EXEERGY DESTRUCTION PRINCIPLE: Is the Optimum Thermodynamic System One that Maximizes It's Use of Exergy?

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In Memory of
James Kay

Colleague, Close Friend,
and Brilliant Mind

Learning From Each Other

- Story of an Engineer and Ecologist discovering new science and understanding.
  - The Engineer discovering ecological concepts with new and exciting engineering applications.
  - The Ecologist discovering engineering clarity to 2nd Law concepts applied to living systems.

Contrasting the Engineer and the Ecologist

Engineer

- lives in world of clarity
- lives in human simplified world
- looks for quantitative patterns / correlations

Ecologist

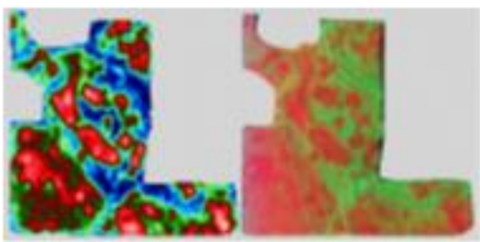
- accustomed to vagueness
- lives in the real world
- looks for qualitative patterns / correlations
- (James -> systems ecologist)

History

- Mid-1990s: James Kay & Eric Schneider "exergy destruction principle" (EDP) [The SCIENCE]

- Late 1990s: Brought in to introduce thermodynamic rigor to EDP

  Introduced to Jeff Luvall [APPLICATION + more SCIENCE]



Harvested September, 1998 June 26, 1998

- 2015-now Precision agriculture [Grain Farmers]

How Does Nature Optimize Complex Thermodynamic Systems?

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- Maximum Efficiency Principle (Energy)

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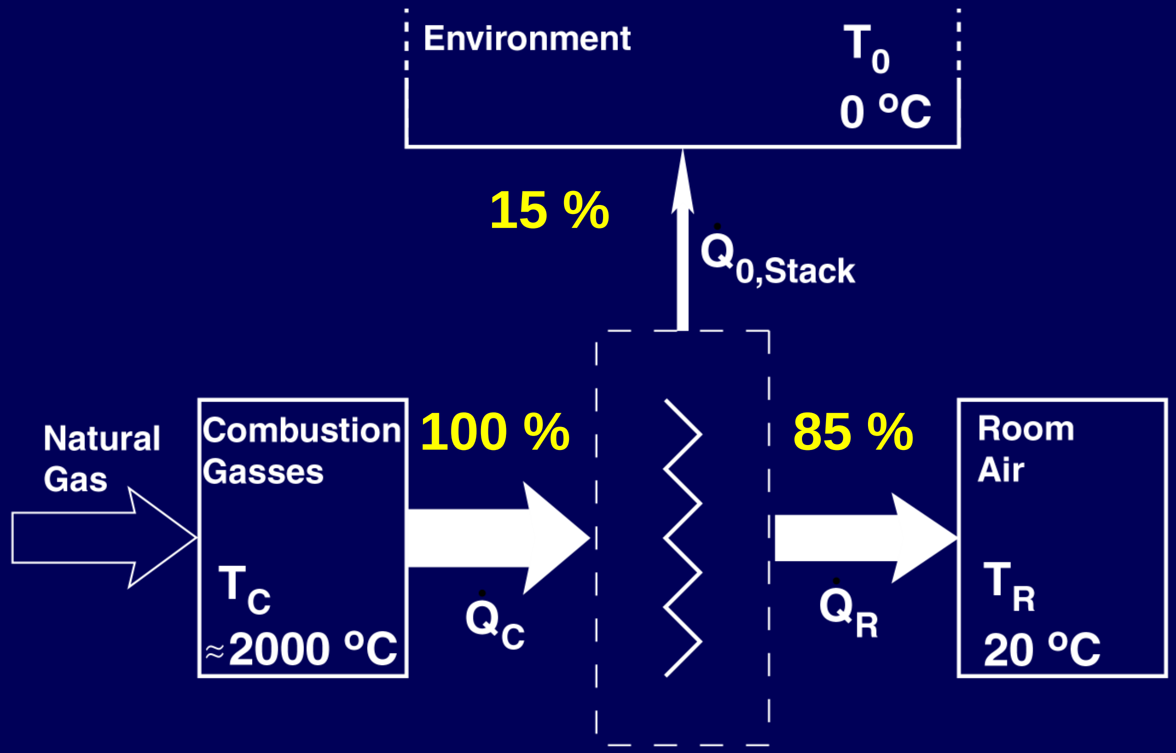
- Maximum Empower Principle (Emergy)
- Constructal theory (Time)
- Exergy Destruction Principle (Exergy)

How Efficient is Your Home Furnace?

Mid-efficiency	85 %
High Efficiency	95 %

$$\eta = \frac{Q_{IntoRoom}}{Q_{NaturalGasCombustion}}$$

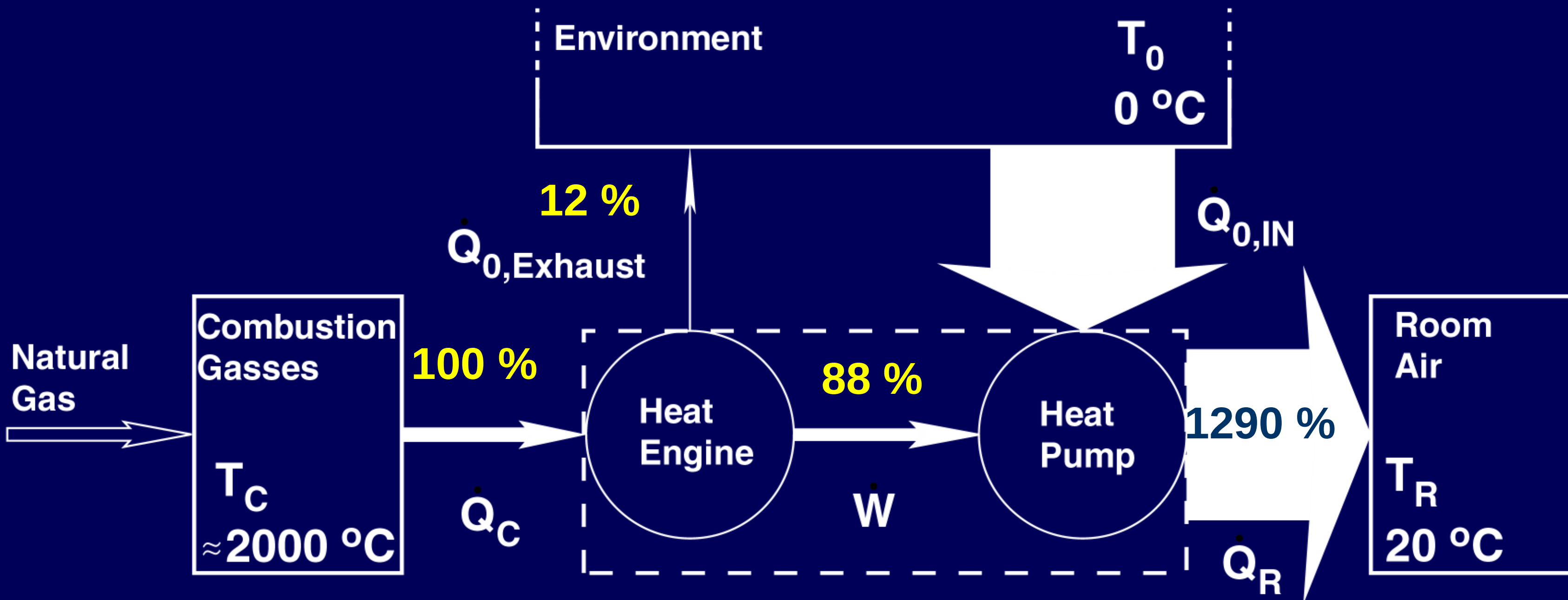


Rerun: How Efficient is Your Home Furnace?

Q: Imagine now, how you would respond to a salesperson who tried to sell you a revolutionary type of furnace with a claimed efficiency of 120 %.

Q: Would you be suspicious?

Exergy Conserving Home Heating Furnace



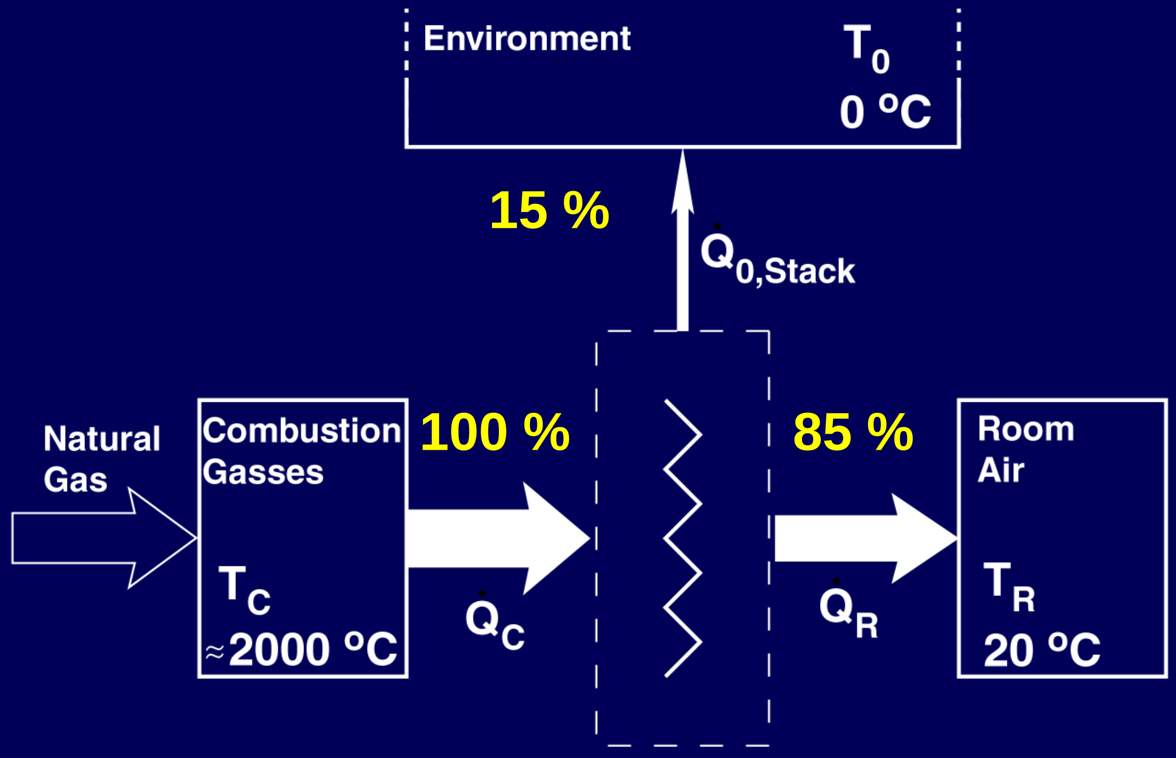
$$\eta_I = \frac{Q_{Into\,Room}}{Q_{Natural\,Gas\,Combustion}} = 1290\%$$

$$\eta_{II} = \frac{Q_{Into\,Room}}{Q_{Maximum,\,Into\,Room}} = 100\%$$

How Efficient is Your Home Furnace?

$\eta_I = 85\%$

$\eta_{II} = 6.6\,\%\,!$



Remember

- Intuition is a poor substitute for the physics of thermodynamics.

- Intuition can seriously limit one’s ability to conceive of alternative systems.

  Corollary: There are an infinite number of exergy conserving systems.

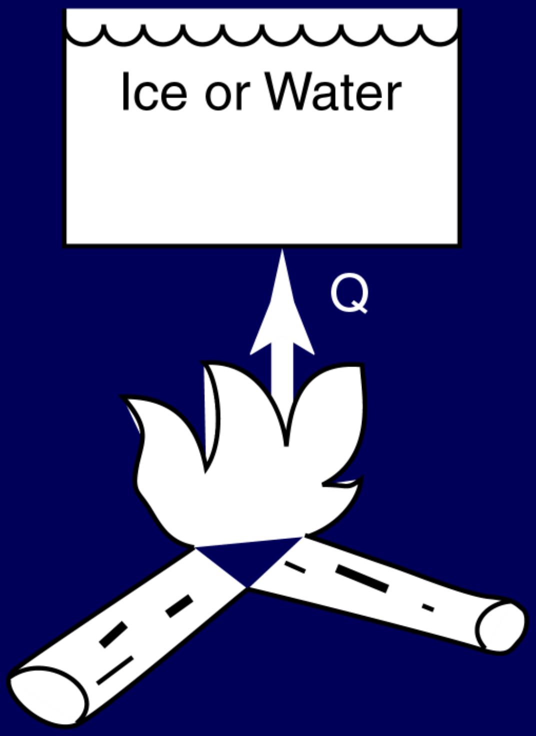
It is Easier to Boil Ice Than Water?

Q: Ideally, does it take less natural gas to bring 1 kg of ice at -20 ^{o}C, or 1 kg of water at 60 ^{o}C, to a 100 ^{o}C boil?

A: It takes a factor of 3.3 less natural gas to bring the -20 ^{o}C ice to a boil!

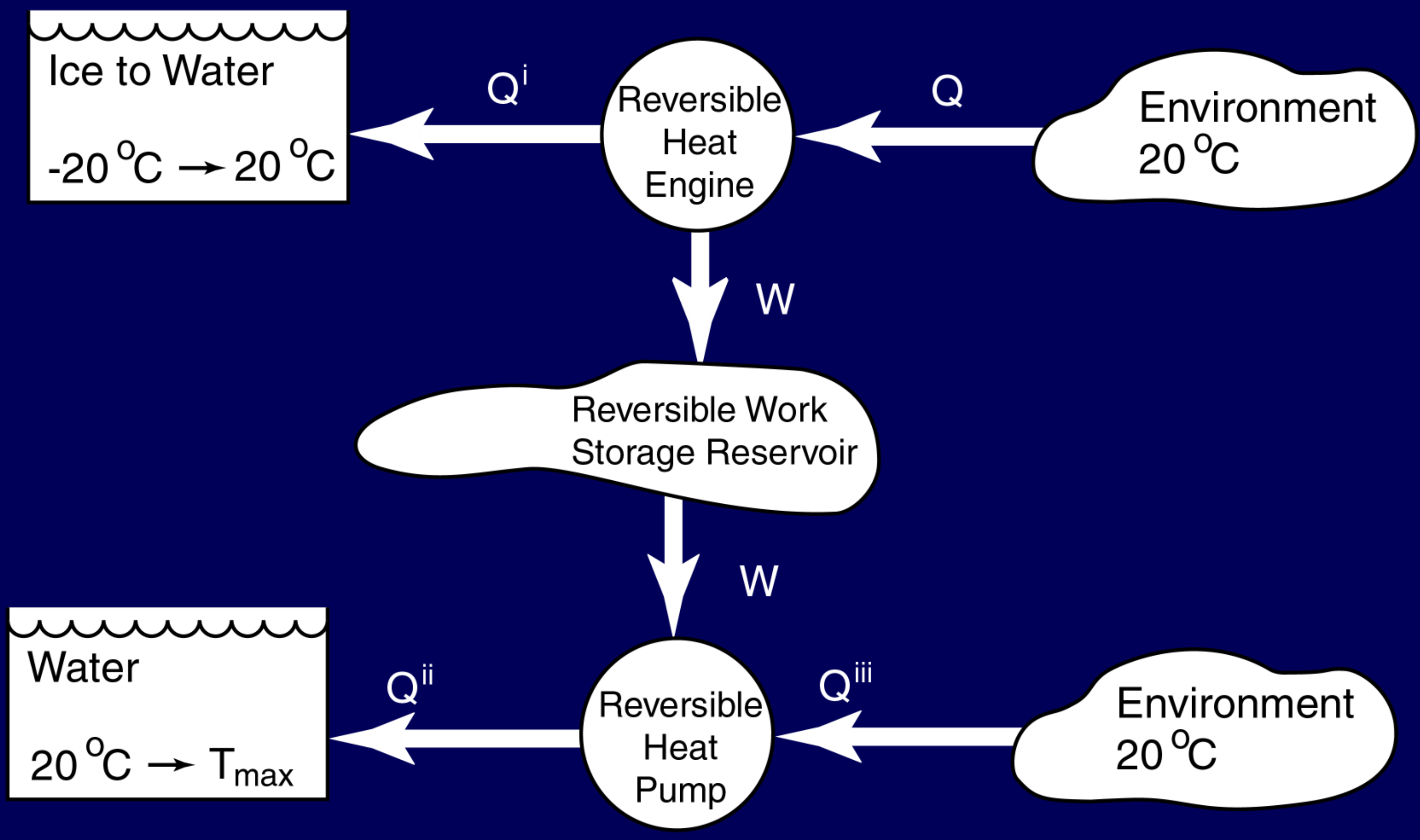
Theoretically, the -20 ^{o}C ice can be heated to 88 ^{o}C with no natural gas.

Energy, not Exergy, Approach

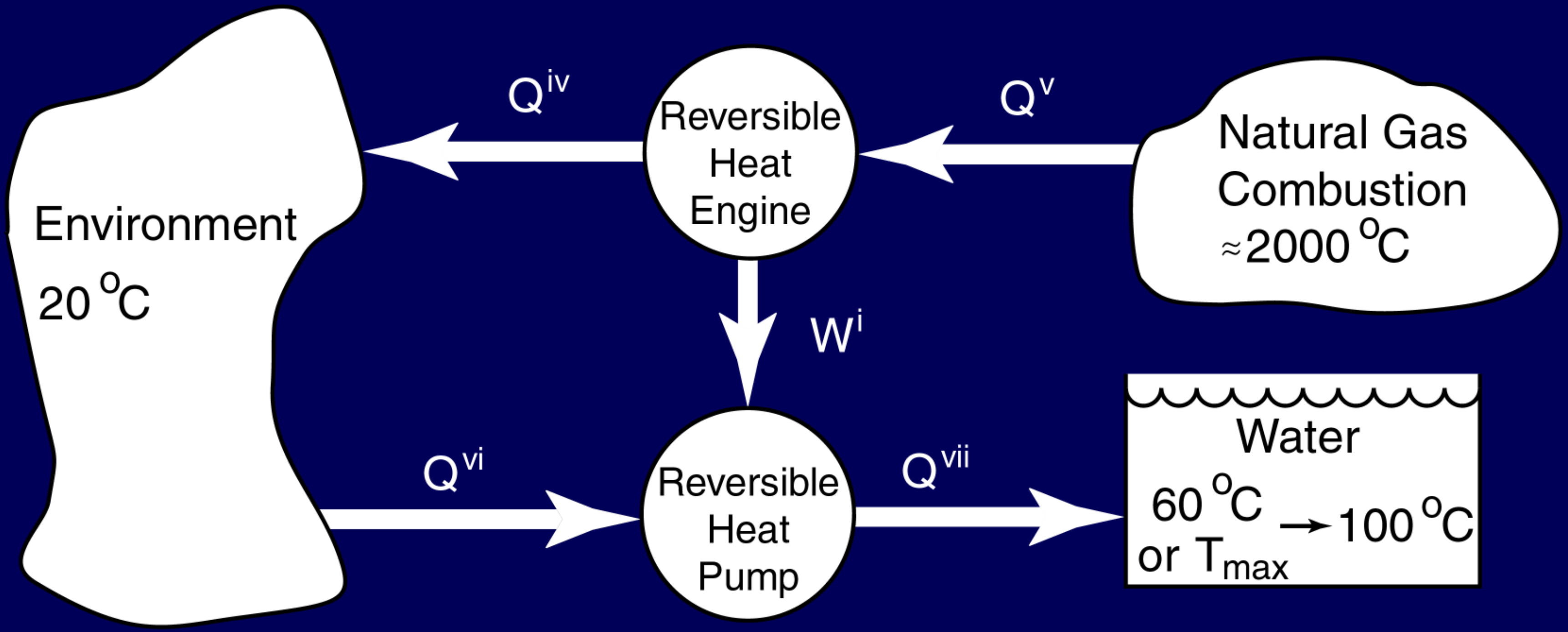


Energy approach requires
less Natural Gas
to heat 60 ^{o}C water
to 100 ^{o}C.

Exergy Approach



Exergy Approach (Continued)



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- Any system out of equilibrium with environment has potential to do useful work.

