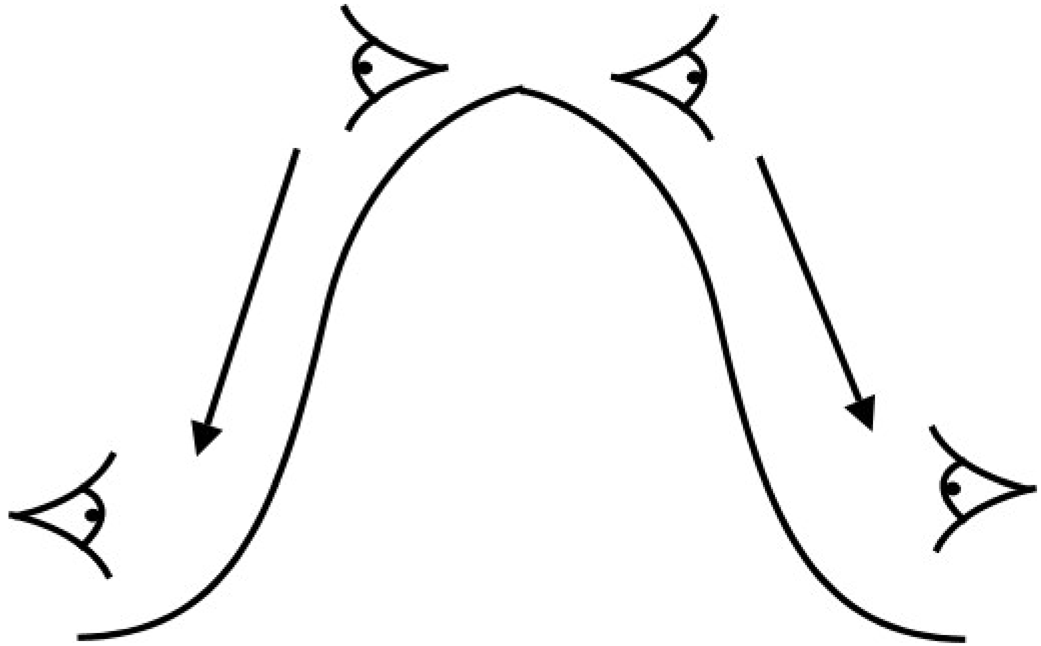
# Agents and Arrows

## (some things statistical mechanics cannot possibly explain)



"For the universe, the two directions of time are indistinguishable, just as in space there is no up and down. However, just as at a particular place on the earth's surface we call 'down' the direction toward the center of the earth, so will a living being in a particular time interval of such a single world distinguish the direction of time toward the less probable state from the opposite direction (the former toward the past, the latter toward the future)."

