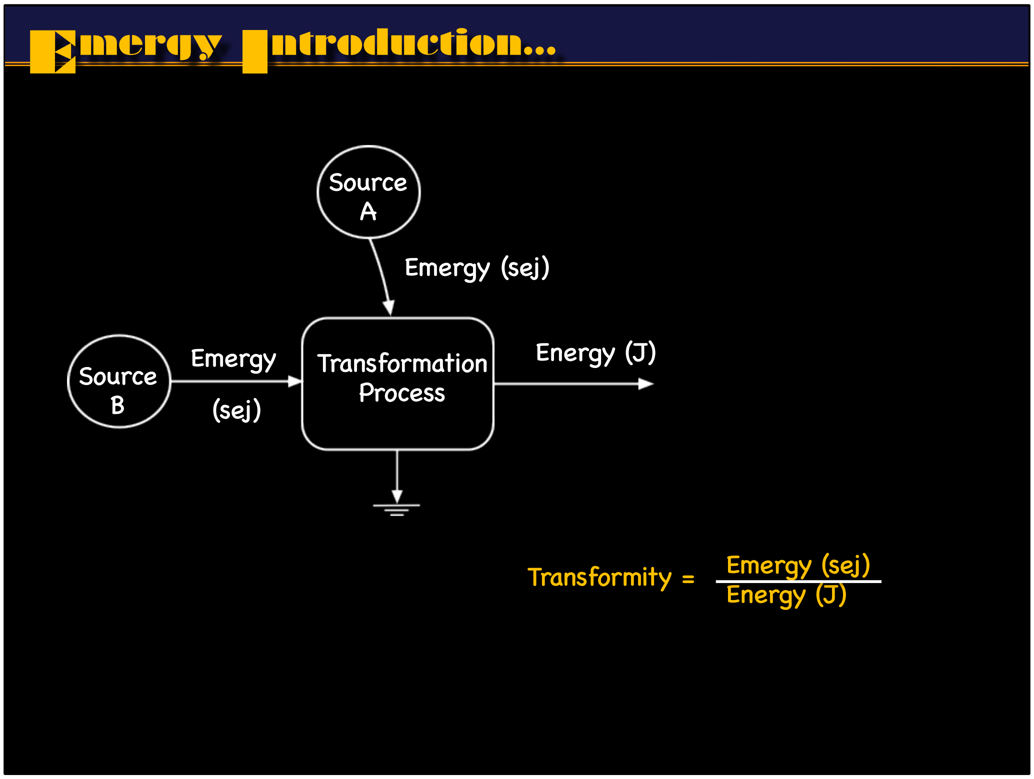
The transformity of that output is the ratio of the emergy supporting its production to the energy contained in the output.

What does transformity tell us?

A high transformity indicates that a large amount of environmental work was required to produce each joule of output.

In general, products with higher transformities have a greater capacity to support useful work because they are the result of more extensive transformations and concentration of energy.

Transformity therefore provides a measure of energy quality expressed on an emergy basis.



Transformity is easy to calculate.

First, we determine the total emergy supporting production of the output.

Next, we measure the energy contained in the output.

Transformity is simply the ratio of these two quantities:

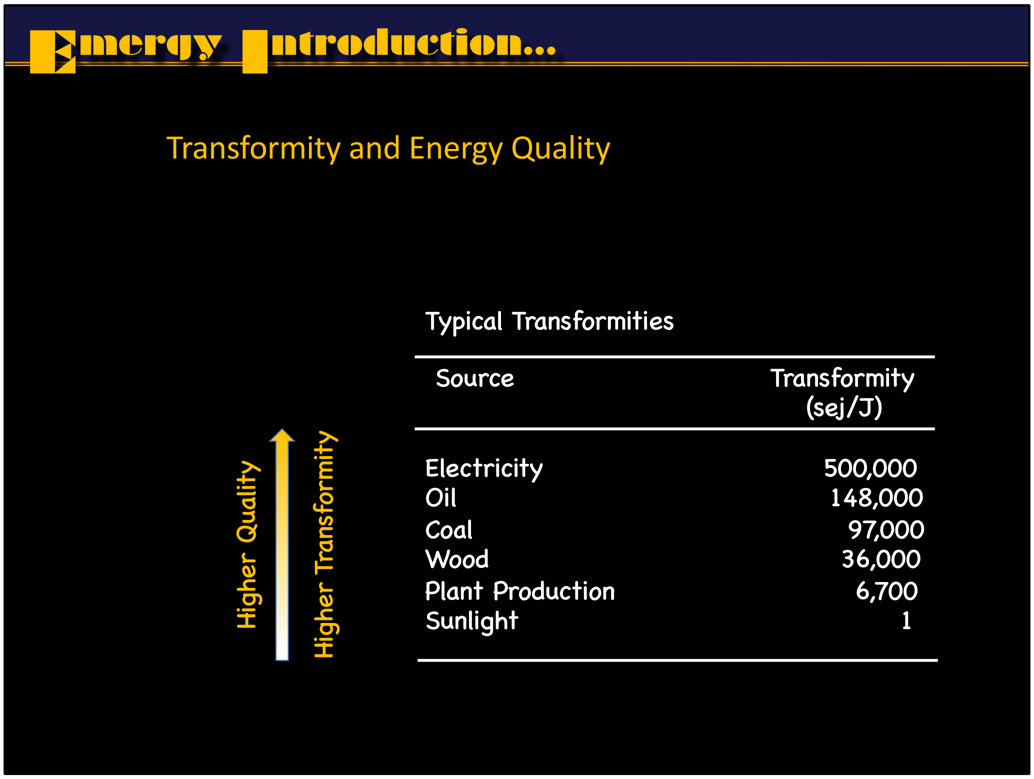
Transformity = Emergy ÷ Energy

The units are solar emjoules per joule, or sej per joule.

A transformity of 100,000 sej/J means that 100,000 solar emjoules were required to produce each joule of output.

Higher transformities indicate that more environmental support was required per unit of output.

Because greater environmental support is generally associated with greater energy quality, transformity provides a quantitative measure of energy quality on a common basis.



Transformities vary enormously among different resources.

By definition, sunlight has a transformity of one because it serves as the common basis for emergy accounting.

As we move from sunlight to plant production, wood, fossil fuels, and electricity, transformities become progressively larger.

This increase reflects the growing environmental support required to produce each joule of output.

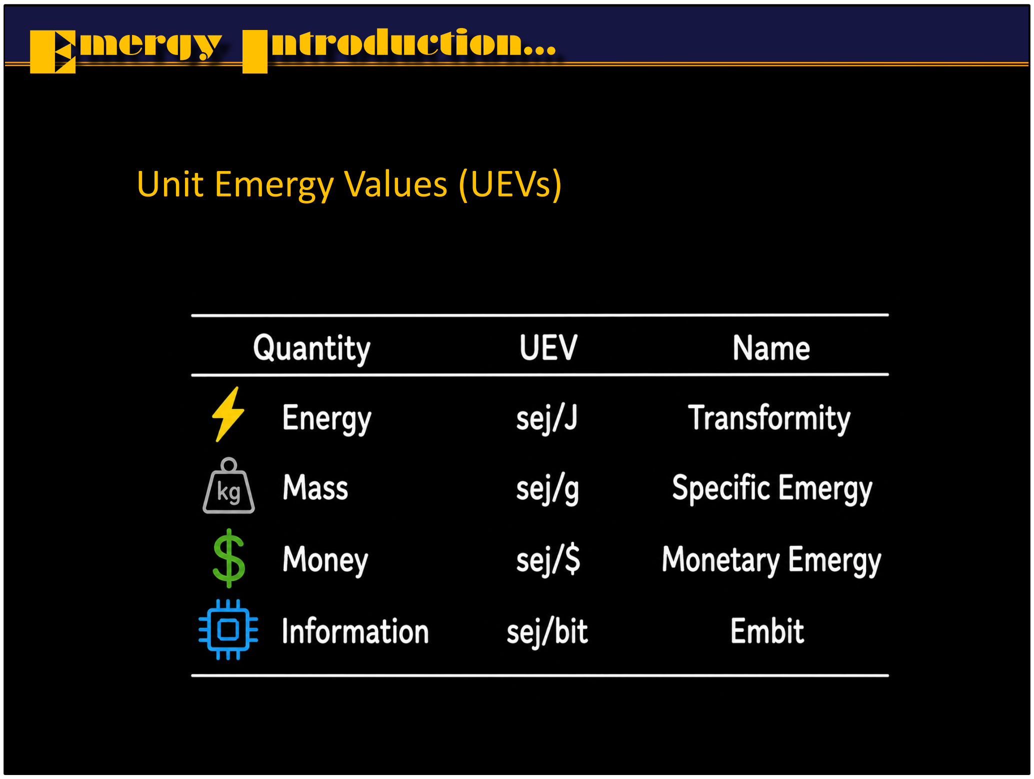
But the important point is not simply that more support was required.

The additional support produces resources that are capable of supporting increasingly specialized and useful forms of work.