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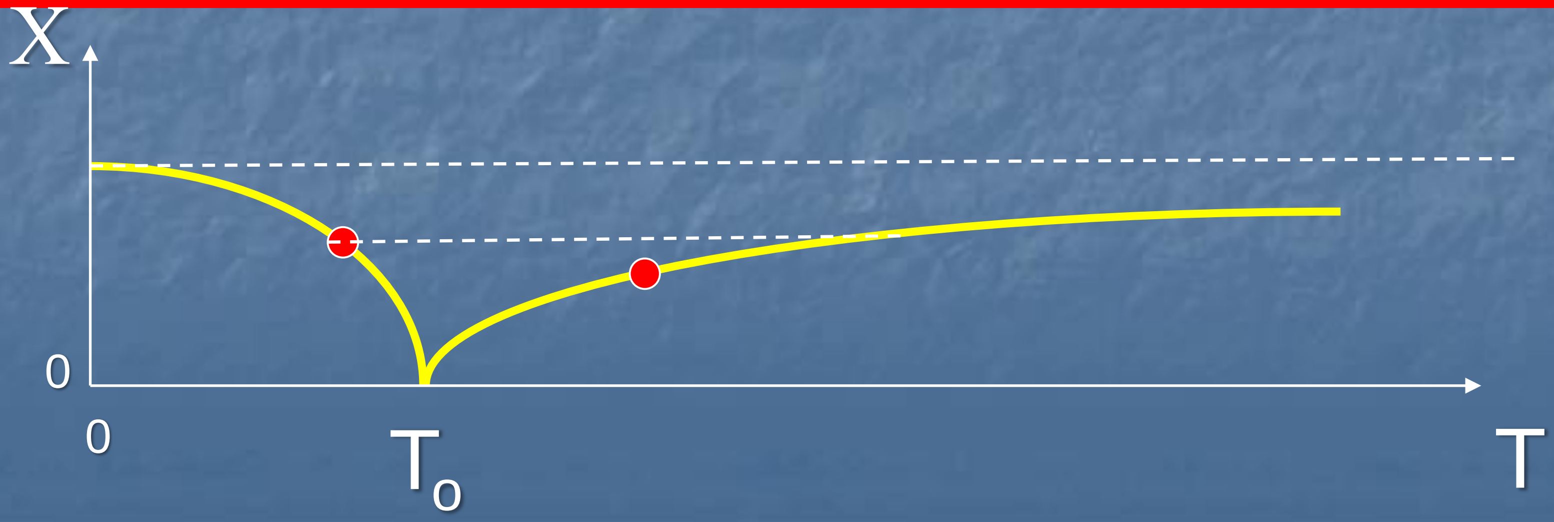
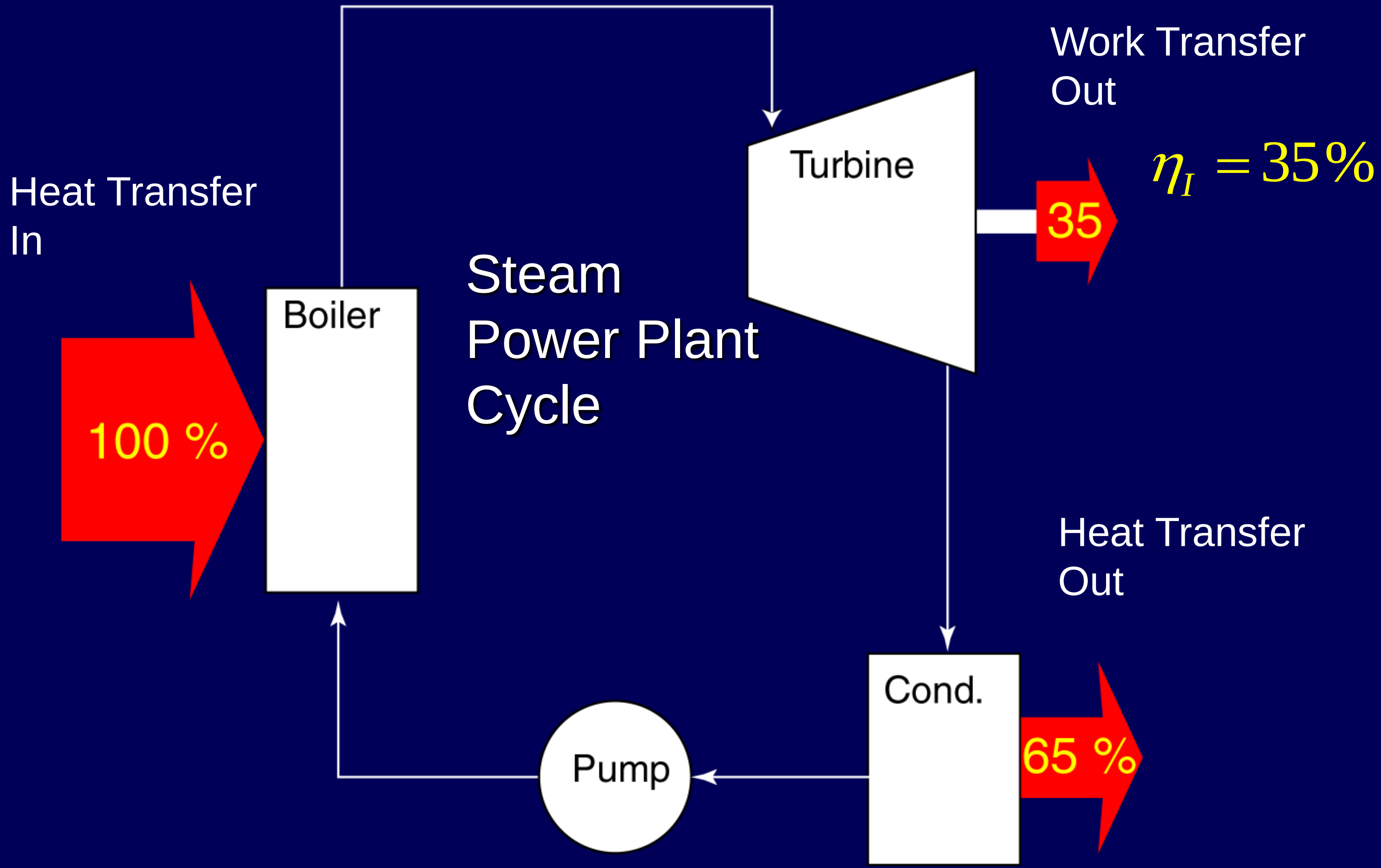


Decision Making by Energy



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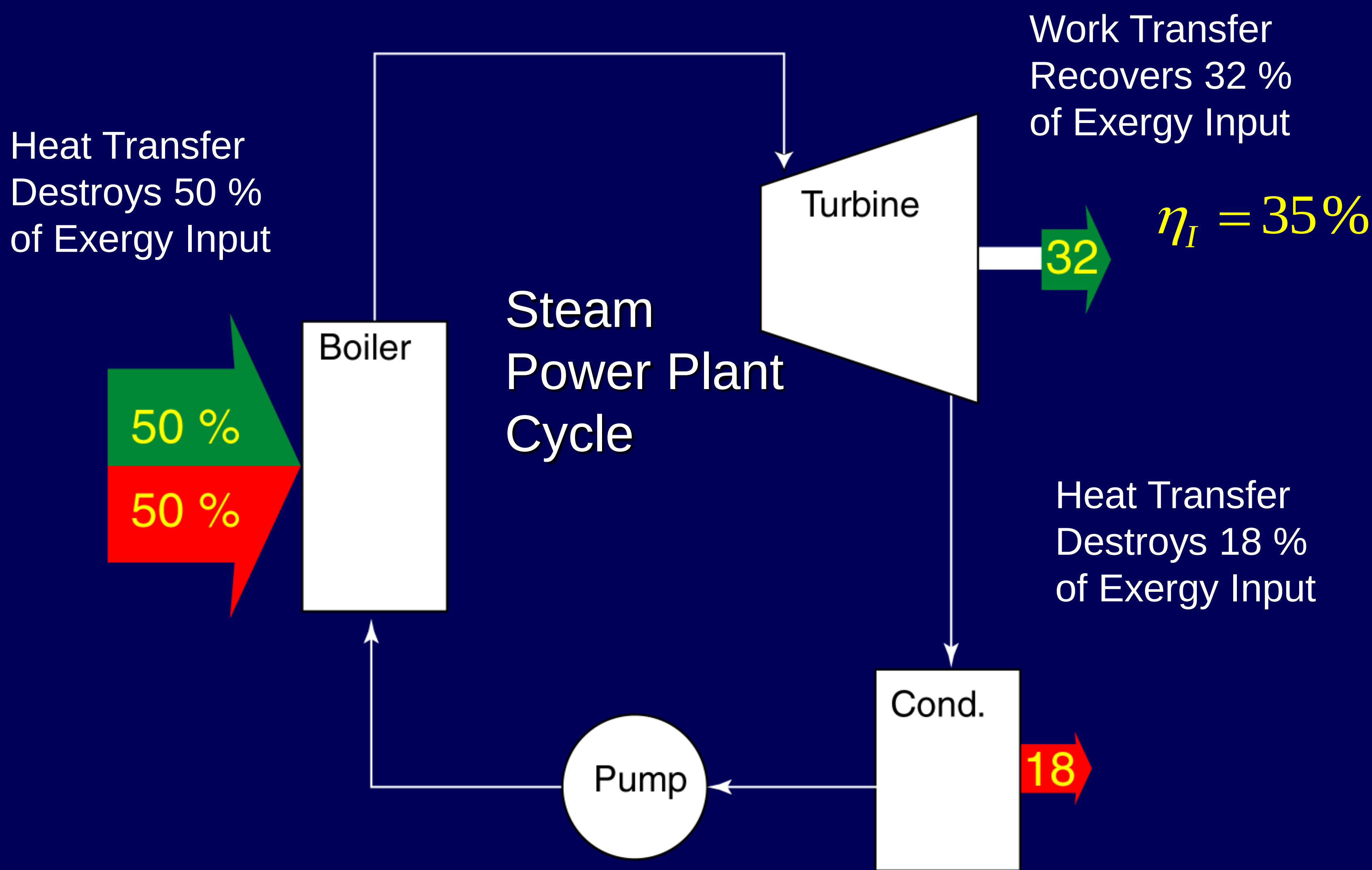
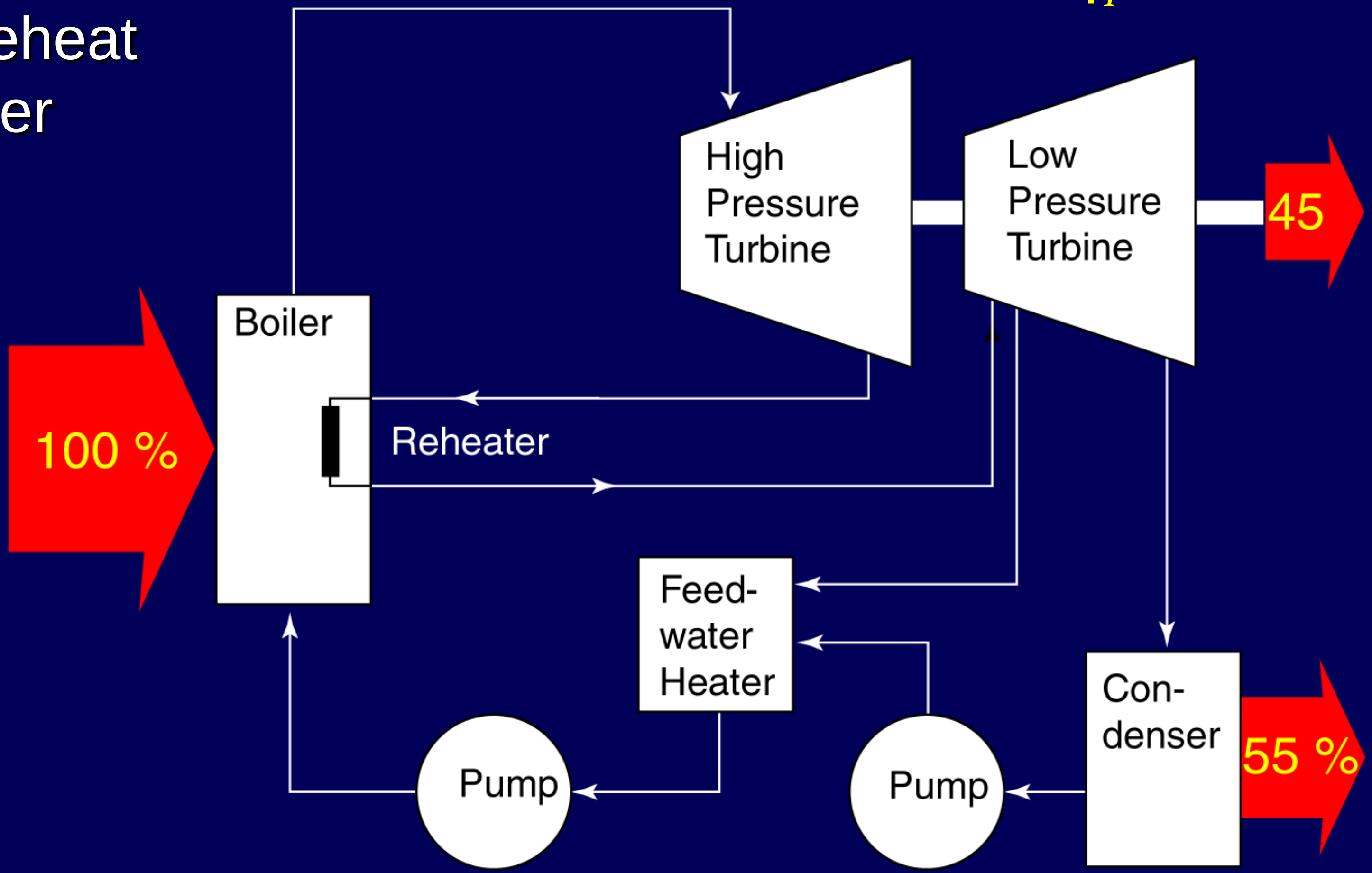


Decision Making by Exergy

Steam Power Plant Cycle with Reheat and Feedwater Heating

$\eta_I = 45\%$



What is Exergy?

Four Characteristics of Energy

Magnitude	Energy	(First Law)
Form	KE, PdV	(Phenomena)
Direction	$P_S \geq 0$	(Second Law)
Quality	eXergy	(First + Second Laws)

Four Characteristics of Energy

Magnitude	Energy	(First Law)
Form	KE, PdV	(Phenomena)
Direction	$P_S \geq 0$	(Second Law)
Quality	eXergy	(First + Second Laws + Environment)

General Exergy Concept

Exergy ≡ Maximum Useful To-The-Dead-State Work ≡ Energy Quality or Usefulness

- ANY SYSTEM out of equilibrium with its environment has the potential to do useful work.
- *Intrinsic exergy* provides a measure of how far out of equilibrium with the environment a system happens to be.

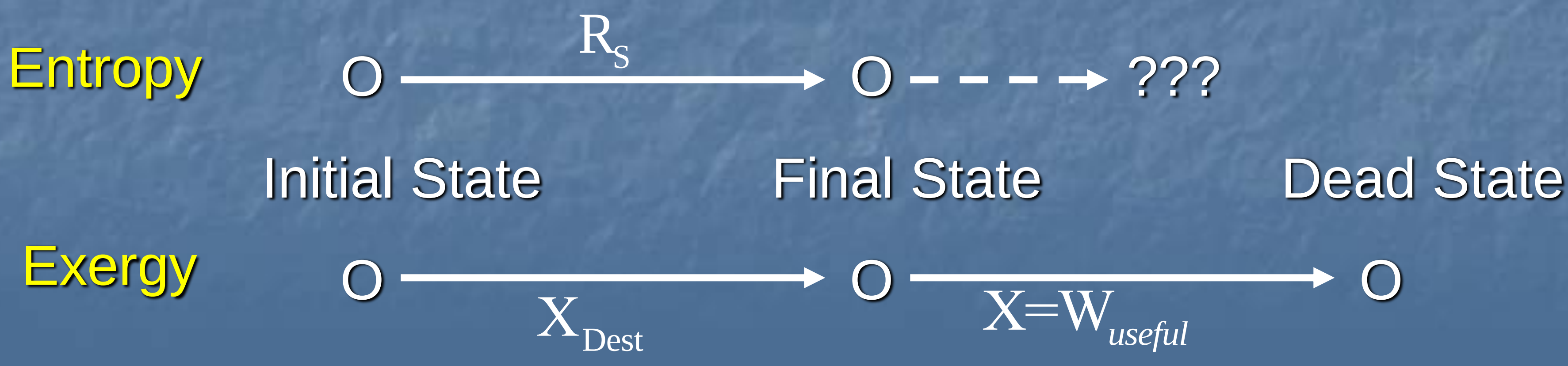
A
BLACK BOX
Principle

Exergy versus Entropy

Exergy and Entropy Intimately Linked

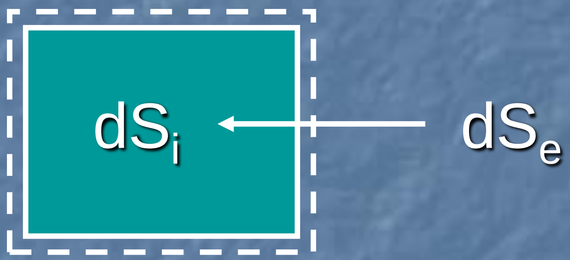
Guoy-Stodola Theorem:

$$X_{Dest} = T_0 P_S$$



“Literally” Look Outside the Box

Prigogine's
Local Entropy Production



$$dS_{sys} = dS_i + dS_e$$

A system-centric viewpoint.

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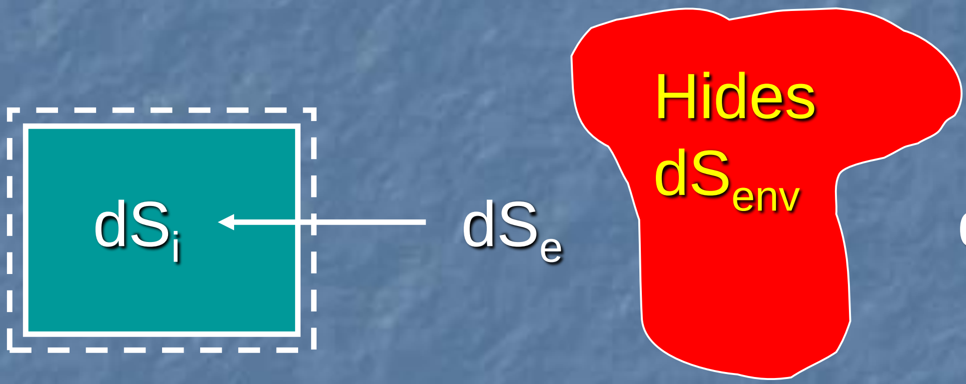


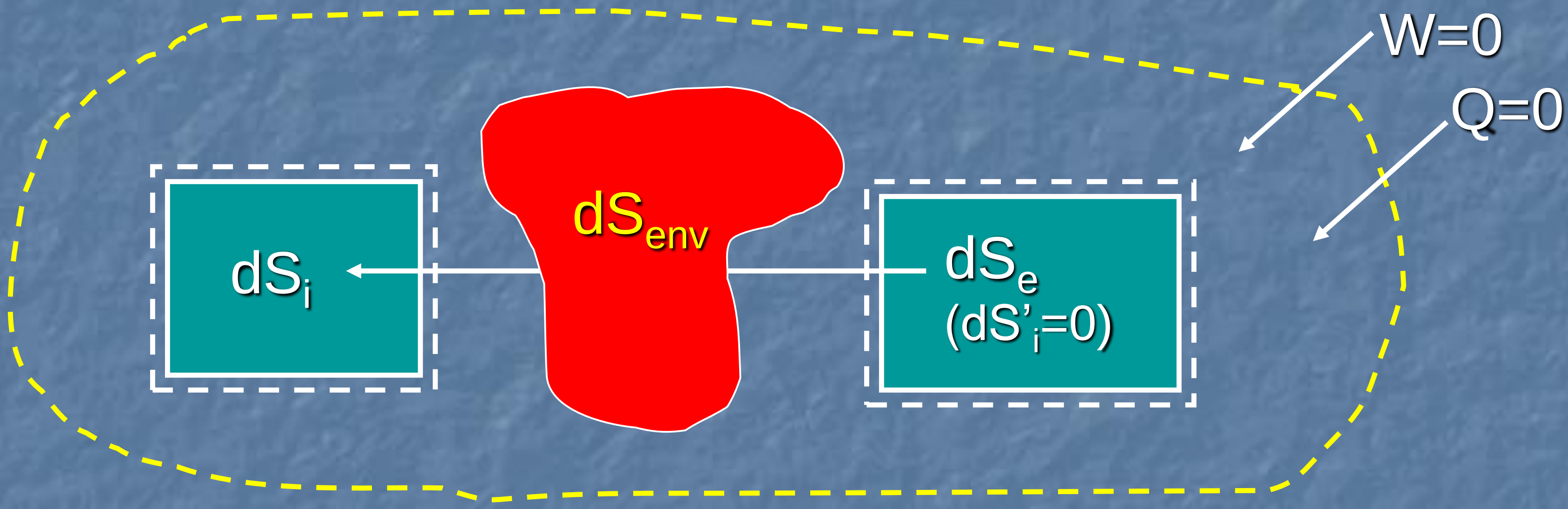
$$dS_{sys} = dS_i + dS_e$$

A system-centric viewpoint.

Detrimentally de-emphasises critical role of environment.

Must construct system until $dS_e=0$ or $dS_{env}=0$.

Classical Entropy Production

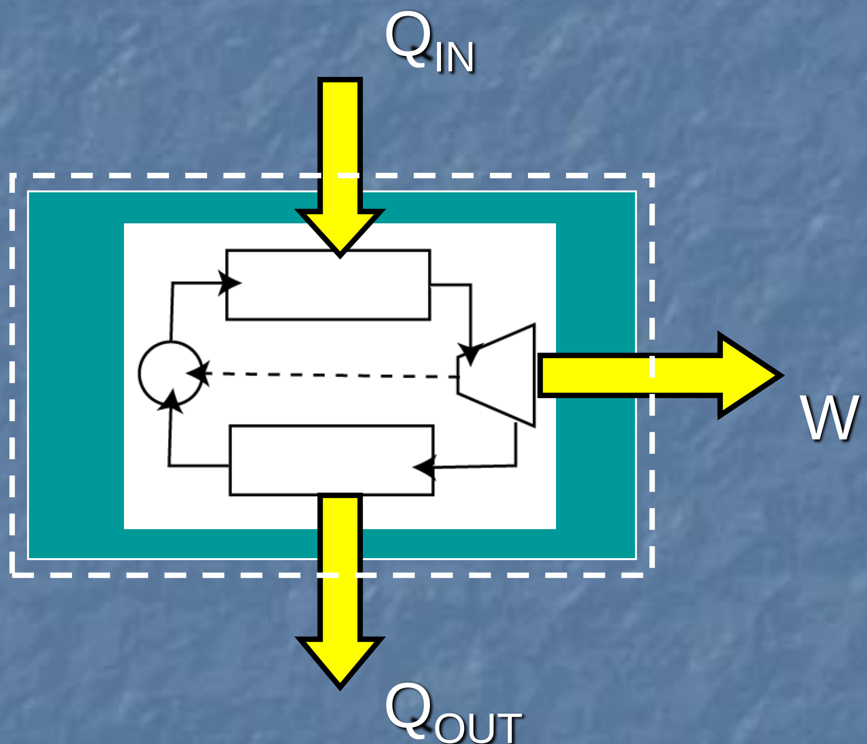


An isolated-system viewpoint. $dS_{sys} = dS_i + dS_e + dS_{env}$

Second Law of Thermodynamics:

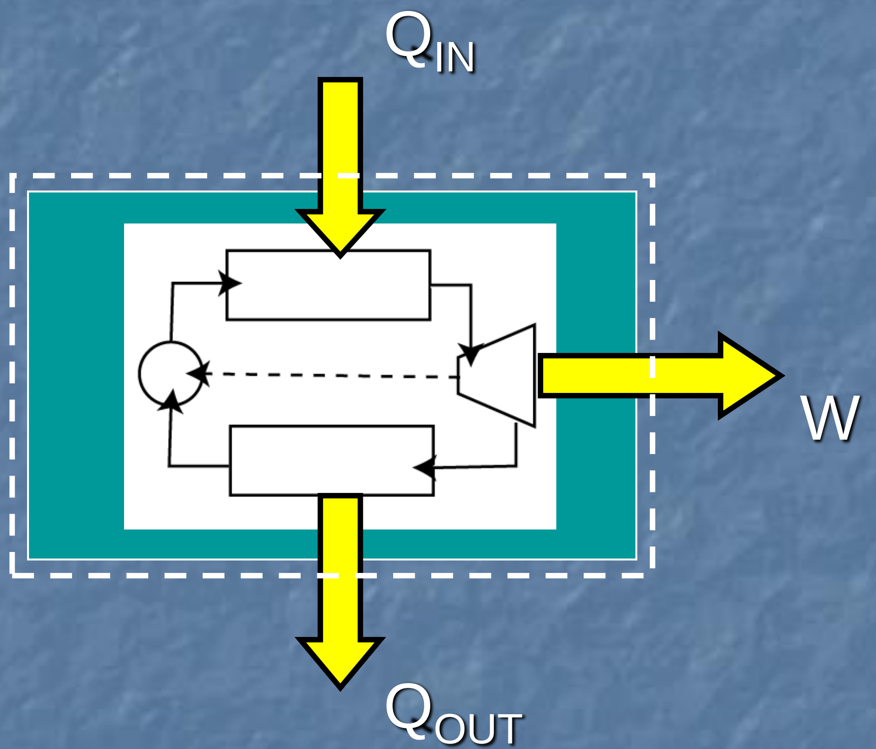
$$dS_{prod,\ isolated\ system} = dS_i + dS_{env} >= 0$$

Cycle Efficiency
(System Centric)



Biology and Ecology tend to define the system and then look inside.

Mechanistic Analysis of Cycle Efficiency

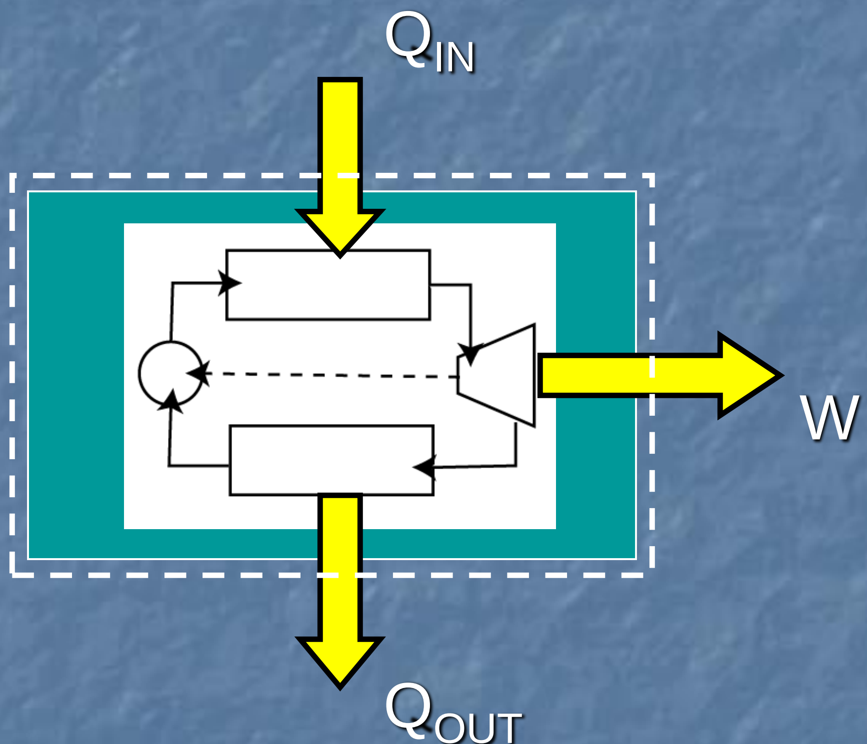


System is no longer viewed as a Black Box.

Easy to loose focus of the whole system.

$$\eta = \frac{W}{Q_{IN}} = 40\%$$

Mechanistic Analysis of Cycle Efficiency



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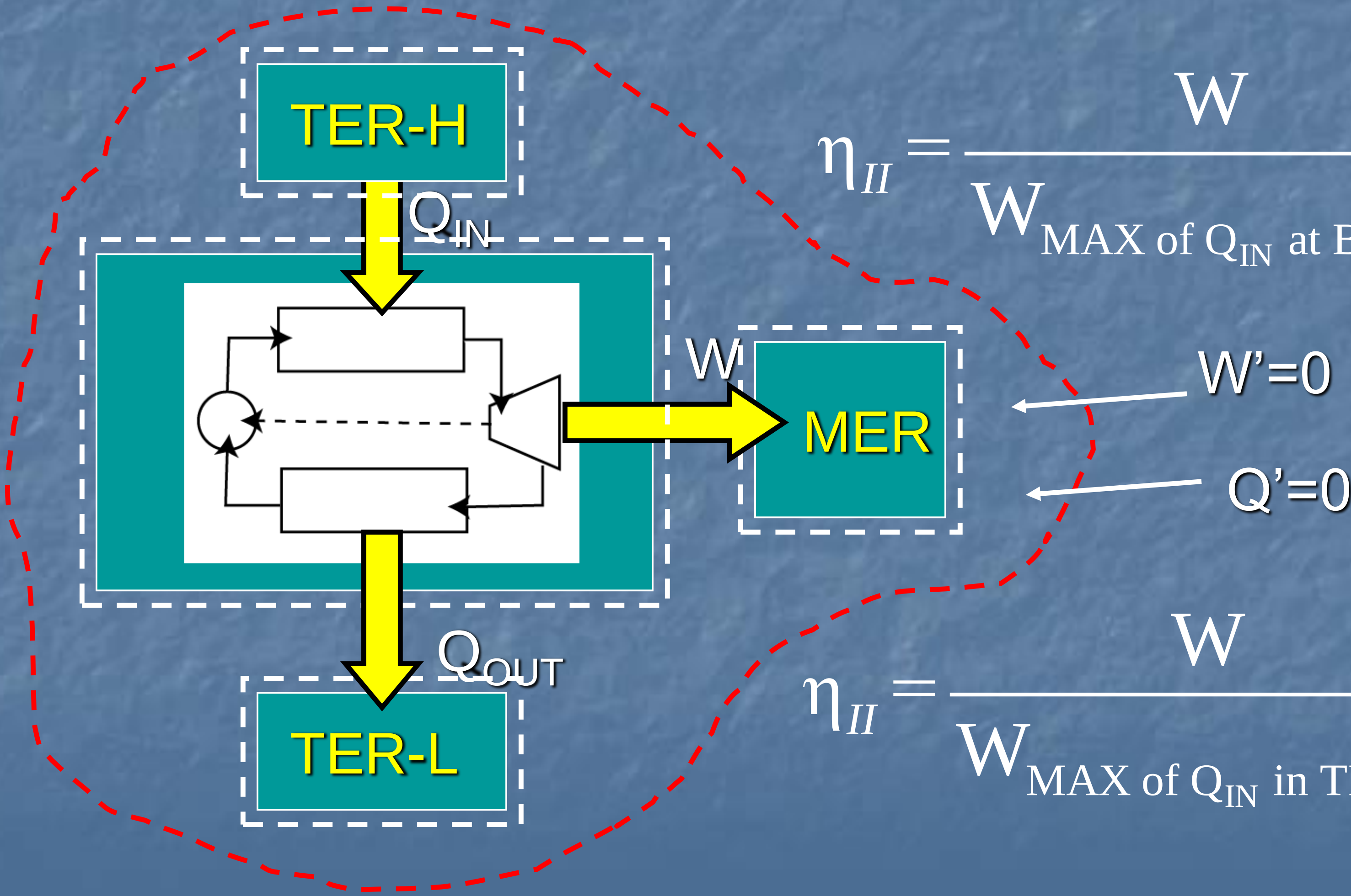
Bottom Up Approach

Plant Efficiency

(Isolated-System or Exergy View)

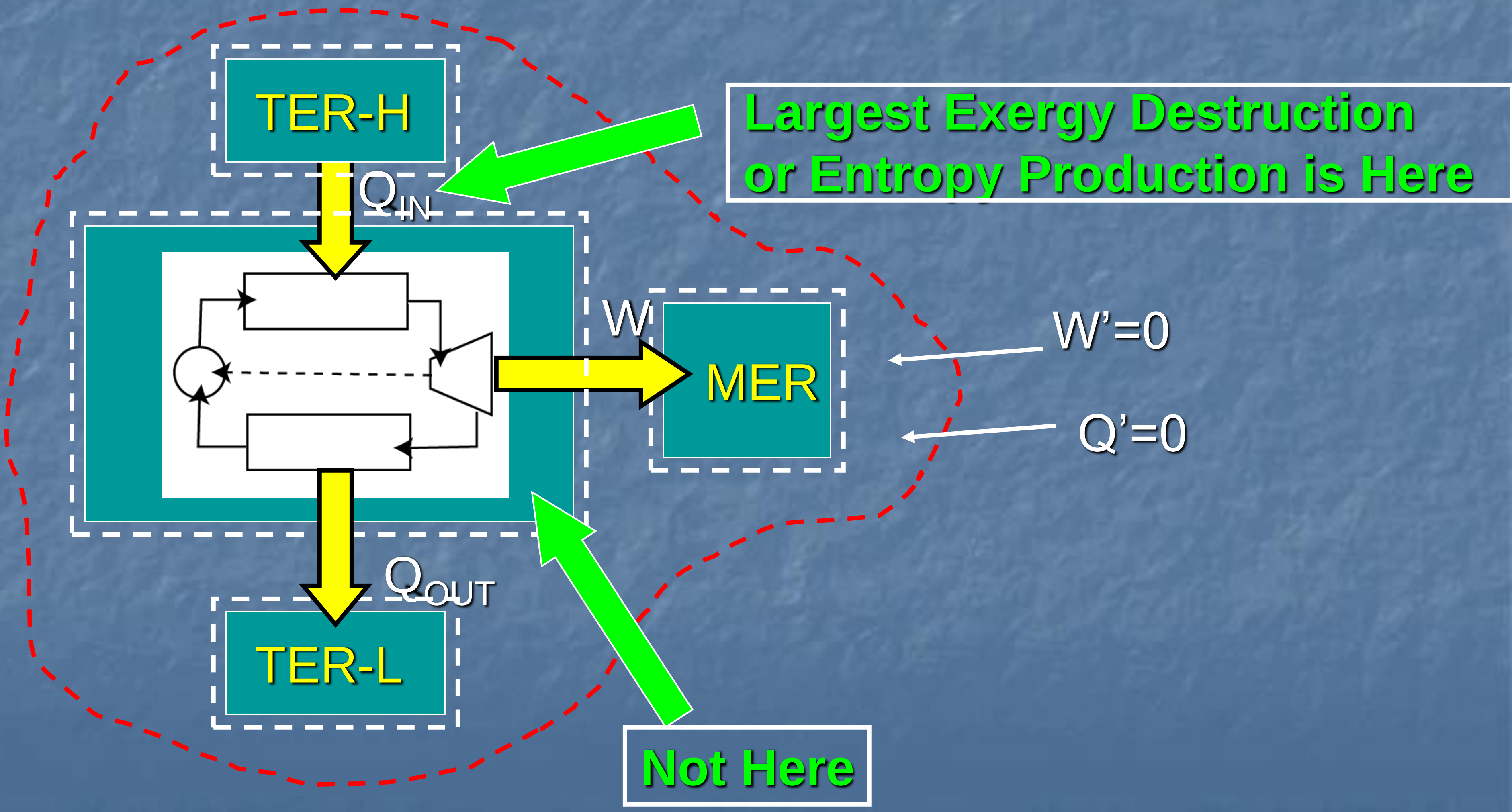


$$\eta_{II} = \frac{W}{W_{\text{MAX of } Q_{IN} \text{ at Boiler}}} = 80\%$$

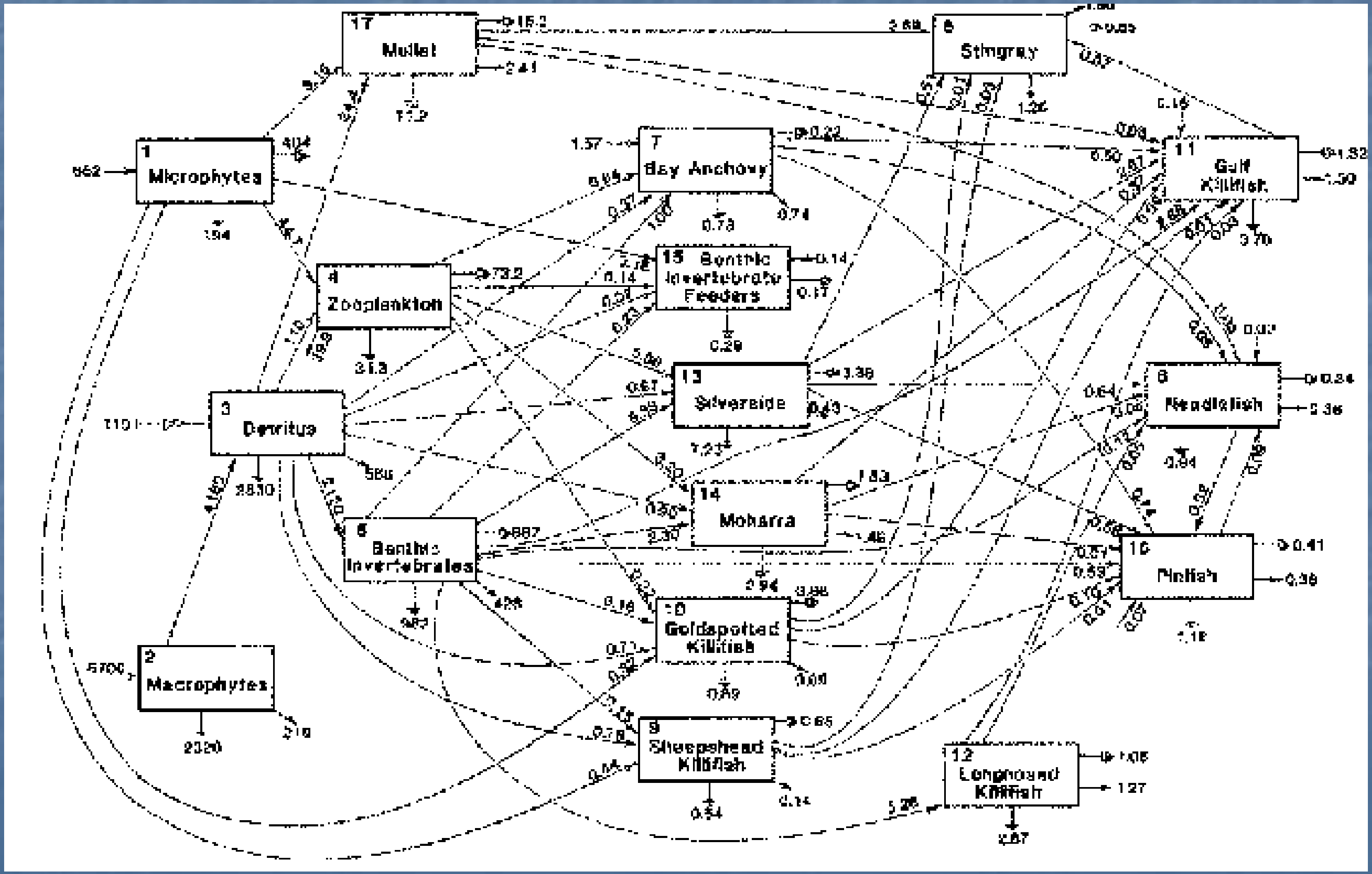
$$\eta_{II} = \frac{W}{W_{\text{MAX of } Q_{IN} \text{ in TER-H}}} = 47\%$$

Plant Efficiency

(Isolated-System or Exergy View)



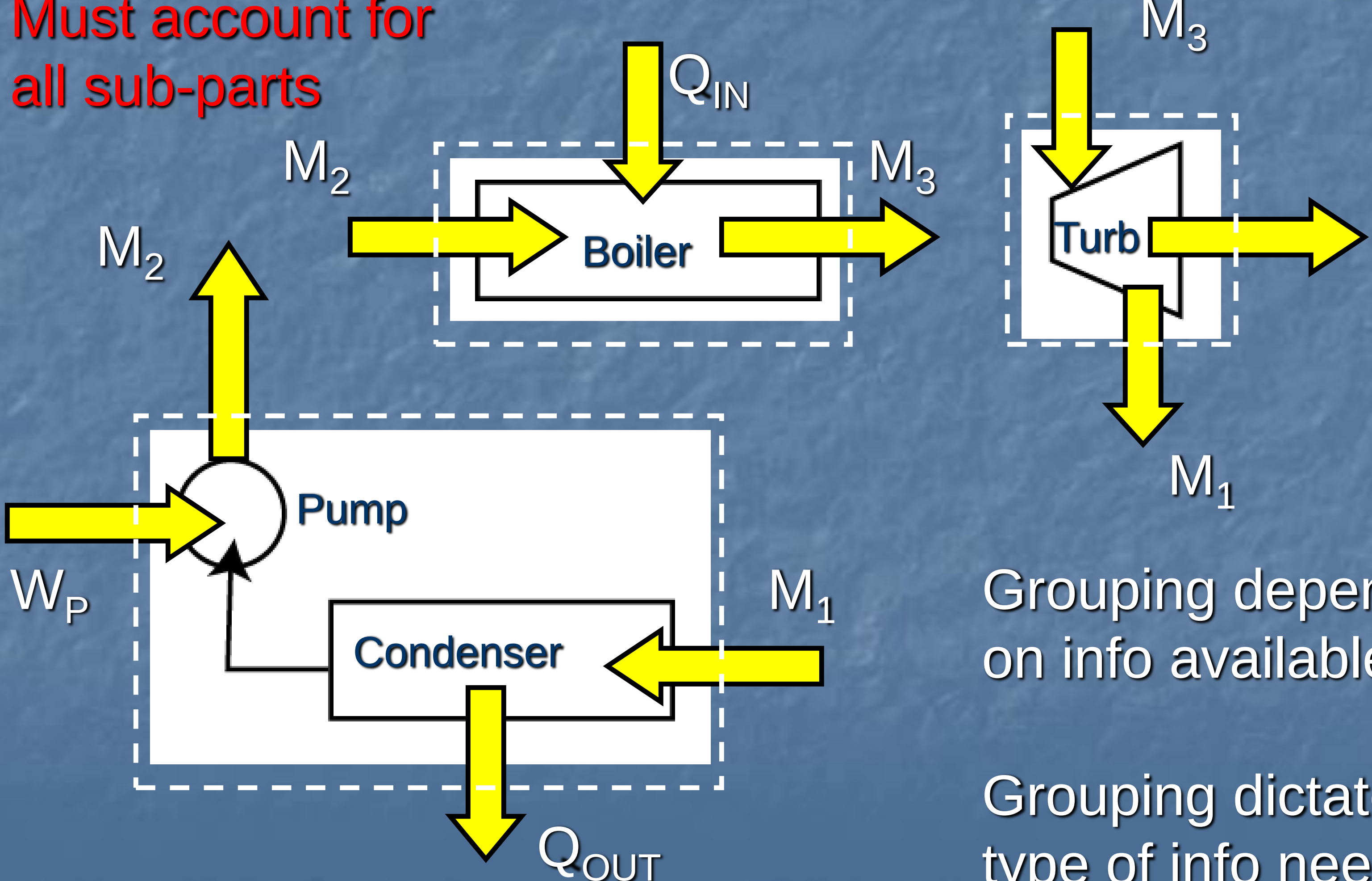
Food Web



17 Mullet
6 Stingray
1 Microphytes
7 Bay Anchovy
11 Gulf Killifish
4 Zooplankton
15 Benthic Invertebrate Feeders
3 Detritus
13 Silverside
8 Needlefish
14 Moharra
5 Benthic Invertebrates
16 Pinfish
10 Goldspotted Killifish
2 Macrophytes
9 Sheepshead Killifish
12 Longnosed Killifish

Isolated-System View of Sub-Systems (Top-Down)

Must account for all sub-parts



Grouping depends on info available.

Grouping dictates type of info needed.

Still Black Boxes

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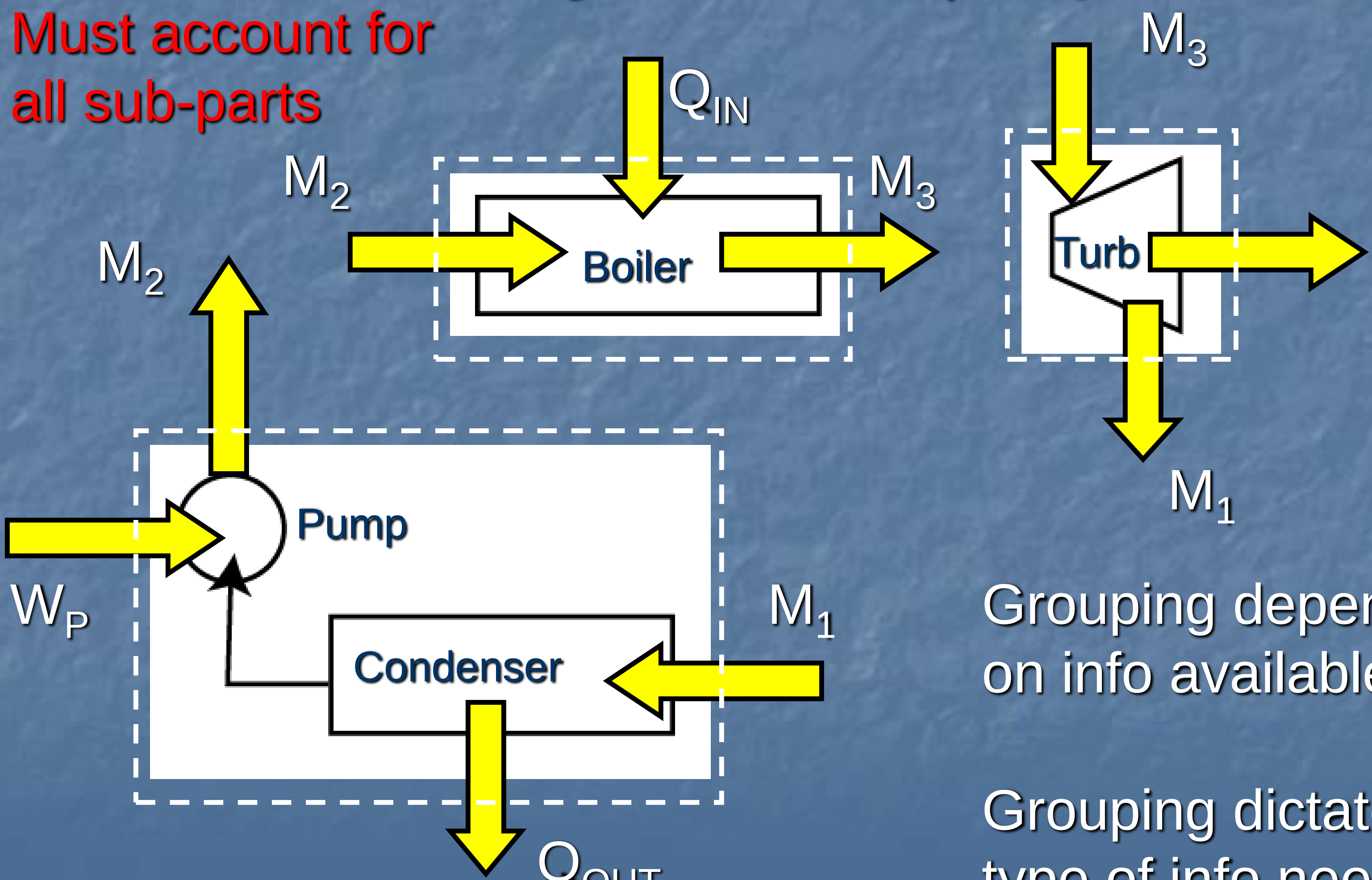