A joule of electricity can power a computer, operate a motor, transmit information, or control industrial processes. A joule of sunlight cannot perform those functions directly.

Thus, higher transformities generally correspond to higher energy quality and a greater capacity to support useful work.

Transformity therefore provides a quantitative link between environmental support, energy quality, and the potential for useful work.



Transformity is an important Unit Emergy Value, but it is not the only one.

A Unit Emergy Value, or UEV, relates emergy to some measurable quantity.

The name depends on the quantity being used.

When emergy is expressed per unit of energy, the UEV is called transformity.

When emergy is expressed per unit mass, the UEV is called specific emergy.

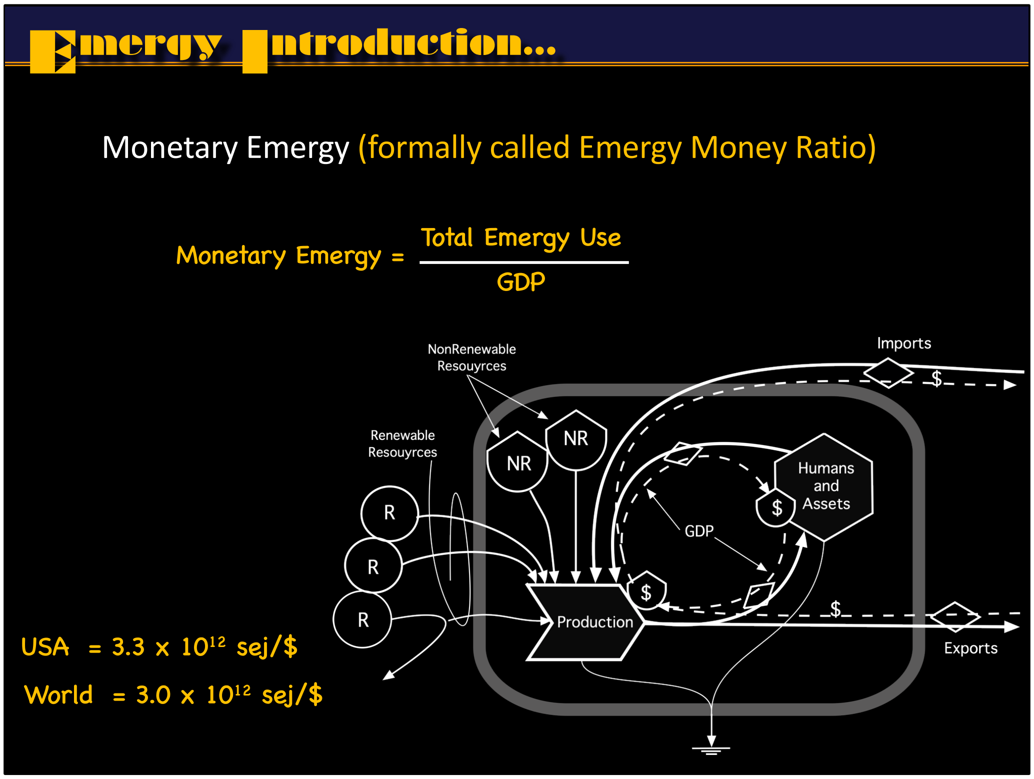
When emergy is expressed per unit of money, we refer to it as monetary emergy.

Similarly, emergy associated with information may be expressed as embits.

Although the units are different, the underlying idea is the same.

Each UEV relates the environmental support embodied in a product, service, material, or information to a quantity that we can measure.

The purpose of all UEVs is to place very different things on a common emergy basis so that they can be compared consistently.



Emergy accounting is often applied to entire economies as well as individual products and ecosystems.

To relate economic activity to environmental support, we use a Unit Emergy Value called Monetary Emergy.

For national economies, Monetary Emergy is typically calculated using the Emergy Money Ratio, or EMR.

The EMR is obtained by dividing the total emergy supporting an economy by its Gross Domestic Product, or GDP.

The resulting value, expressed in solar emjoules per dollar, is the Monetary Emergy UEV for that economy.

It represents the average environmental support associated with each dollar of economic activity.

Just as transformity relates emergy to energy, Monetary Emergy relates emergy to money.

With these Unit Emergy Values in hand, we can now begin calculating the emergy of real systems.