Top Down Approach

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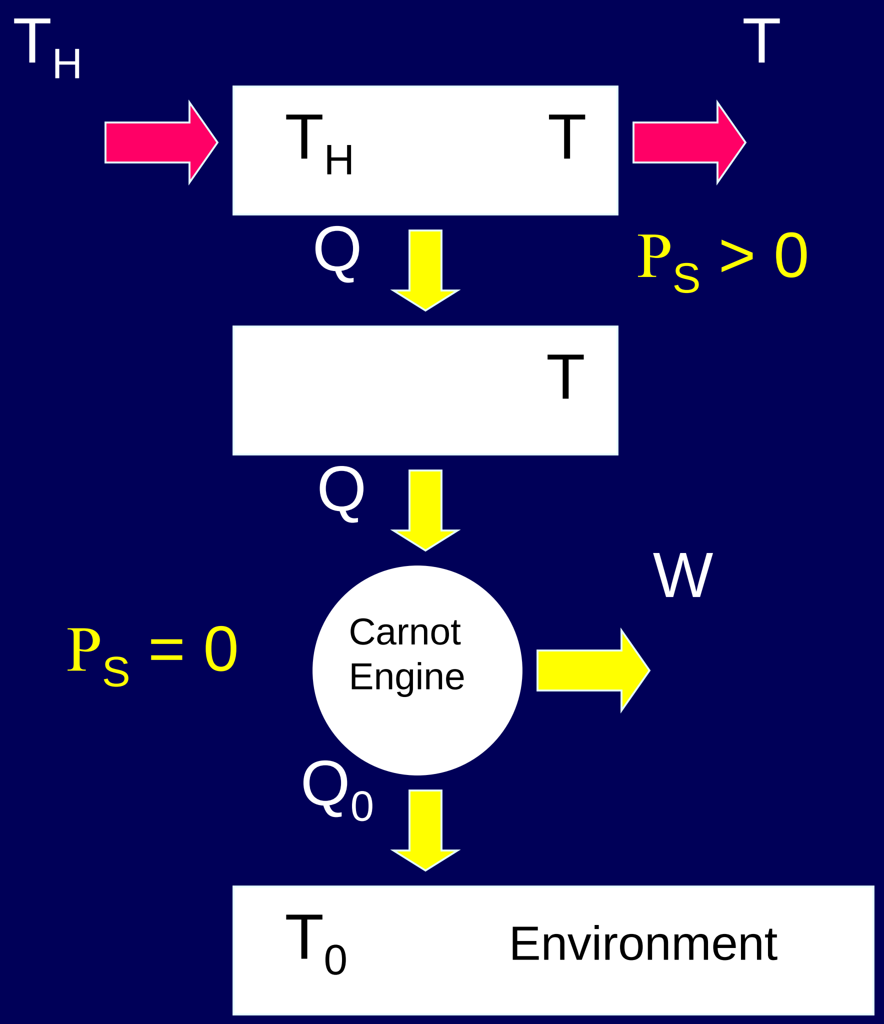
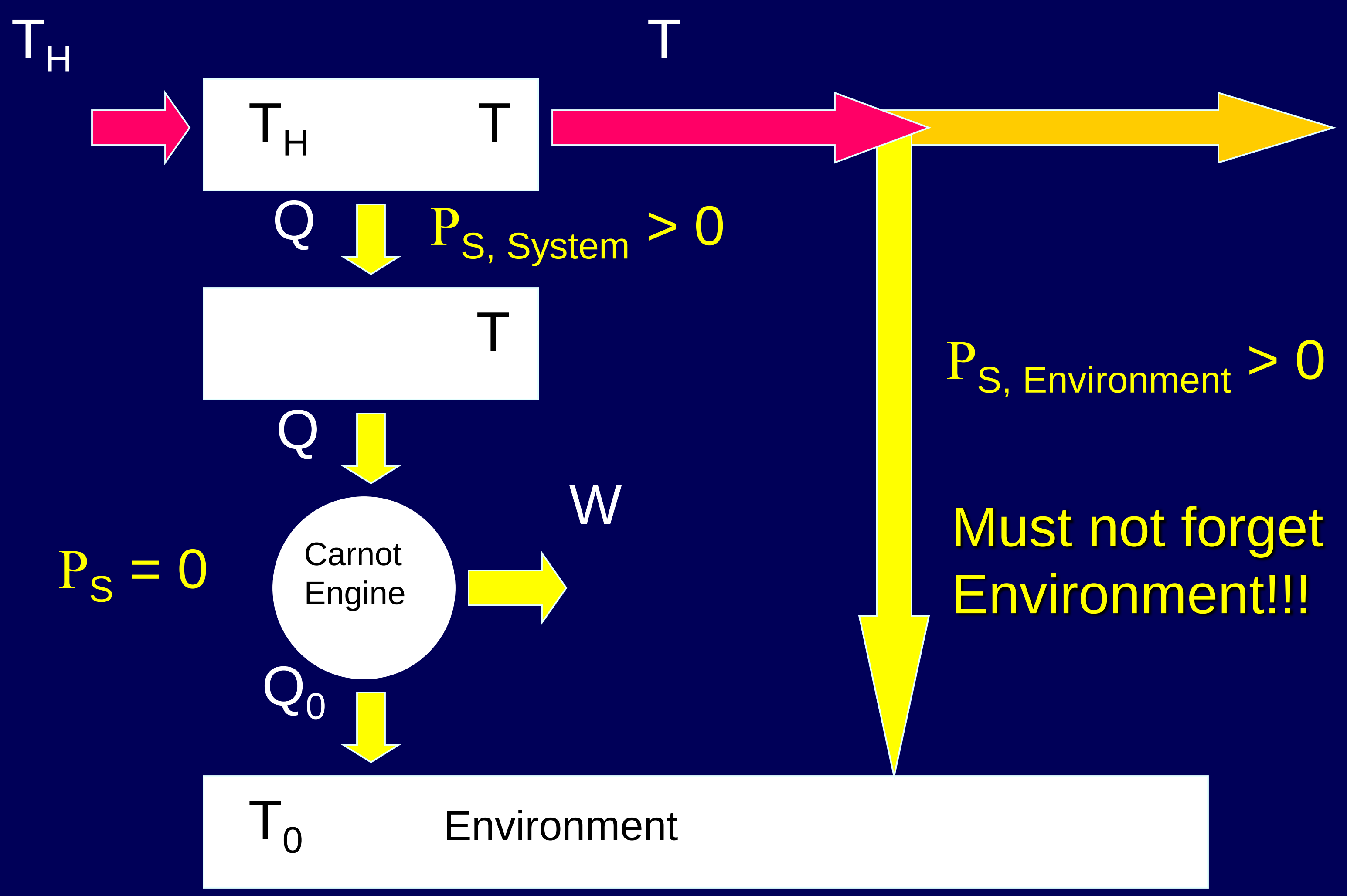
Still Black Boxes

Chambadal's Engine

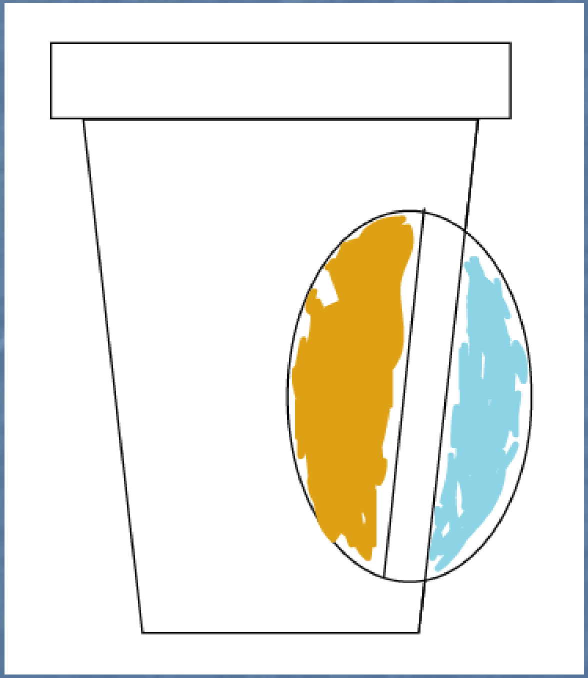


$T_{Optimum}$ = ?
for maximum W

Chambadal's Engine



Coffee cup: where is all the fun?



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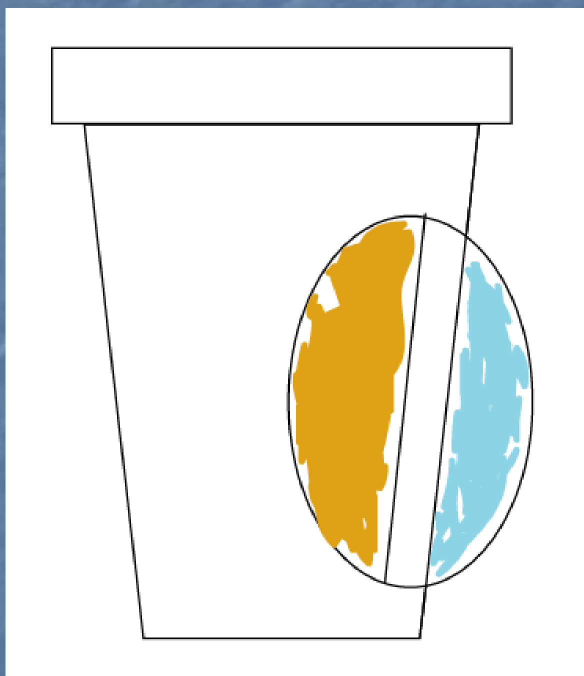

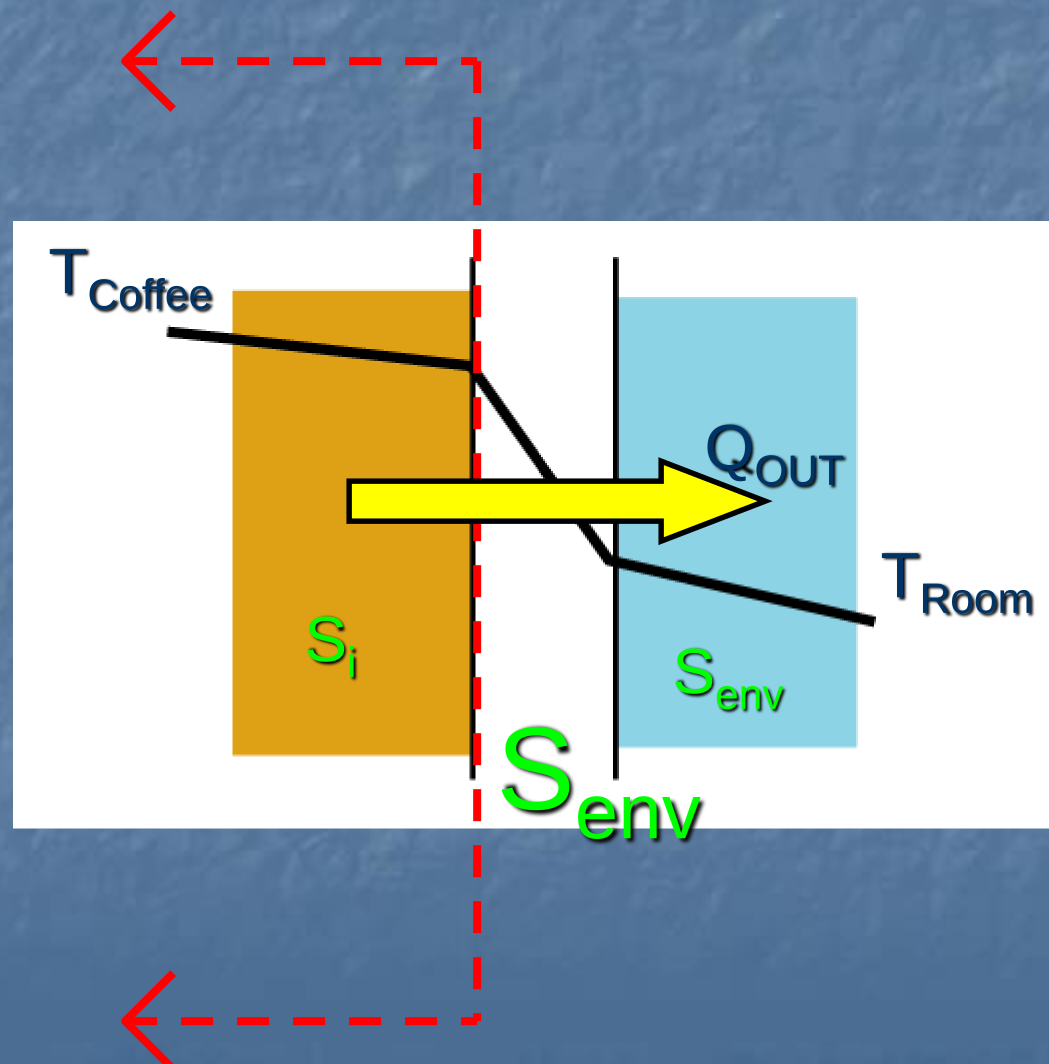

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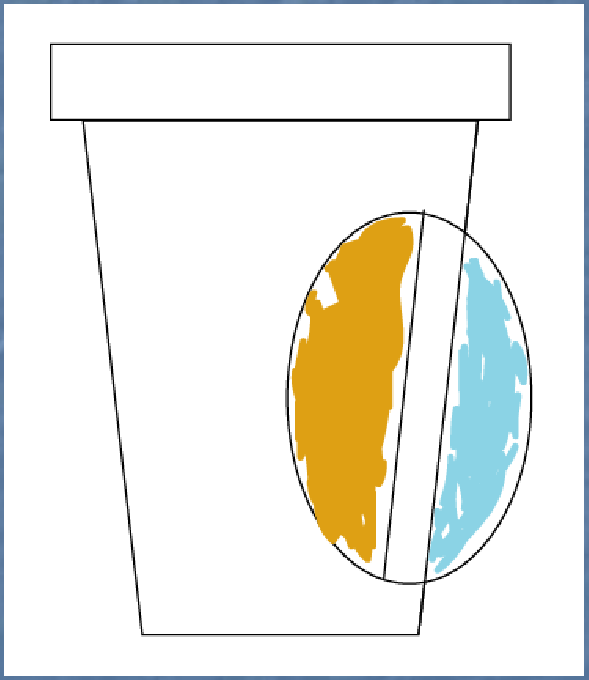
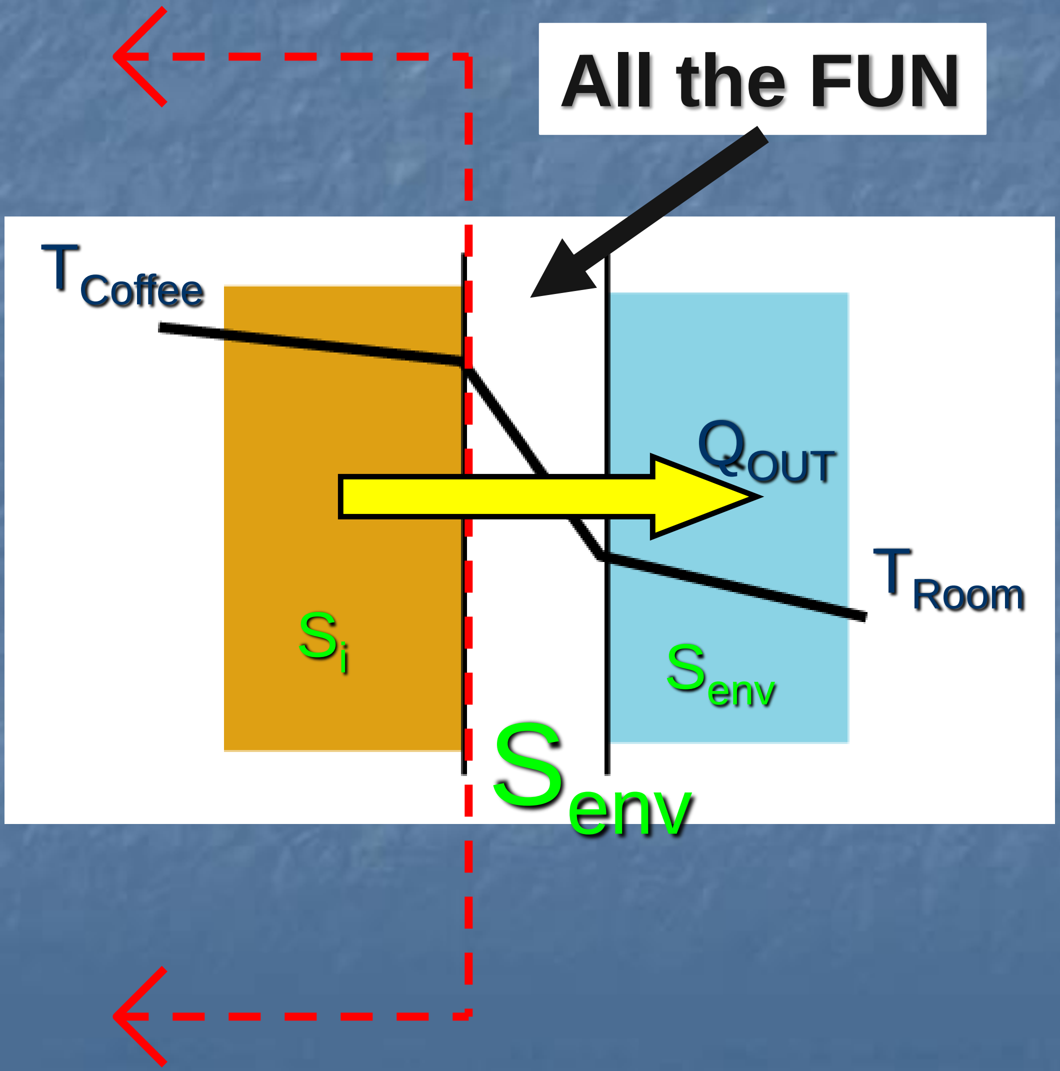
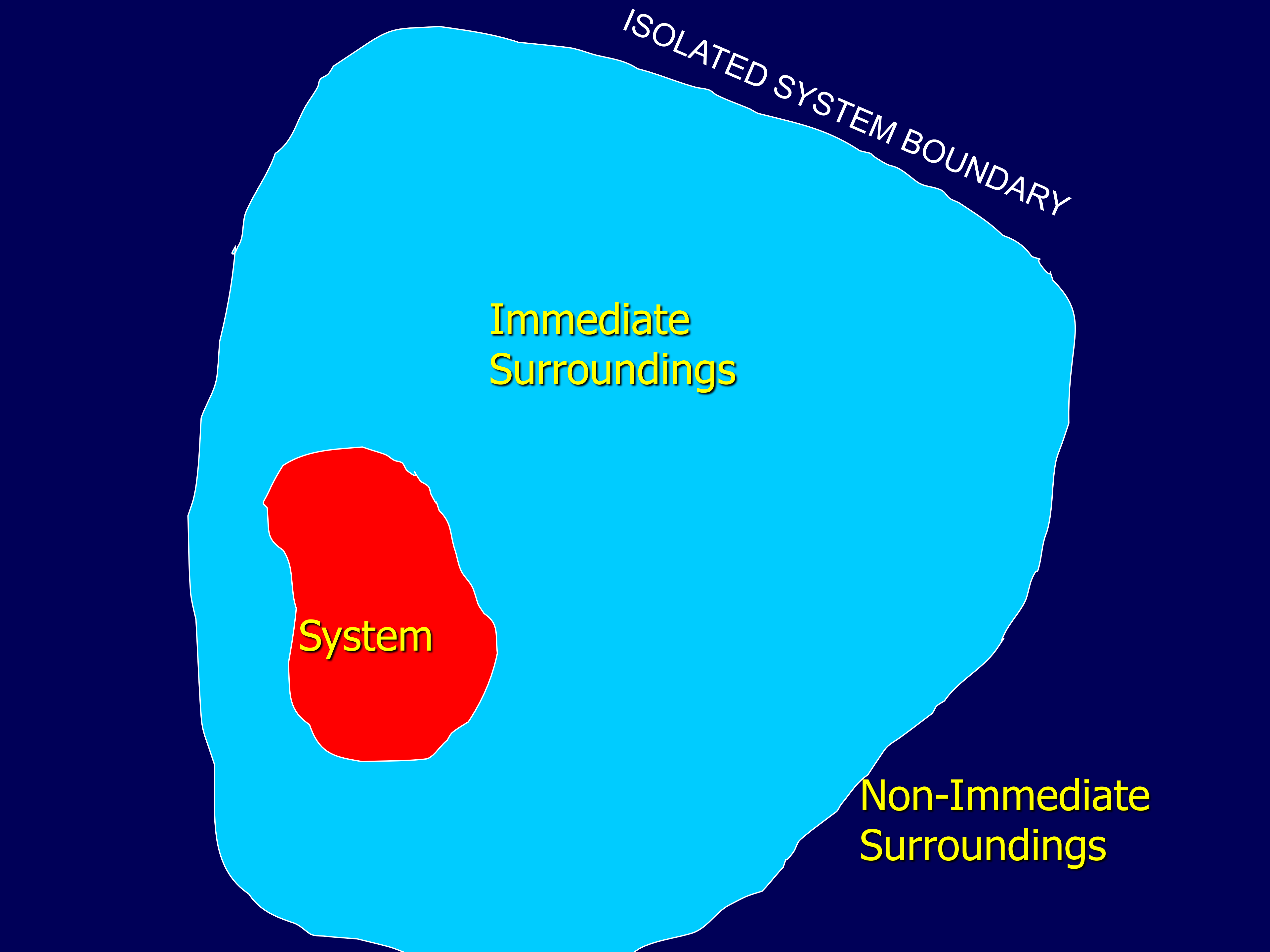
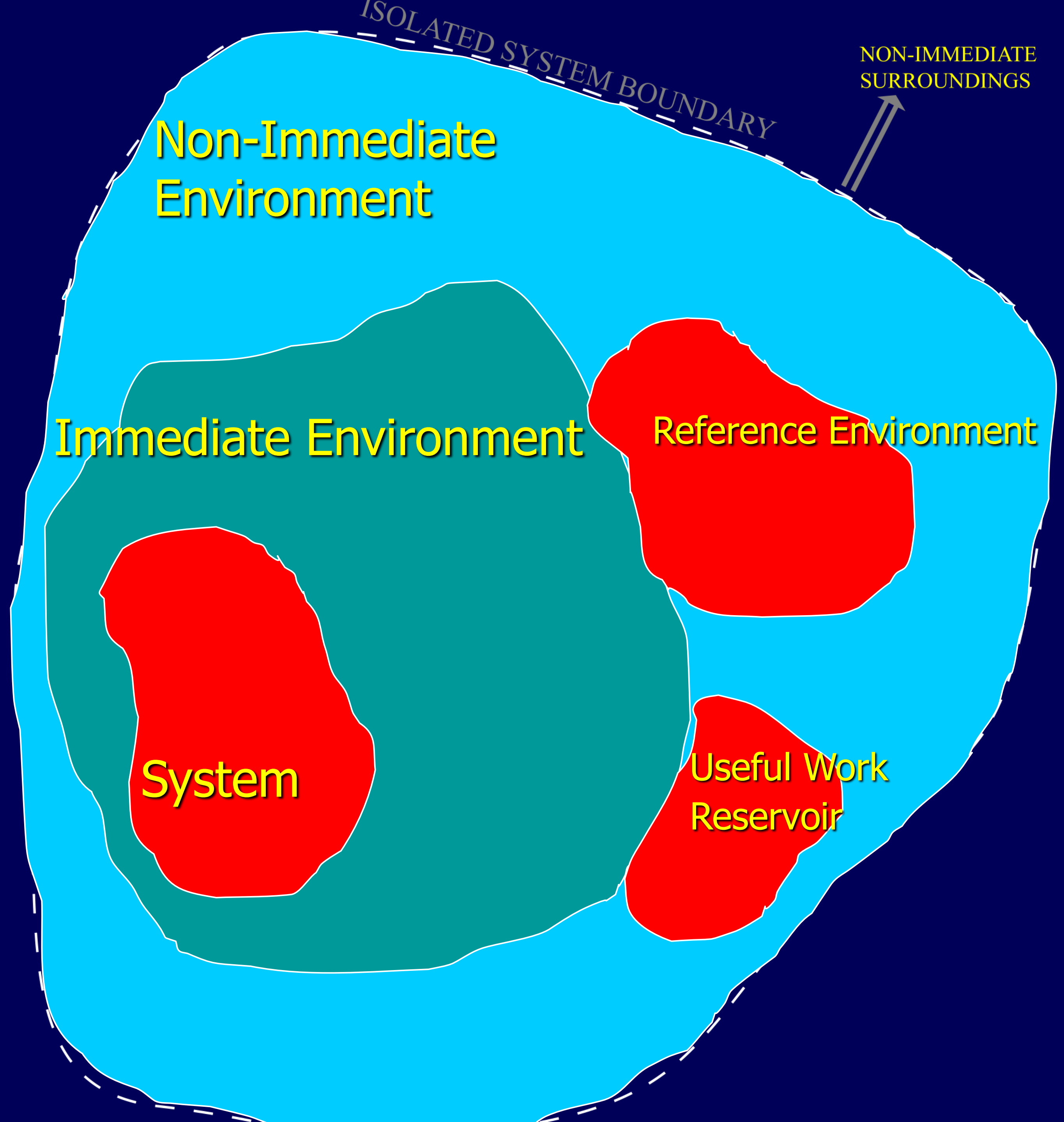
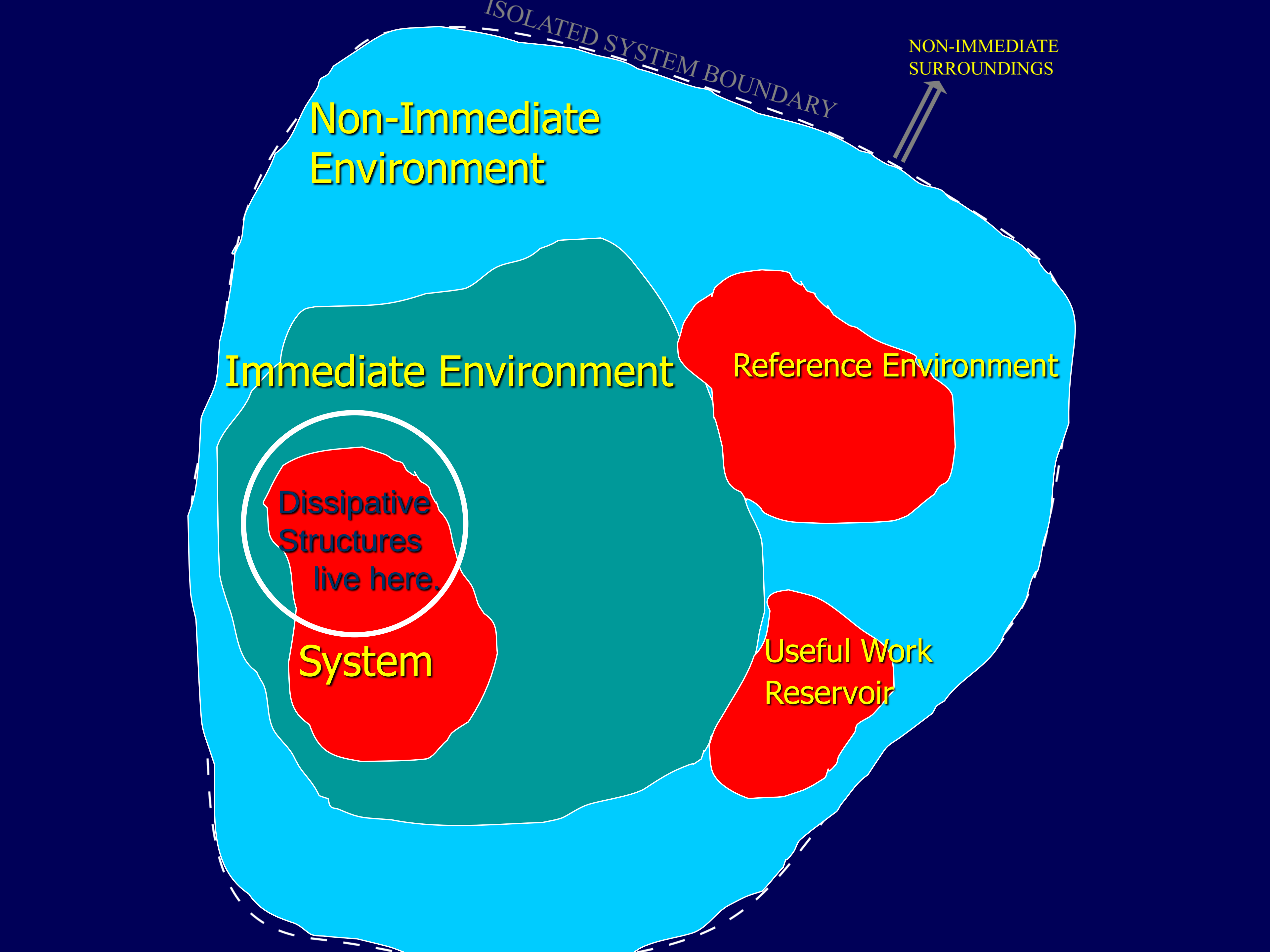


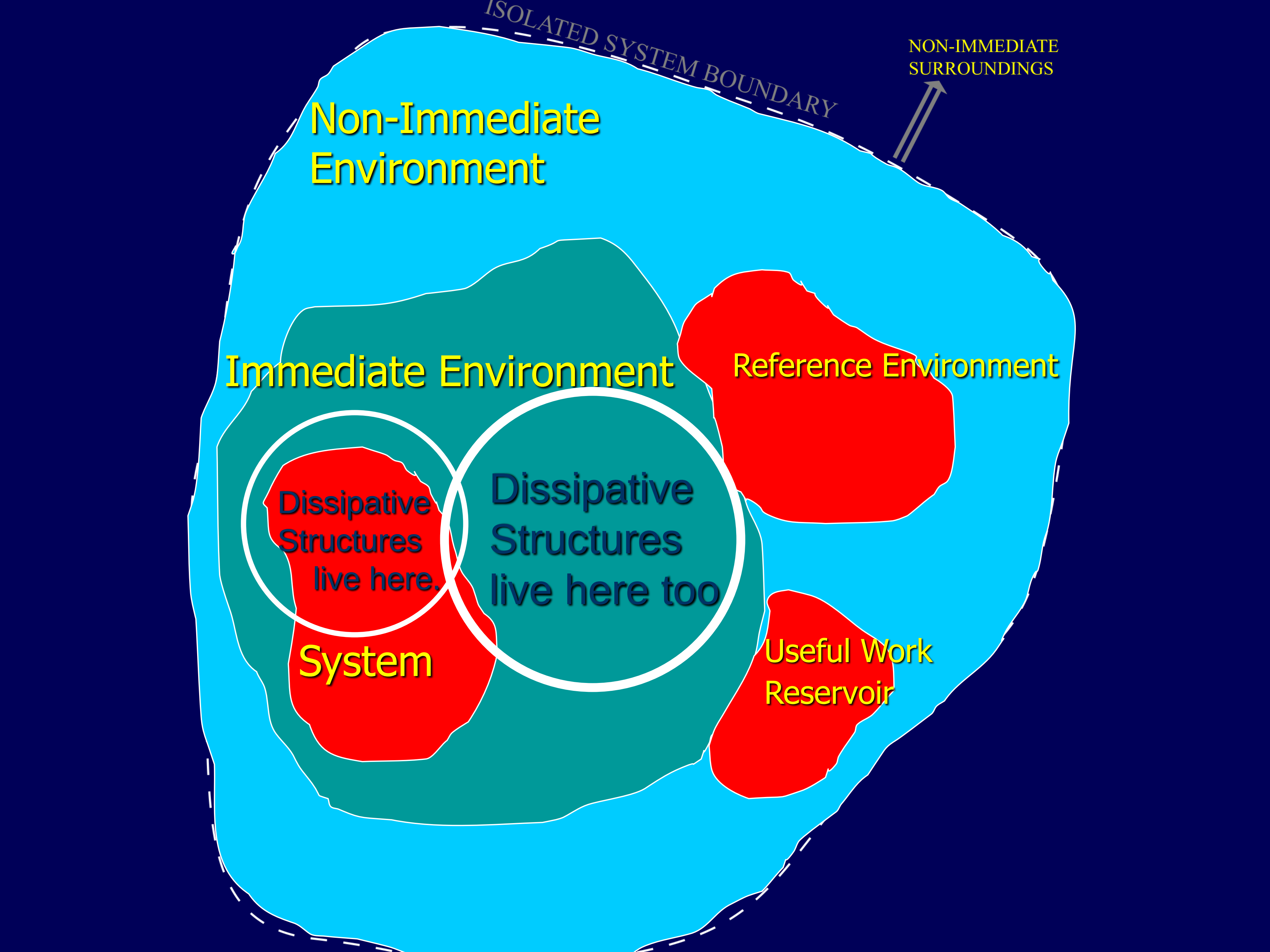



ISOLATED SYSTEM BOUNDARY
Immediate Surroundings
System
Non-Immediate Surroundings


ISOLATED SYSTEM BOUNDARY
NON-IMMEDIATE
SURROUNDINGS
Non-Immediate
Environment
Immediate Environment
Reference Environment
System
Useful Work
Reservoir



ISOLATED SYSTEM BOUNDARY
NON-IMMEDIATE SURROUNDINGS
Non-Immediate Environment
Immediate Environment
Reference Environment
Dissipative Structures live here.
System
Useful Work Reservoir



ISOLATED SYSTEM BOUNDARY
NON-IMMEDIATE SURROUNDINGS
Non-Immediate Environment
Immediate Environment
Reference Environment
Dissipative Structures live here.
Dissipative Structures live here too
System
Useful Work Reservoir

Remember

- Do not ignore the environment.
- Exergy destruction (or energy degradation) necessitates that one deals with the environment.

New Thought

Think
Degrative Structures
& Gradients

not
Dissipative Structures

Generalized Exergy

Generalized Exergy

EXERGY = Maximum Useful
To-the-dead-state Work

Generalizations:

1. Environment properties may change.
2. Introduces exergy types.

Exergy Types

1. Intrinsic Exergy	Exergy within system
2. Transport Exergy	Adds SSSF
3. Restricted Exergy	Adds access restriction
4. Accessible Exergy	Adds inaccessibility
5. Restricted-Access Exergy	
6. Extracted Exergy	Actual work
7. Hidden Exergy	Unknown exergy

Energy Quality Issues

The following four issues are not found in non-generalized exergy analyses:

1. Existence of Different Dead States,
2. Ability to Change Dead States,
3. Time, Space, and Structure Restrictions, and
4. Accessibility to *Gradients*.

Exergy Destruction Principle

Exergy Destruction Principle

Ecosystems strive to maximize their utilization of exergy.

"Nature abhors a gradient"

Ecosystems, urban systems, climate systems, etc. are complex thermodynamic systems that should be influenced by the exergy destruction principle.

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Ecosystems are complex thermodynamic systems that degrade energy more effectively the further they are out of equilibrium (i.e., more developed).

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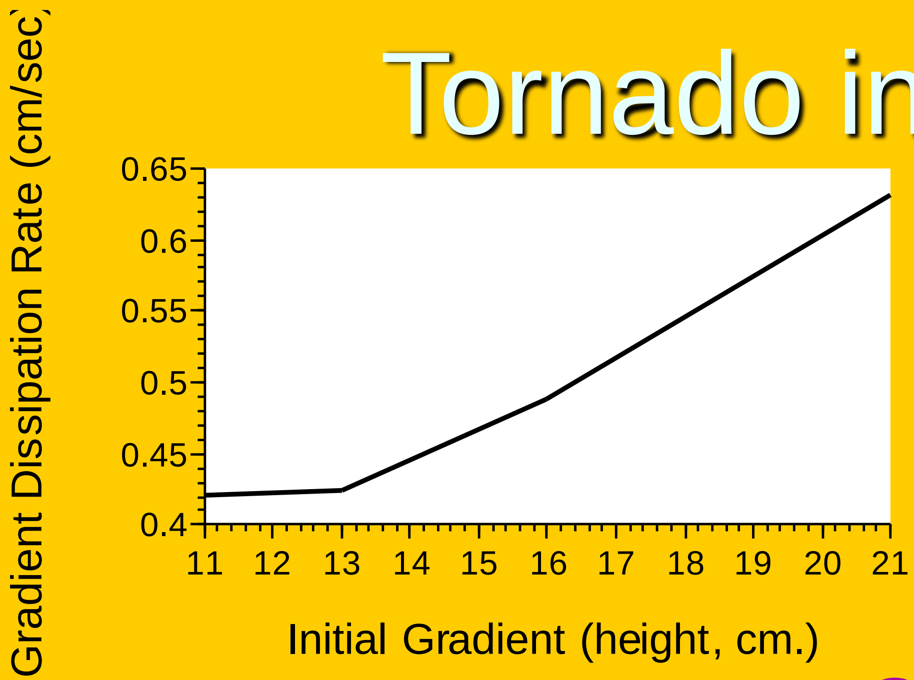
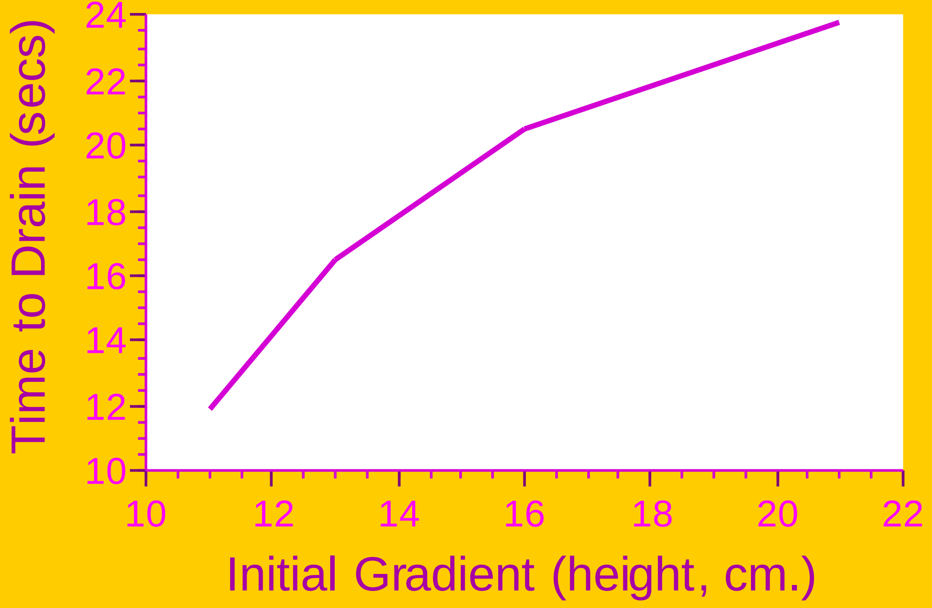
A BLACK BOX Principle