Emergy Introduction…

Emergy Evaluation of Corn (Grain), per ha per year

Note Item	Inputs	Units	UEV	Solar Emergy
1 Sun	6.35E+13	J	1.00E+00	6.35E+13
2 Rain	6.05E+10	J	1.29E+04	7.80E+14
3 Wind	2.20E+11	J	5.40E+02	1.19E+14
3 Net topsoil loss	1.01E+05	gC	1.09E+08	1.11E+13
4 Fuel	8.12E+09	J	2.12E+05	1.72E+15
5 Electricity	7.85E+08	J	2.50E+05	1.96E+14
6 Potash	1.12E+05	g K	1.60E+10	1.79E+15
7 Lime	3.73E+05	g	2.08E+10	7.76E+15
8 Pesticides	1.69E+03	g	1.86E+10	3.14E+13
9 Phosphate	2.11E+04	g P	7.76E+09	1.64E+14
10 Nitrogen	5.71E+04	g N	1.04E+10	5.92E+14
11 Labor	1.01E+01	p-hrs	1.10E+14	1.11E+15
12 Services	1.06E+03	$	3.34E+12	3.55E+15
13 Total emergy				1.79E+16
Total yield, mass	9.17E+05	g		
Total yield, energy	1.81E+10	J		
Specific Emergy	1.95E+10	sej/g		
Transformity	9.88E+05	sej/J		

$$\text{Transformity} = \frac{\text{Total Emergy (sej)}}{\text{Yield (J)}} = \frac{1.79E{+}16\ \text{sej}}{1.81E{+}10\ \text{J}} = 9.88E{+}05\ \text{sej/J}$$

$$\text{Specific Emergy} = \frac{\text{Total Emergy (sej)}}{\text{Yield (g)}} = \frac{1.79E{+}16\ \text{sej}}{9.17E{+}05\ \text{g}} = 1.95E{+}10\ \text{sej/g}$$

We can now see how Unit Emergy Values are calculated in practice. This table shows a simplified emergy evaluation of corn production.

The inputs include environmental resources such as sunlight, rain, and wind, as well as economic inputs such as fuel, electricity, labor, and services.

Each input is multiplied by an appropriate Unit Emergy Value to calculate its emergy contribution.Summing these contributions gives the total emergy supporting production of the crop.

In this example, the total emergy supporting the corn yield is approximately 1.79×10^{16} solar emjoules.

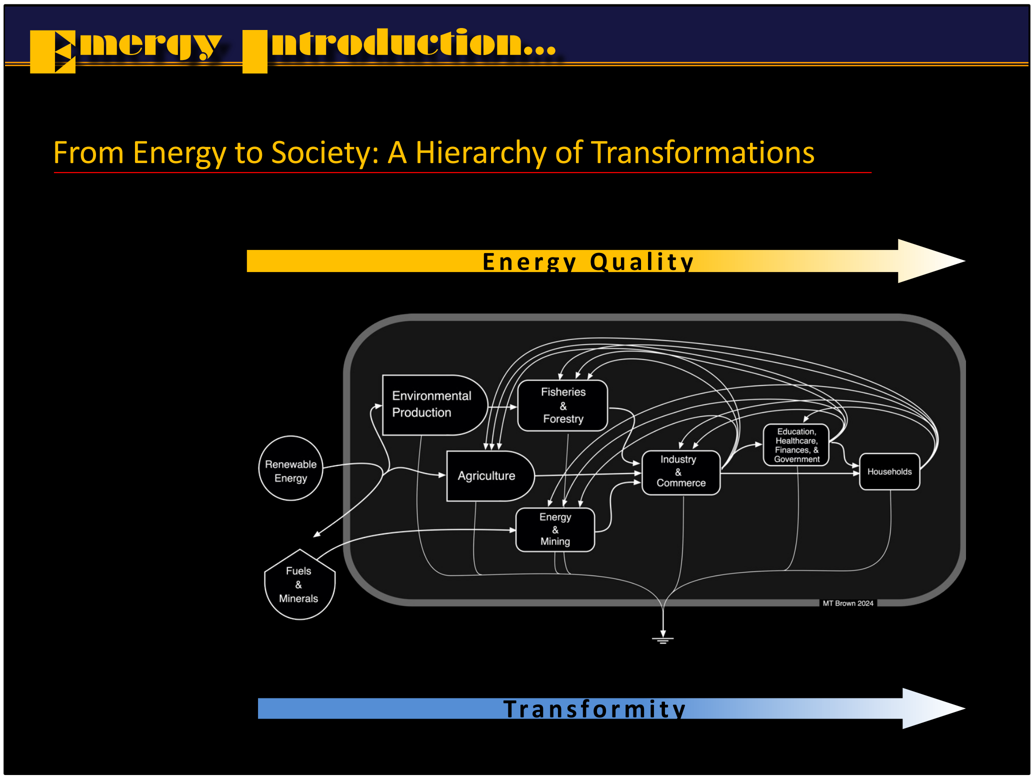
Once the total emergy is known, different Unit Emergy Values can be calculated simply by changing the denominator.