Self-organizing dissipative systems

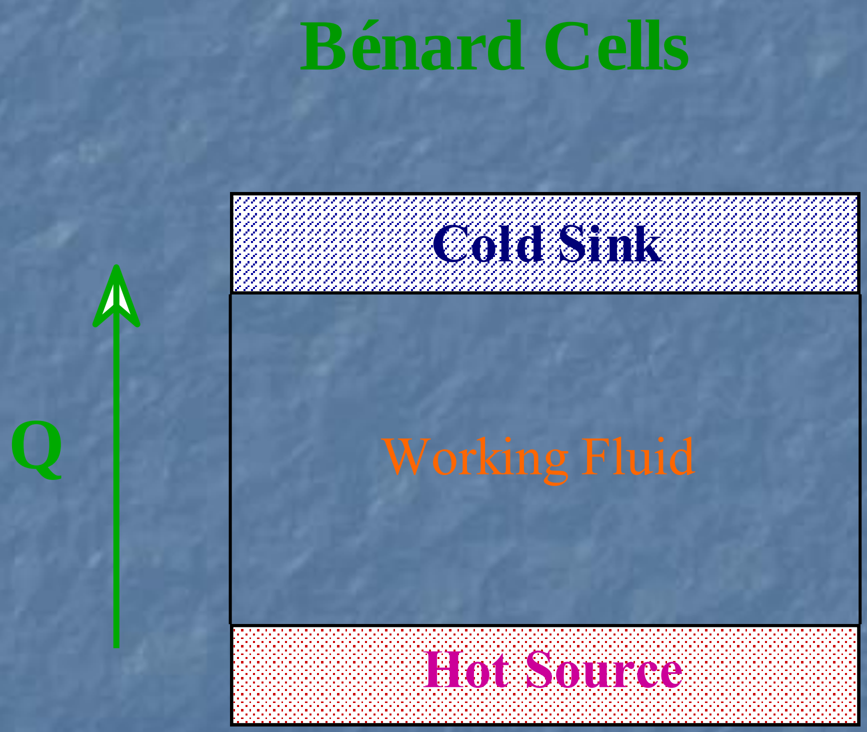
Tornado in the bottle

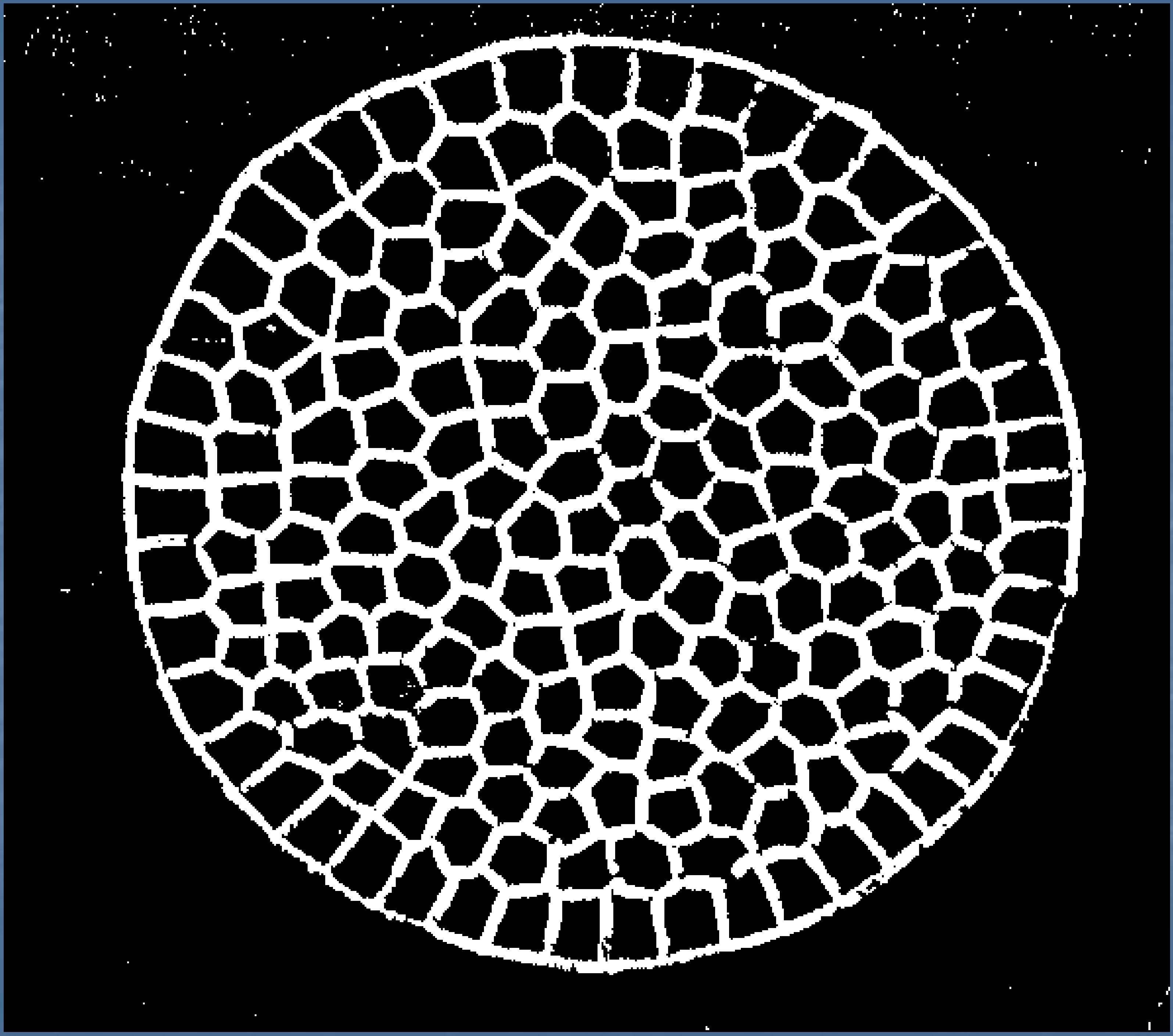
Tornado in the bottle

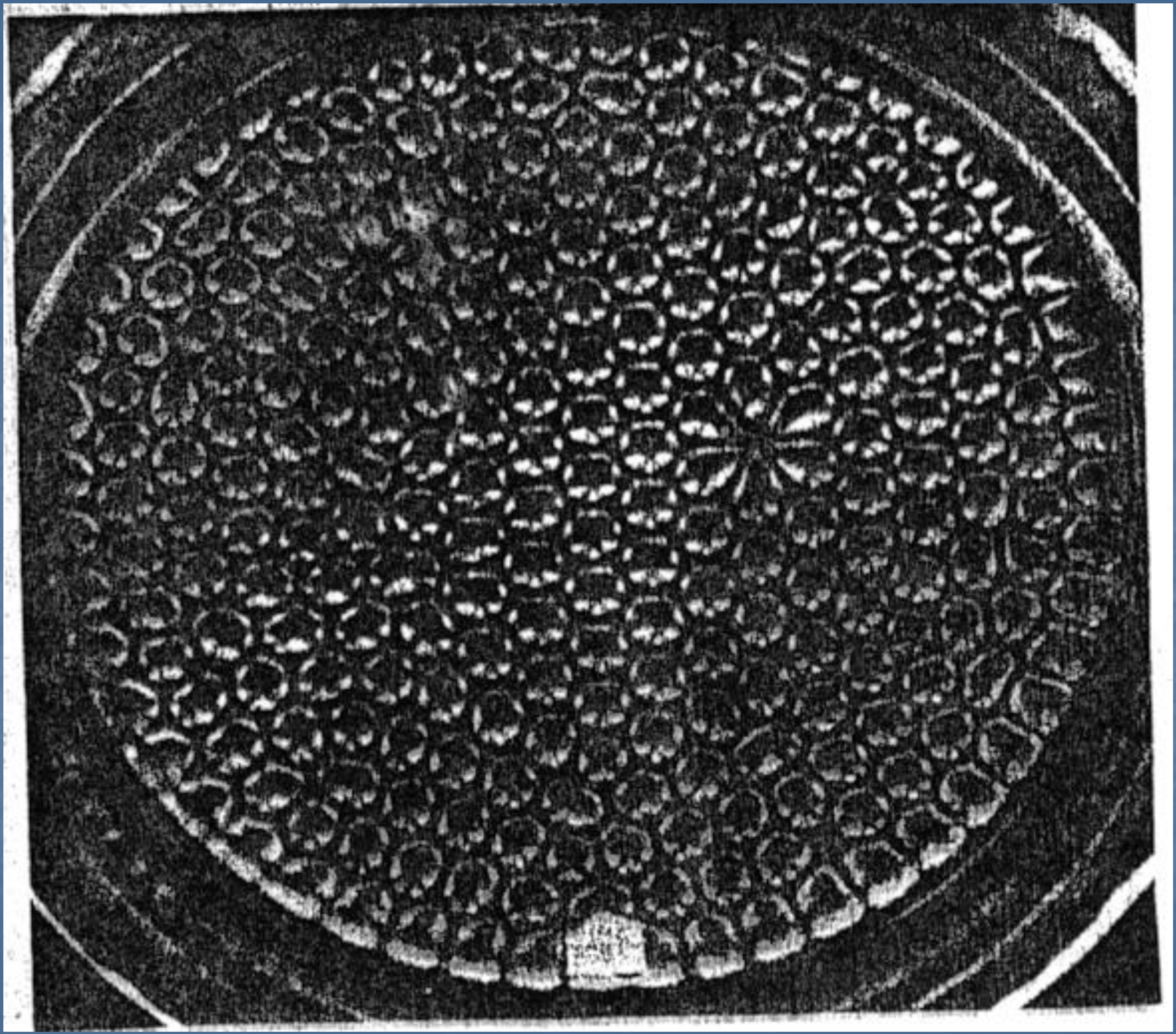




Benard Cells







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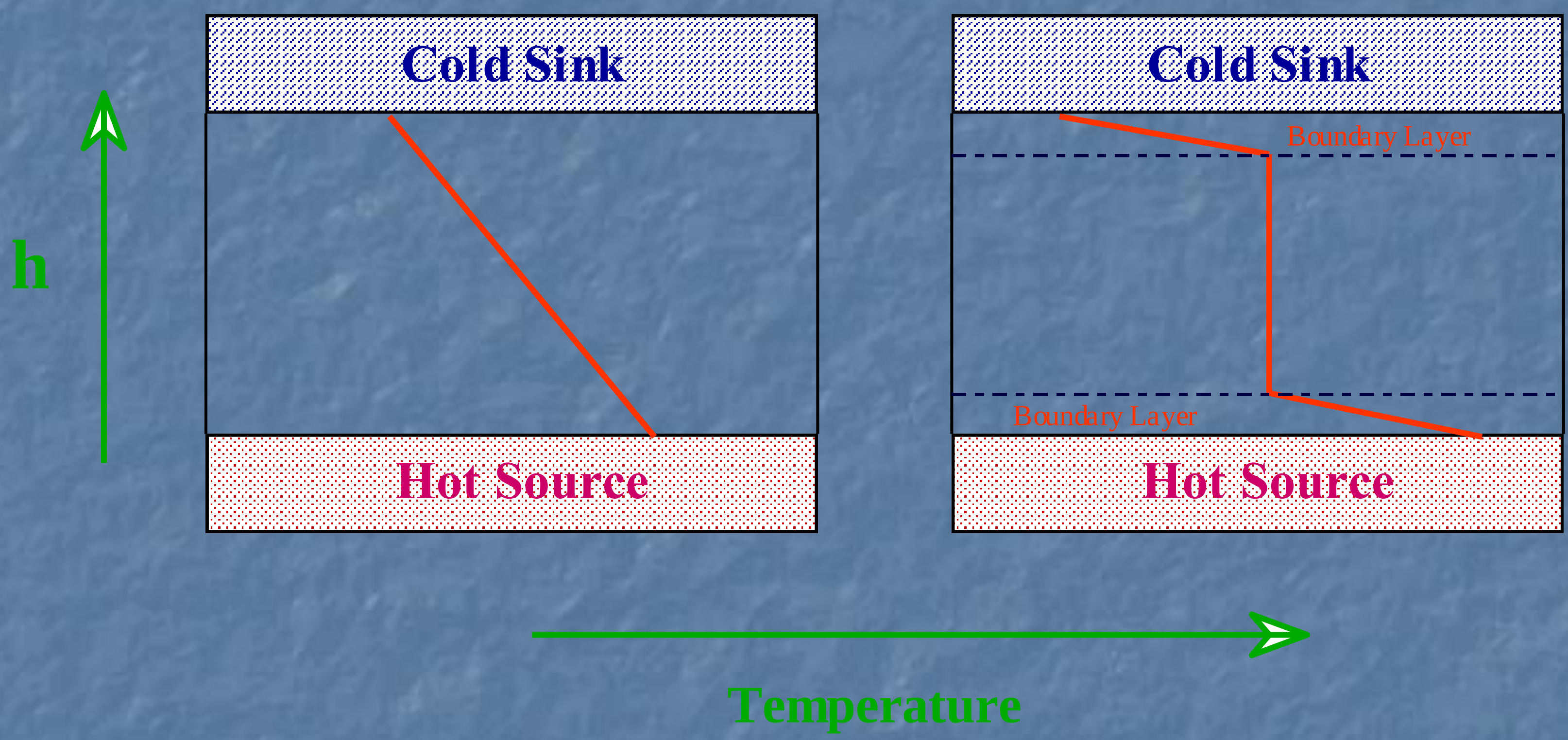
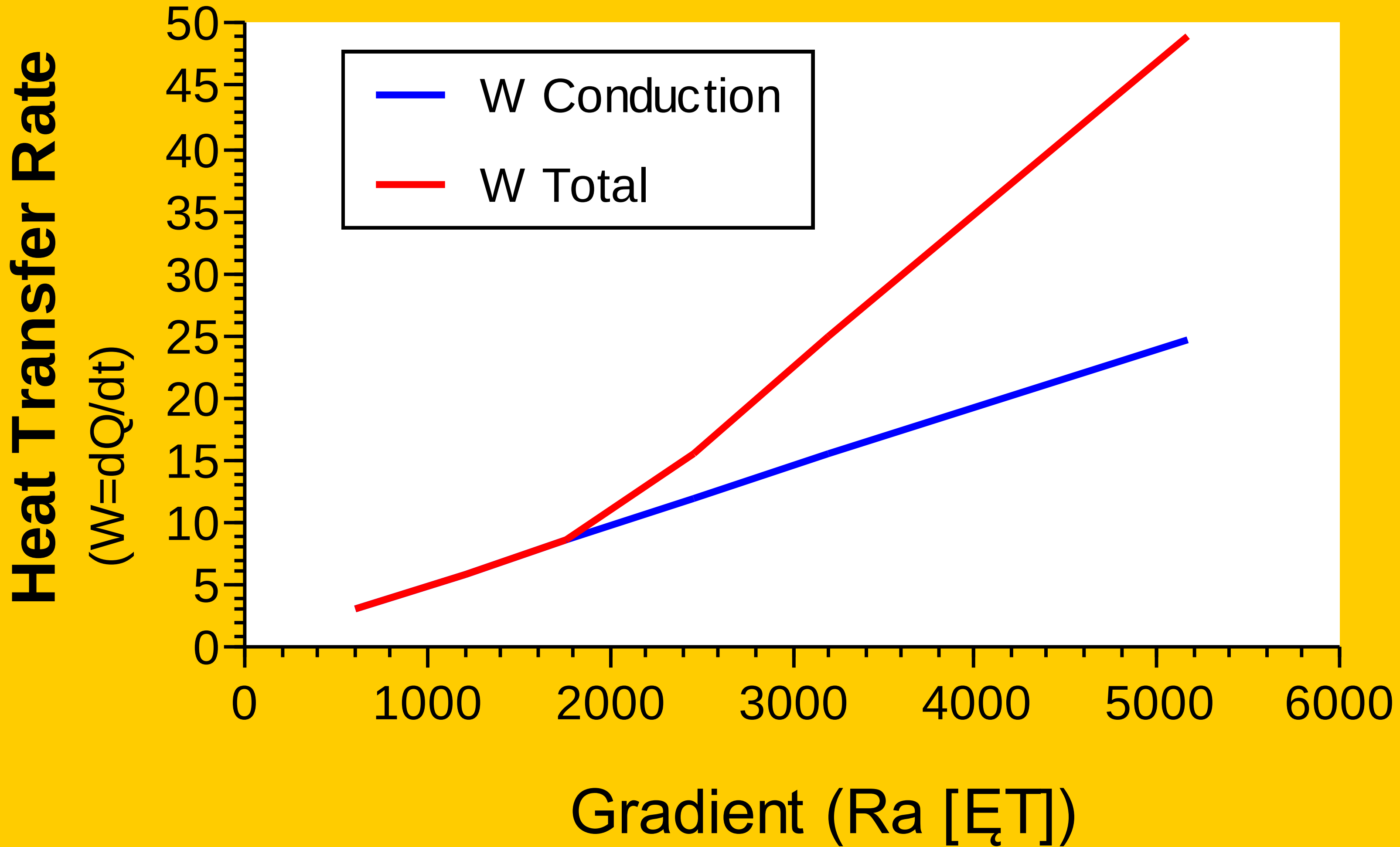
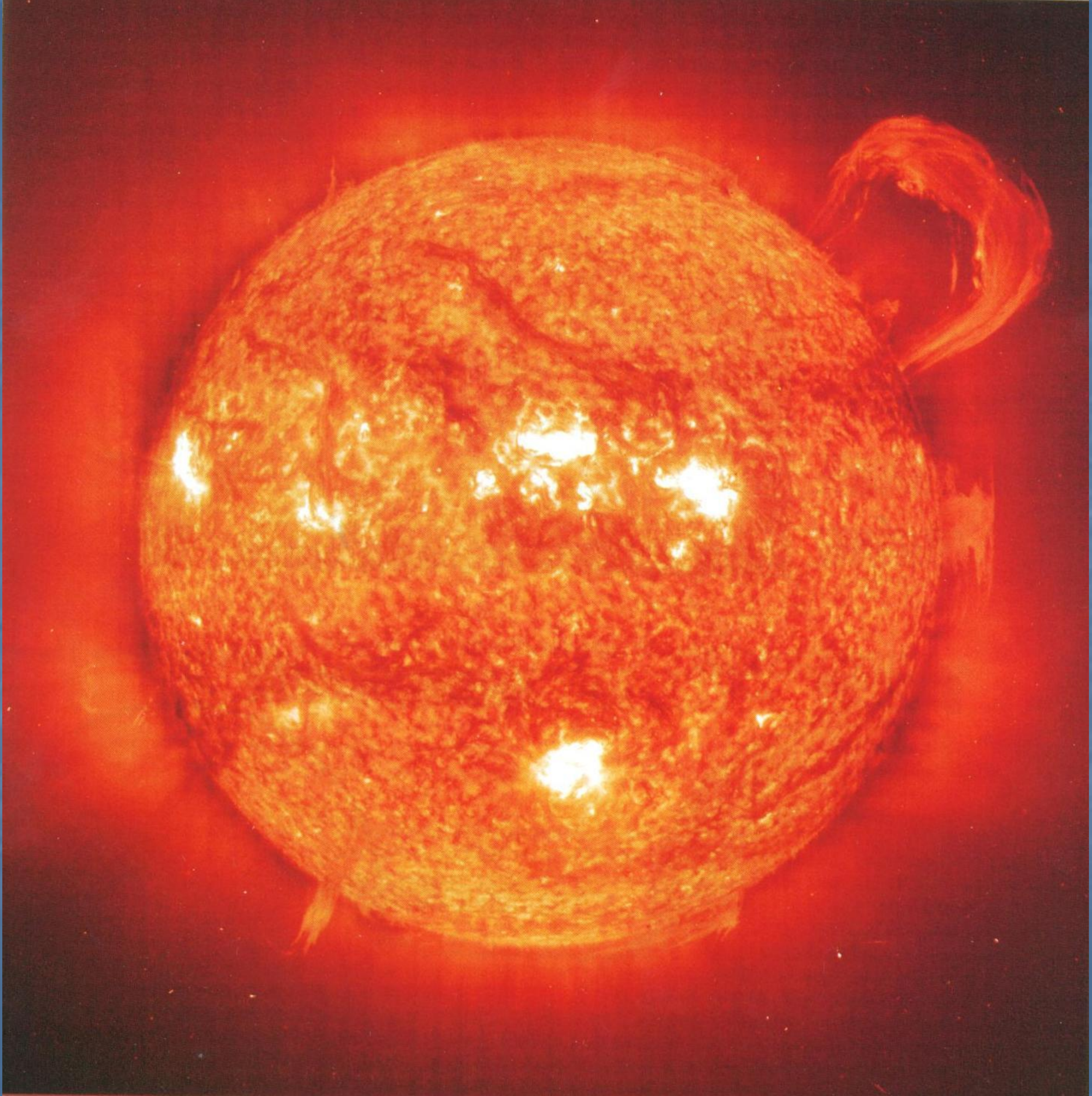


Bénard Cells (Heat Transfer)



Surface Temperature and Ecosystem Development



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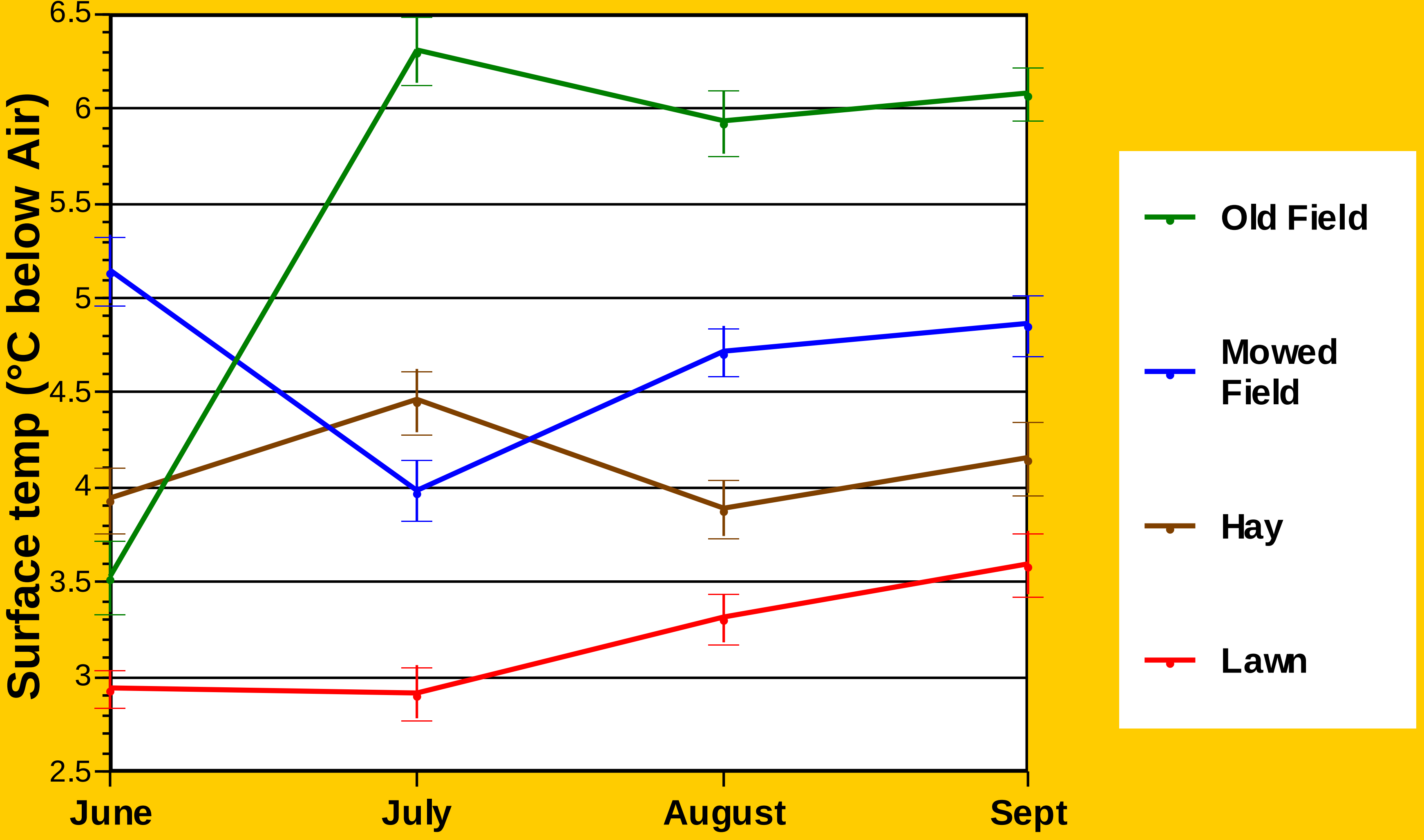
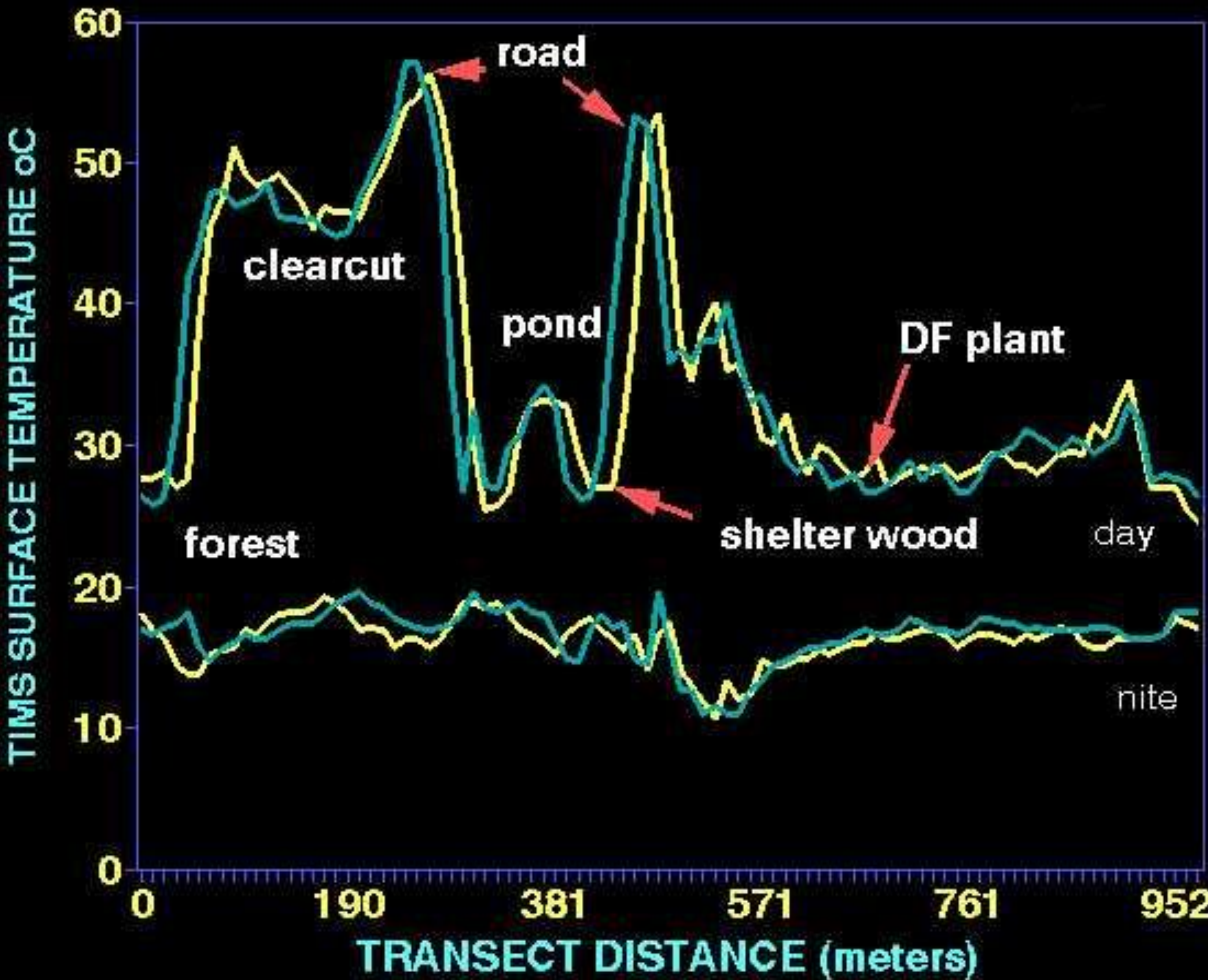
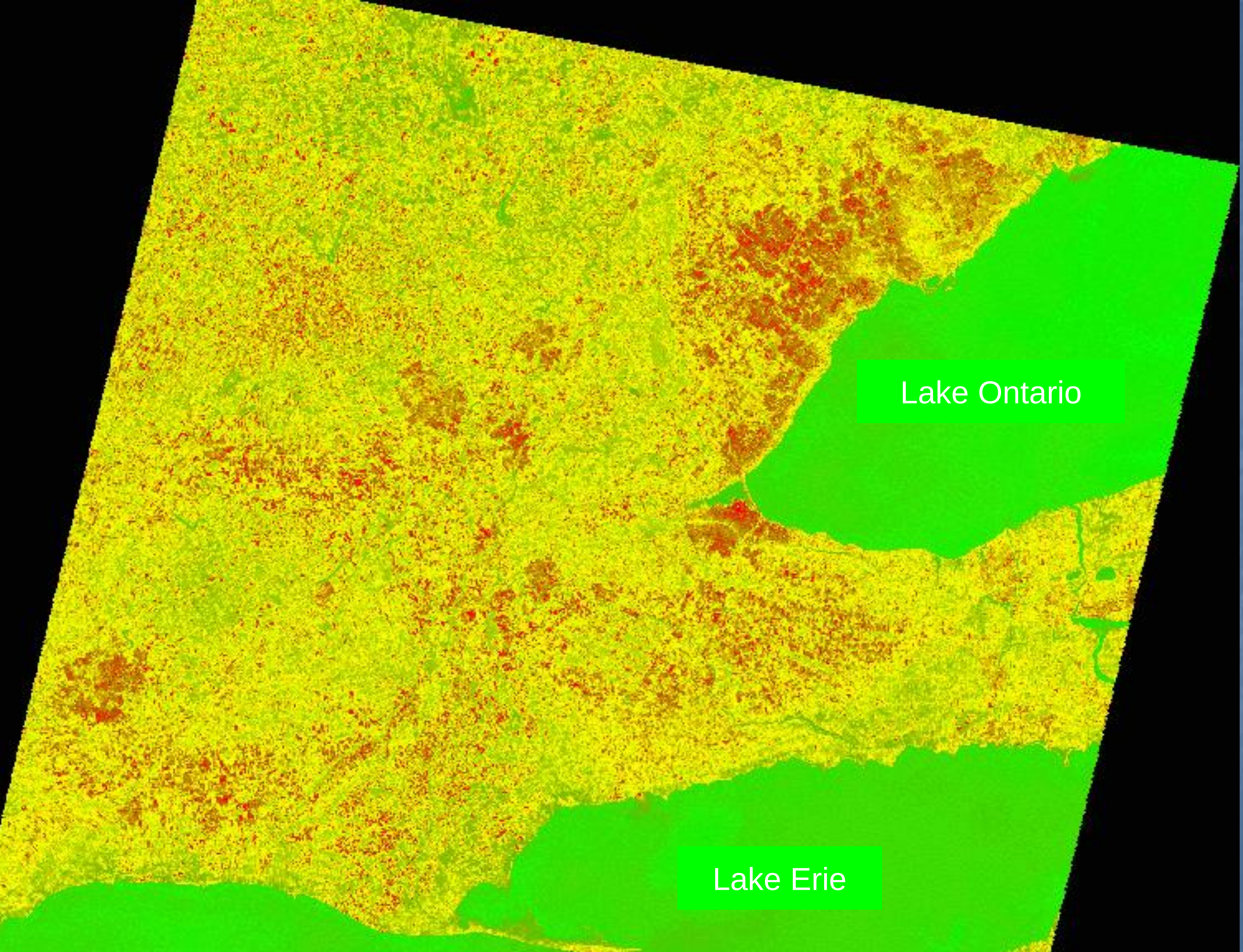
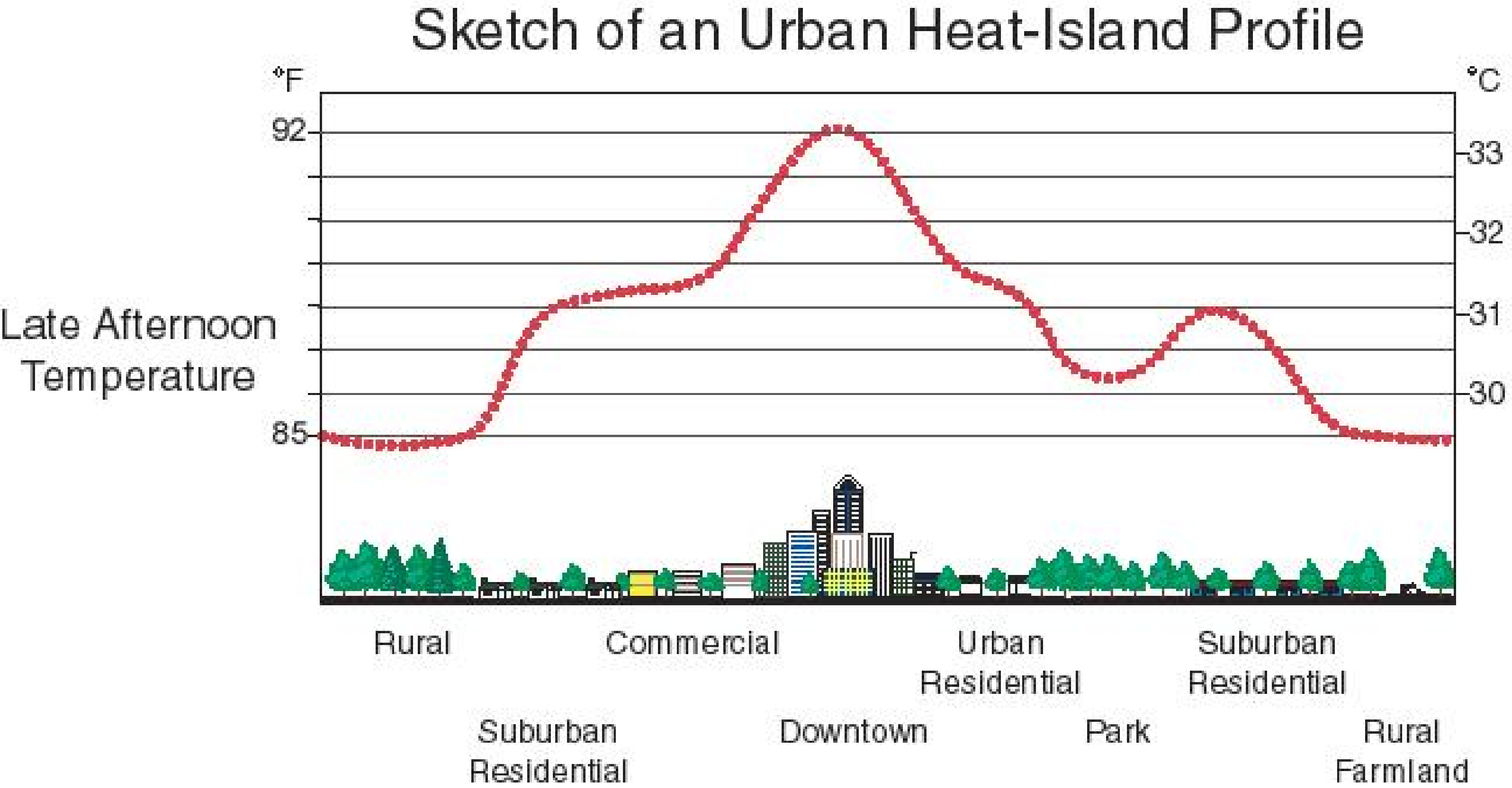




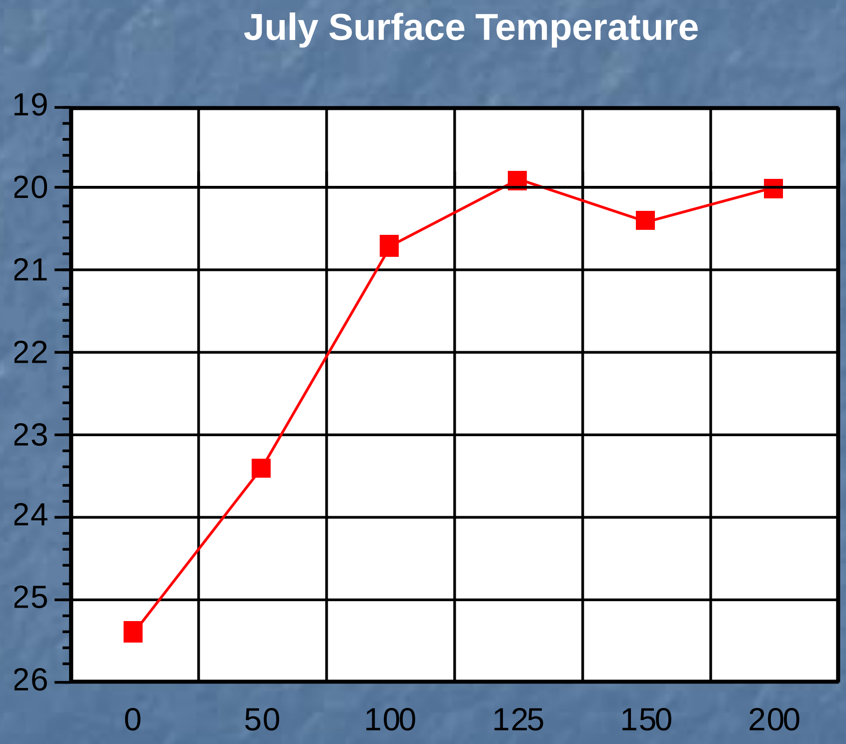
TIMS SURFACE TEMPERATURE oC
60
50
40
30
20
10
0
road
clearcut
pond
DF plant
shelter wood
forest
day
nite
0
190
381
571
761
952
TRANSECT DISTANCE (meters)

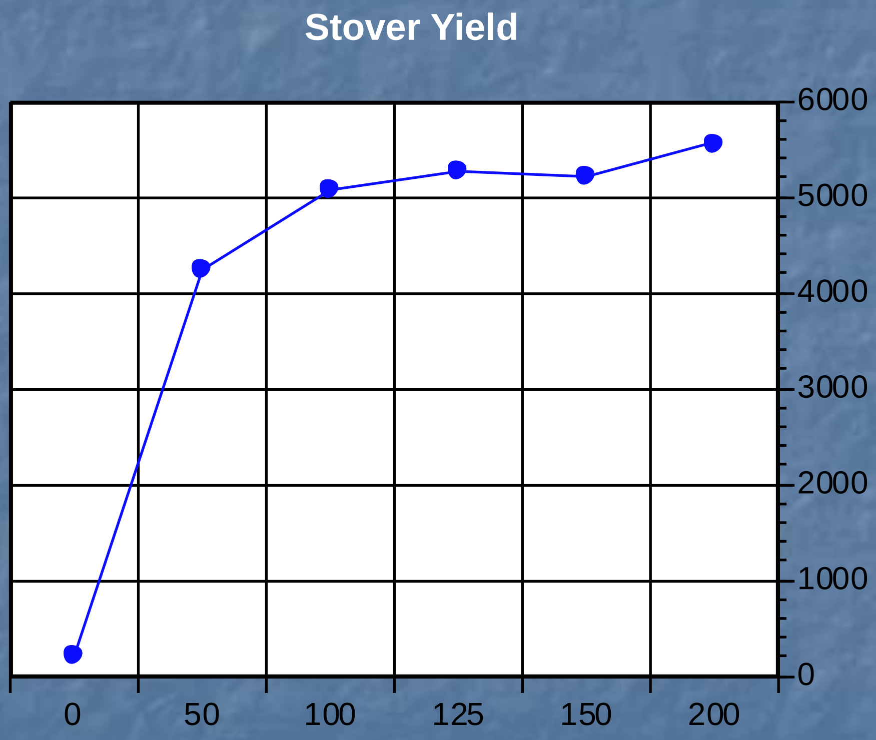

Lake Ontario
Lake Erie

Cooling cities



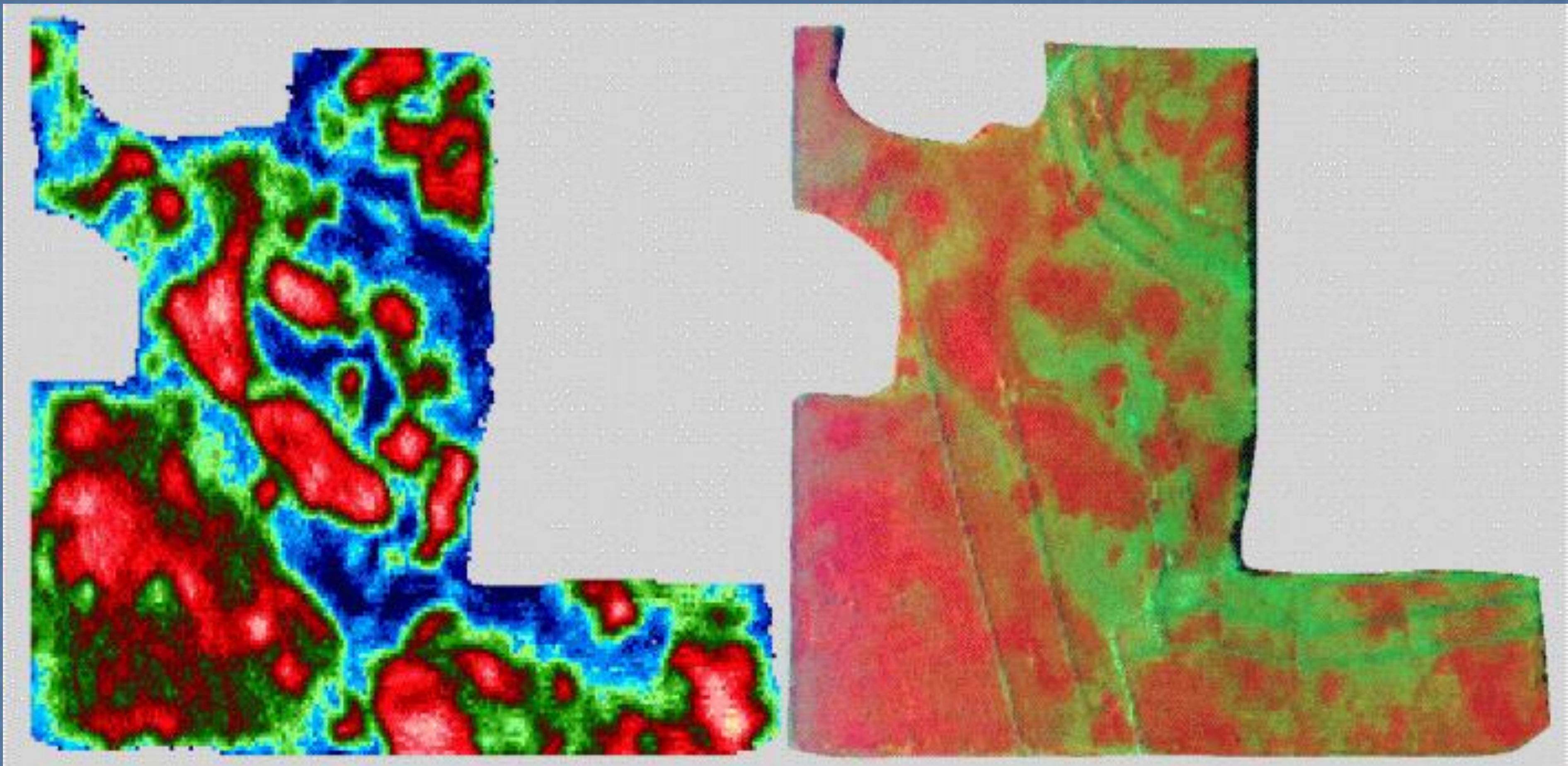
Surface temperature vs fertilizer application (Akbari et al)





Nitrogen applied kg/ha

Corn yield from remote sensing



Harvested September, 1998 June 26, 1998

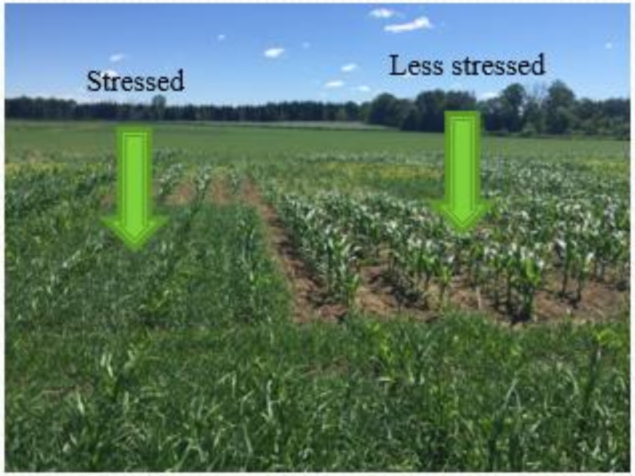
Thermal Band correlation > 0.86

D. Rickman, et al., 1999

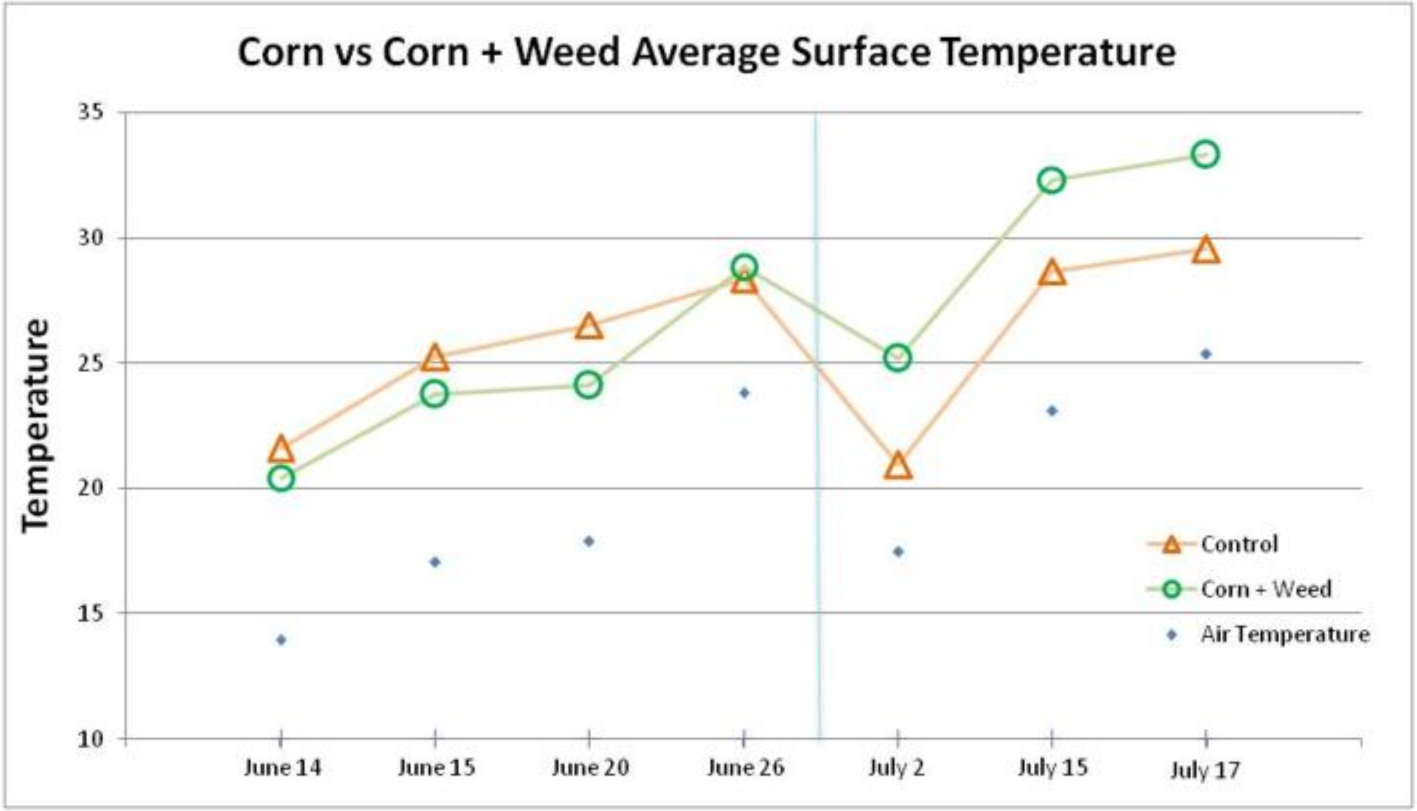
Control & with Weeds

A visual difference between stressed and less stressed plants with weed in Woodstock (ON, Canada) weed trial

June 8^{th} , 2016

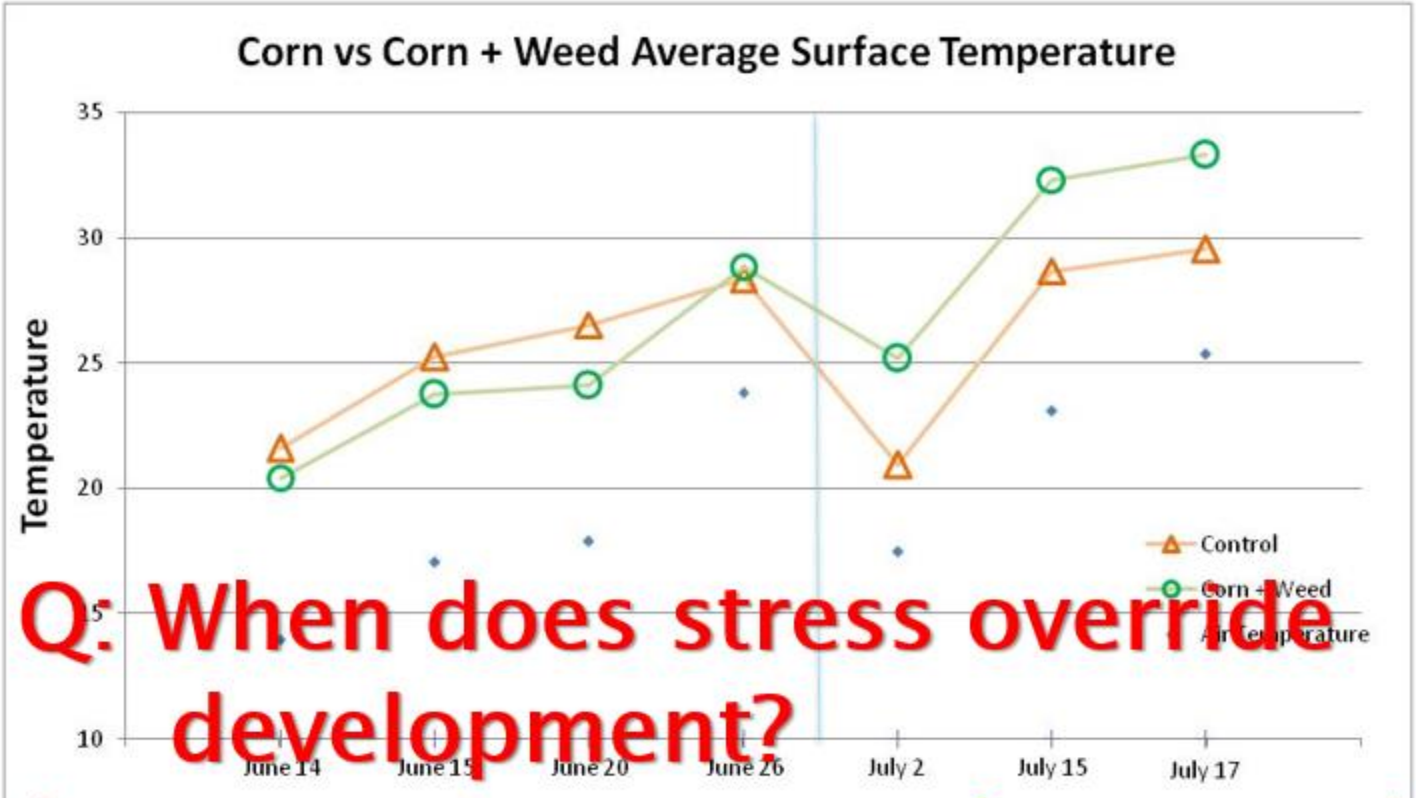


June 22^{nd} ,2016



Corn vs Corn + Weed Average Surface Temperature
Temperature
35
30
25
20
15
10
June 14
June 15
June 20
June 26
July 2
July 15
July 17
Control
Corn + Weed
Air Temperature

2015



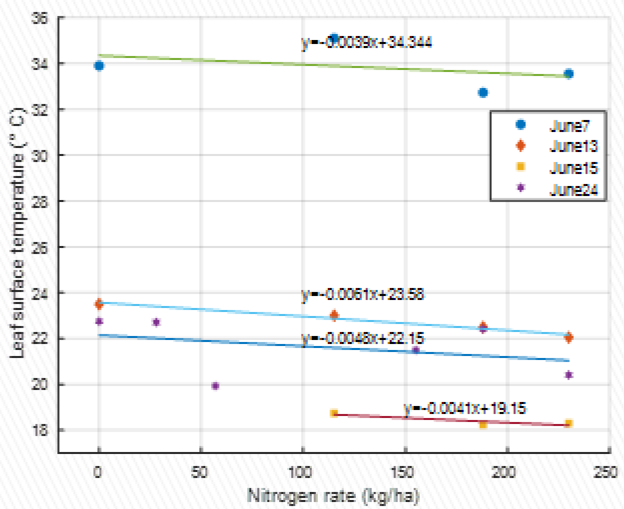
Q: When does stress override development?