Dividing total emergy by the energy content of the corn yield gives the transformity, approximately 9.88×10^{5} solar emjoules per joule.

Dividing the same total emergy by the mass of corn produced gives the specific emergy, approximately 1.95×10^{10} solar emjoules per gram.

Notice that the numerator remains the same in both calculations.

What changes is the quantity used to express the result.



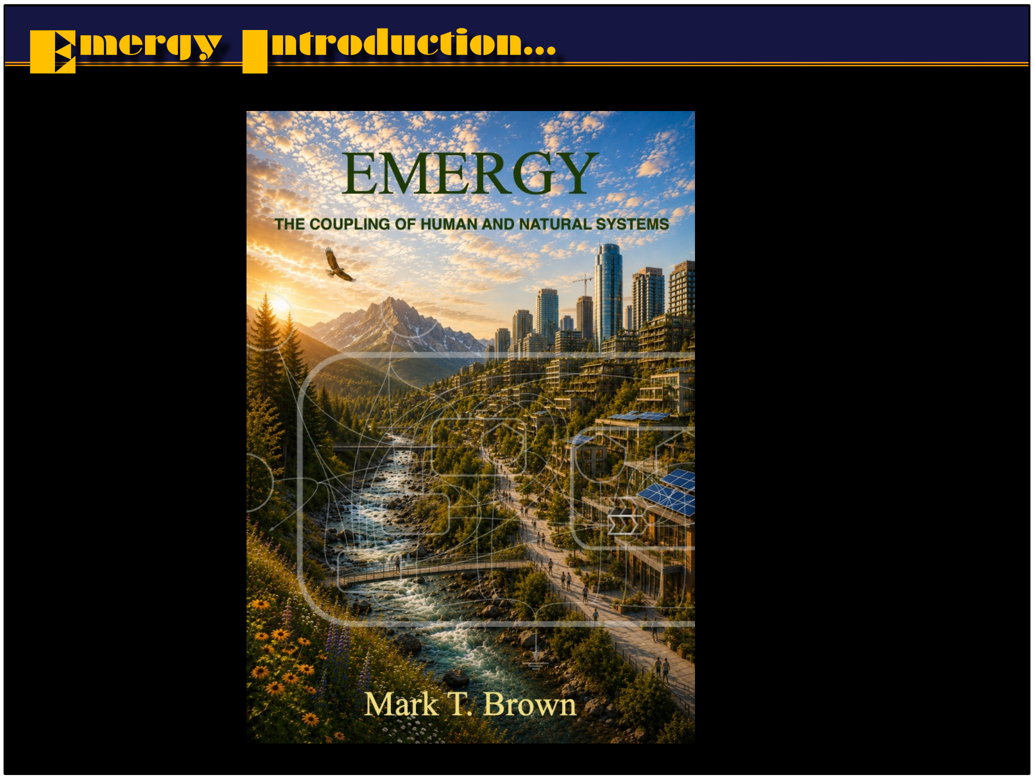
Throughout this lecture we have seen that energy does not flow directly from the environment to society. Instead, it passes through a hierarchy of transformations.

Renewable resources, fuels, and minerals support agriculture, fisheries, industry, and commerce. These, in turn, support increasingly specialized activities such as education, finance, government, and households.

At each step, environmental support is concentrated into forms capable of supporting more specialized and useful work. As a result, the higher levels of the hierarchy depend upon the environmental support embodied in the levels below them.

Emergy provides a common basis for evaluating all levels of this hierarchy, from renewable resource flows to the most complex human activities.

Most importantly, this hierarchy reminds us that human systems are not separate from nature. The highest levels of social and economic organization ultimately depend upon environmental processes operating throughout the geobiosphere.



The landscape shown here represents the coupled natural and human systems that emerge from energy transformations operating across many scales.

Forests, farms, rivers, industries, cities, and economies are not separate systems. They are all connected through the continuous flow and transformation of energy.

Emergy provides a common framework for understanding these connections. By accounting for the environmental support embodied in resources, products, services, and information, emergy helps us compare things that would otherwise seem incomparable.

Most importantly, emergy reminds us that human systems ultimately depend upon the work of nature. The highest levels of social and economic organization are supported by environmental processes operating throughout the geobiosphere.

In the next lecture, we will extend these ideas from individual products to entire economies and nations.

Thank You...

Thank You for Your Attention

感谢您的聆听