(crops are not natural systems)

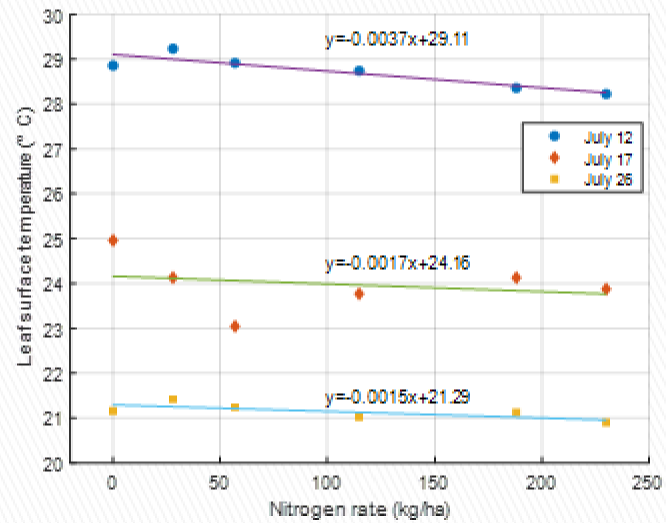
2015

Footer

Mean Leaf Surface Temperature Different Days – Elora, 2017

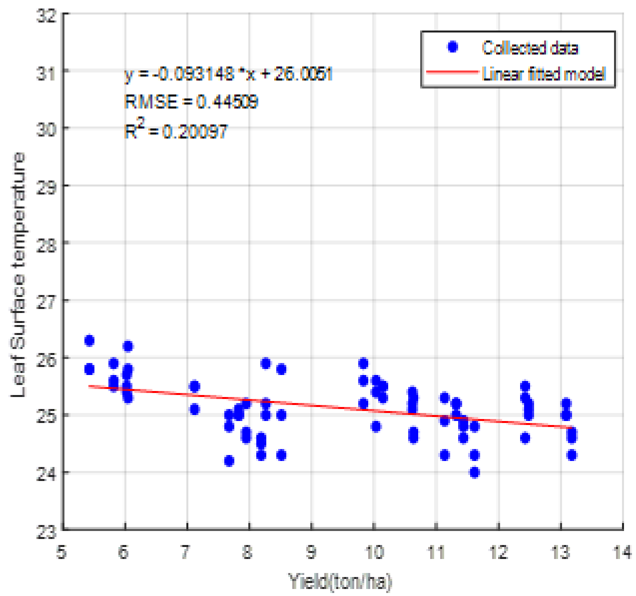


June, 2017

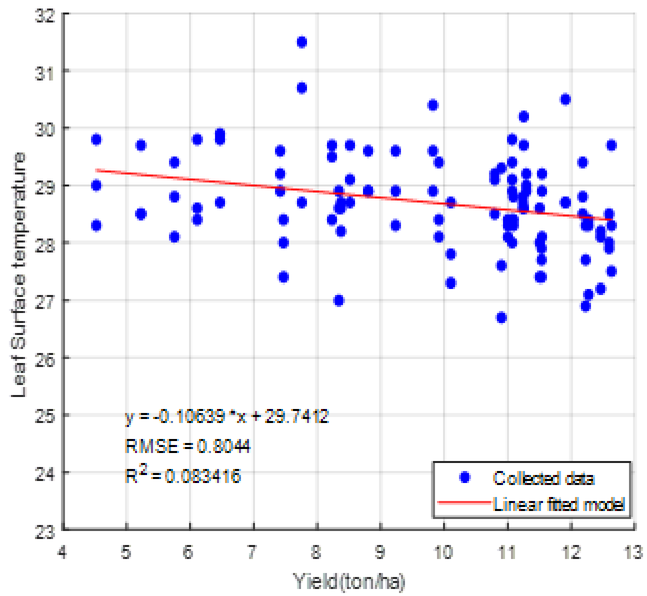


July, 2017

Leaf Temperature Decrease as Yield Increases 2016 and 2017

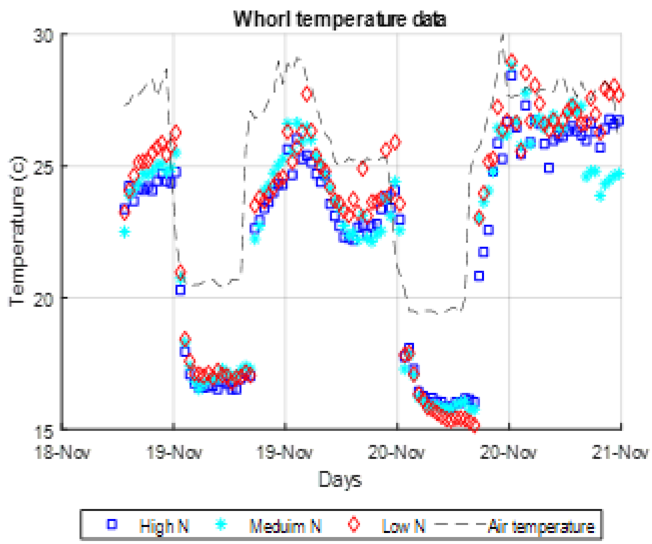


June 6th, 2016

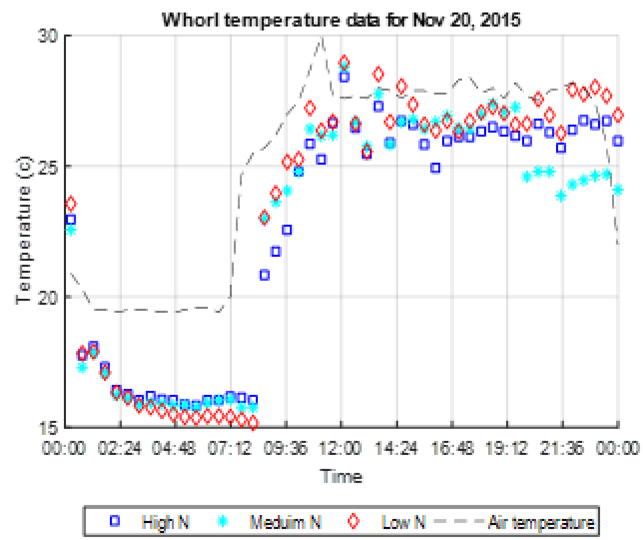


July 12th, 2017

Whorl Temperature Trend Flips with Day vs Night



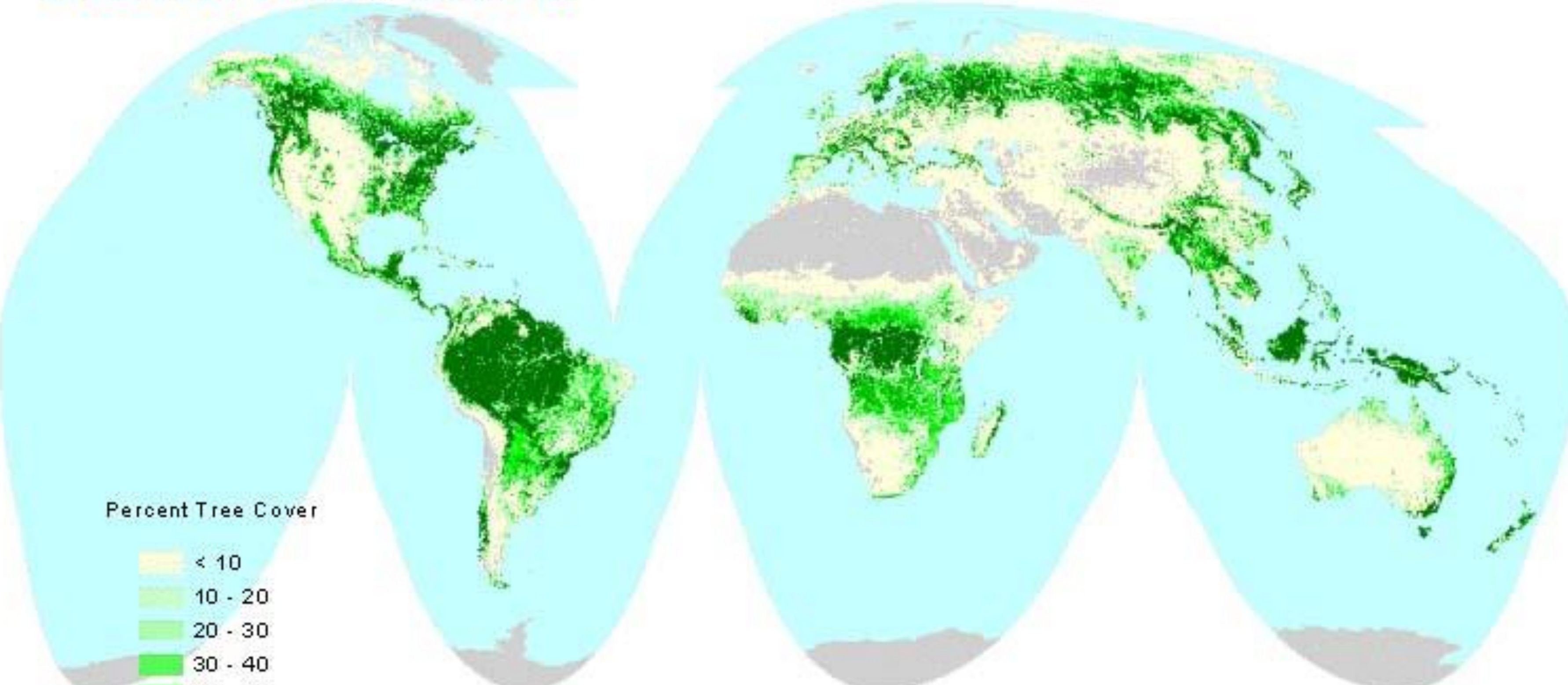
3 days data



One day data

WRI Pilot Analysis of Global Ecosystems:

Global Tree Cover

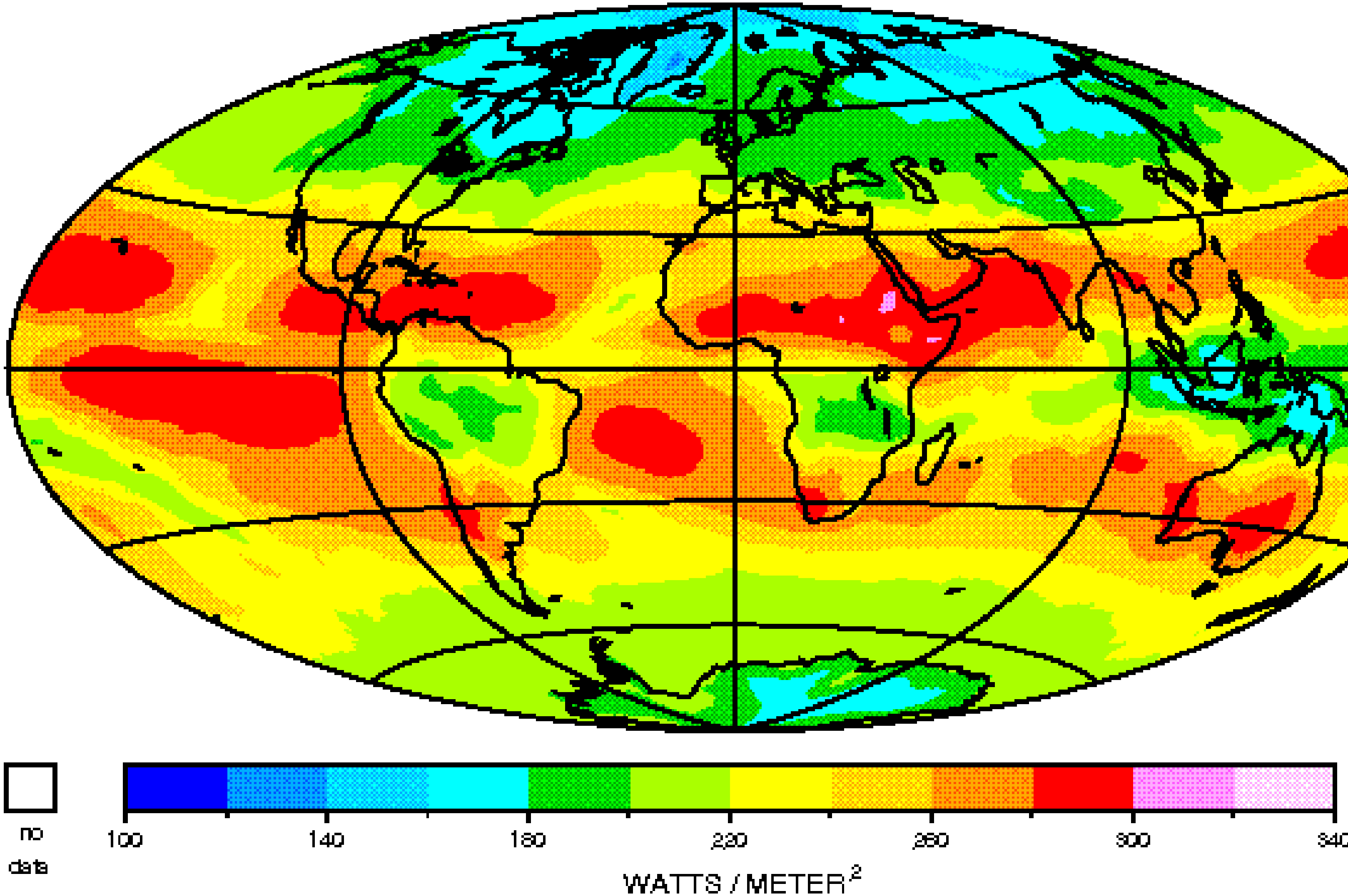


The area of transition between forest and other land cover is one of the most dramatic portions of forest ecosystems and makes up a significant fraction of forest ecosystems in many parts of the world.

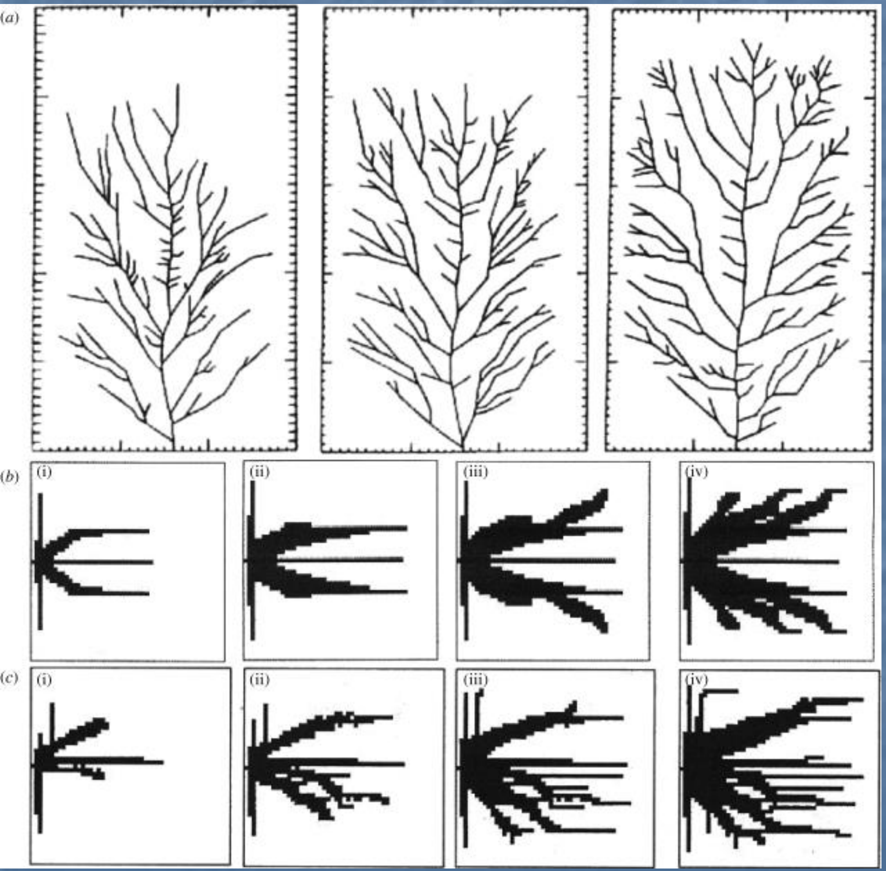
Source: DeFries, R., Hansen, M.C., Townshend, J.R.G., Janetos, A.C., and Loveland, T.R. 2000. A New Global 1-km Dataset of Percentage Tree Cover Derived from Remote Sensing. Global Change Biology, Vol. 6, pp. 247-254.

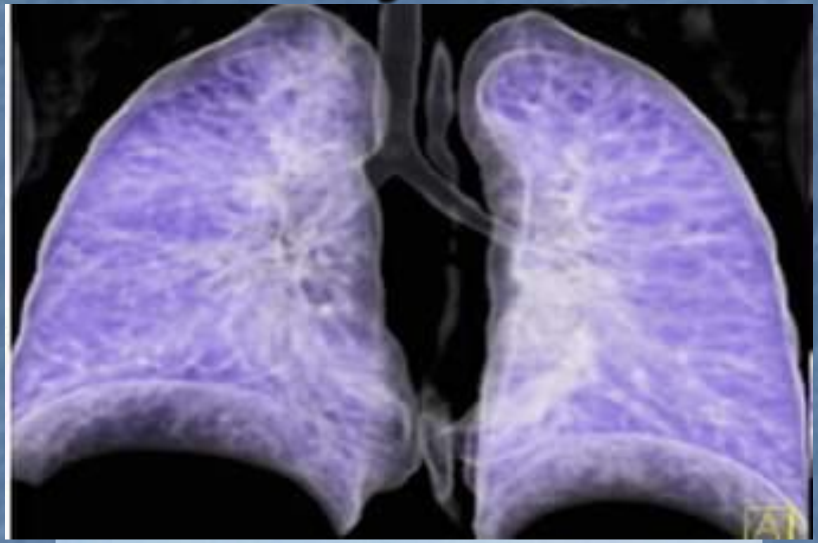
LONGWAVE RADIATION

ERBS + NOAA9 JANUARY 1986



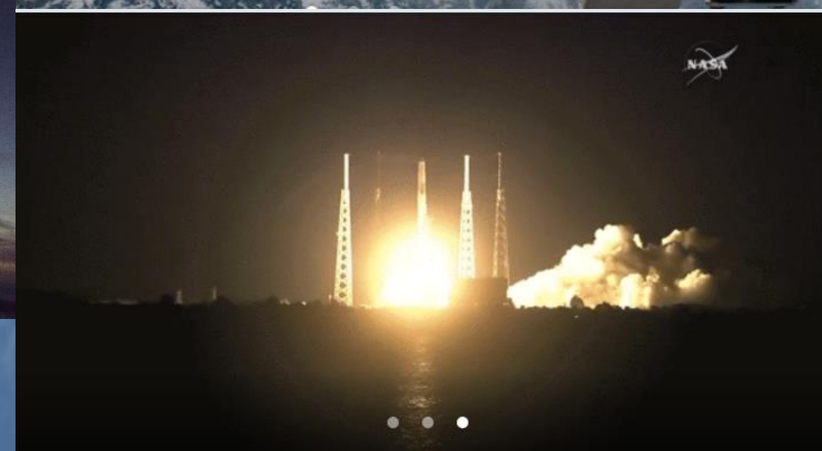
Contructal Theory





https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2871904/

ECOSTRESS
New Space Station IR Camera



https://www.jpl.nasa.gov/news/news.php?feature=7179

Energy Quality Issues

The following four important issues are not found in non-exergy energy analysis:

1. Existence of Different Dead States,
2. Ability to Change Dead States,
3. Time, Space, and Structure Restrictions, and
4. Accessibility to Gradients.

Properties of Complex Systems

- Propensities: As self-organizing systems are moved away from equilibrium they become organized:
  - they use more exergy
  - they build more structure
  - this happens in spurts as new attractors become accessible
  - it becomes harder to move them further away from equilibrium
- Window of Vitality: Must have enough complexity but not too much. Complex systems strive for optimum attractor, not minimum or maximum.
- Window of Viability: A system looses robustness if too efficient or too inefficient.

Properties of Complex Systems

- Hierarchical: The system is nested within a system and is made up of systems. Such nestings cannot be understood by focusing on one hierarchical level (holon) alone. Understanding comes from the multiple perspective of different types and scale.
- Multiple steady states: There is not necessarily a unique preferred system state in a given situation. Multiple attractors can be possible in a given situation and the current system state may be as much a function of historical accidents as anything else.

Properties of Complex Systems

- Dynamically Stable? equilibrium points may not exist for the system.
- Catastrophic Behaviour: The norm
  - Bifurcations: moments of unpredicable behaviour.
  - Flips: sudden discontinuities, rapid change.
  - Holling Four Box ∞: Shifting steady state mosaic
- Chaos Theory: our ability to forecast and predict is always limited regardless of how sophisticated our computers are and how much information we have.

Problematique of Complexity

- Irreducible uncertainty
- Multiple attractors
- Hierarchical (scale and type)
    - Multi scale
    - Multiple perspectives
    - Nested

- Do not confuse complicated with complex

Realities of Complexity

- We must deal with irreducible uncertainty, emergence and surprise, the lack of a preferential perspective, and the reality that life is a trade-off.

Possibilities not predictions

Dissipation vs Destruction

- Dissipation is a microscopic 2nd Law measure involving a system-centric viewpoint.
- Degradation is a macroscopic 2nd Law measure involving environment information.

New Thought

Think

Degrative Structures

& Gradients

not

Dissipative Structures

THE END

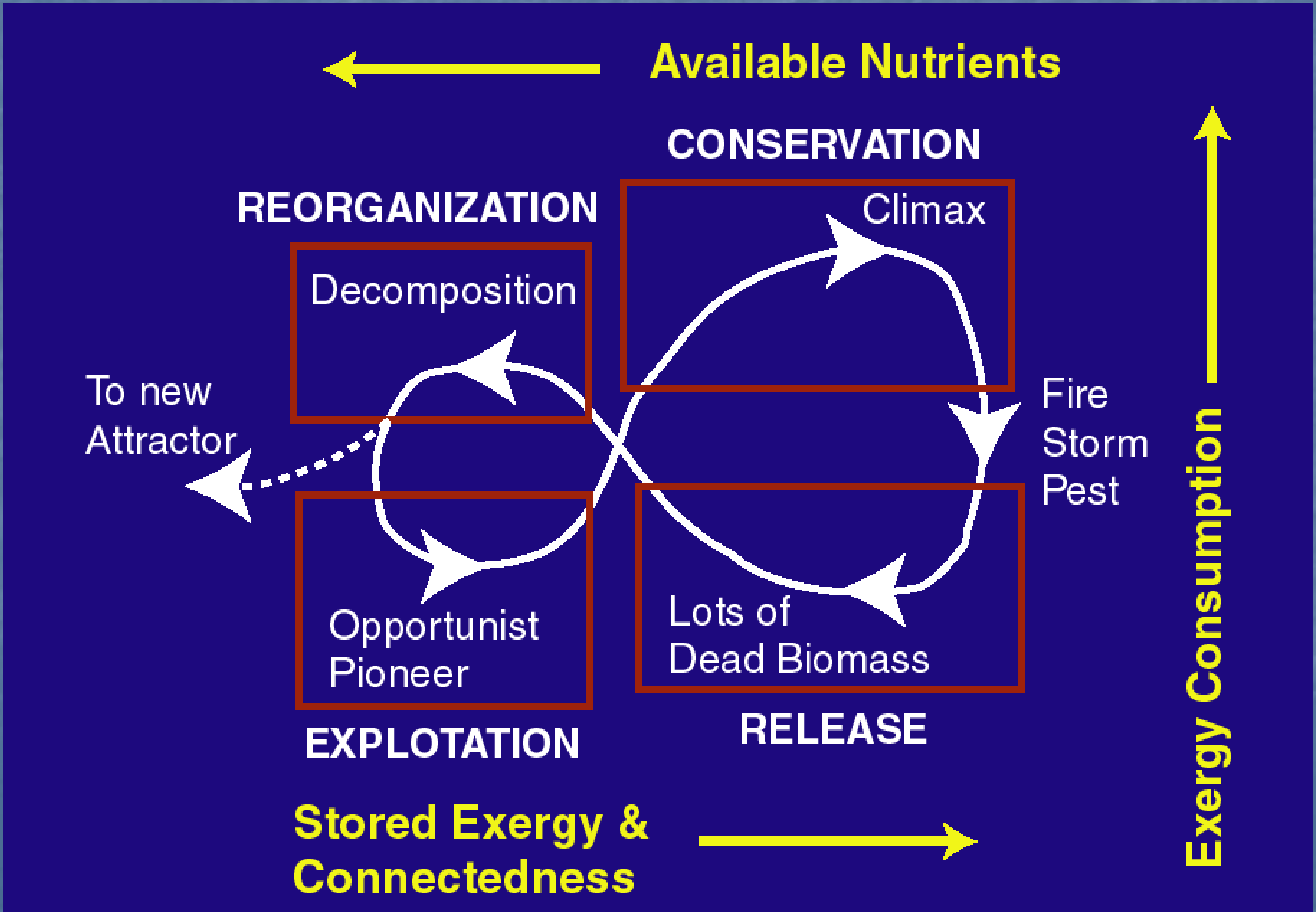
Learning From Each Other

- Engineering Learning from Ecology
  - Intrinsic Exergy
  - Transport Exergy
  - Restricted Exergy
  - Accessible Exergy
  - Restricted-Access Exergy
  - Extracted Exergy
- Ecology Learning from Engineering
  - Energy Dissipation
  - Energy Degradation
  - Energy Partitioning

Restrictions and Accessibility

- Restrictions exist when all gradients are accessible, but the method for accessing these gradients is restricted.
  - Diesel Engine vs Stirling Engine
  - Non-Flow and Flow Exergy
- Accessibility limitations exist when direct access to some, but not all, gradients exists.
  - Champagne
  - Coal Fired Power Plant

Holling Four Box (∞)



Holling Four Box (∞)