*Boltzmann, 1895*

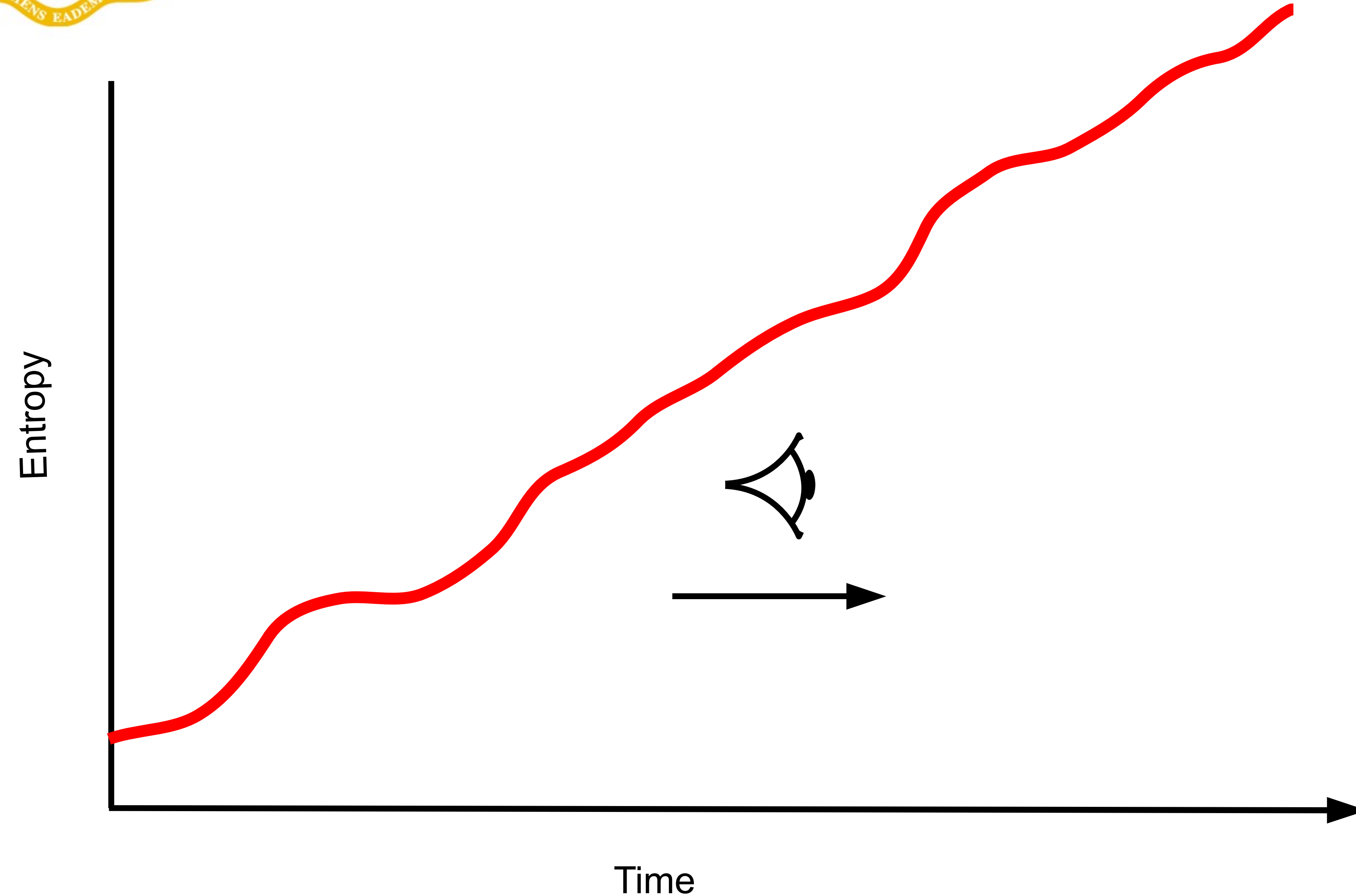
# Outline

- Arrows and Agents: defining the question.
  - Entroy increasing and decreasing universes.
- Agents as IGUS: Memory and computation
  - The suggestion has been made that, whatever else agents might be, their internal processes are like a computer, and this gives them an inherent alignment with the thermodynamic arrow.
  - This fails: computers can operate in entropy decreasing universes
- This generalises from computers to any Quasi-Static Equilibrium States (QSES)
  - If a process can be defined solely in terms of sequences of QSES, then any asymmetry in that process cannot be thermodynamic in origin.
- Implications: macro- and micro-correlations
  - Correlations with 'the environment' come in two different kinds: micro and macro
    - Entropy increase is associated with micro-correlations.
    - Agent interactions are associated with macro-correlations.
  - Attempts to constrain agents through the 'initial condition hypothesis' seem to fail, although some evolutionary possibilities remain

# The Puzzle

- Manifest Temporal Asymmetry of Experience
  - Intervention, Memory
- Manifest Temporal Asymmetry of Thermal Processes
  - Irrecoverable conversion of heat into work
- Both seemingly *emergent, macroscopic* asymmetries
  - Fundamental microscopic laws (largely) symmetric.
  - Thermal asymmetry is believed to be well explained through a statistical mechanical 'initial condition hypothesis'
- Is this statistical mechanical asymmetry the *only* asymmetry?
  - Is the asymmetry of experience a consequence of the *same* underlying physical asymmetry?

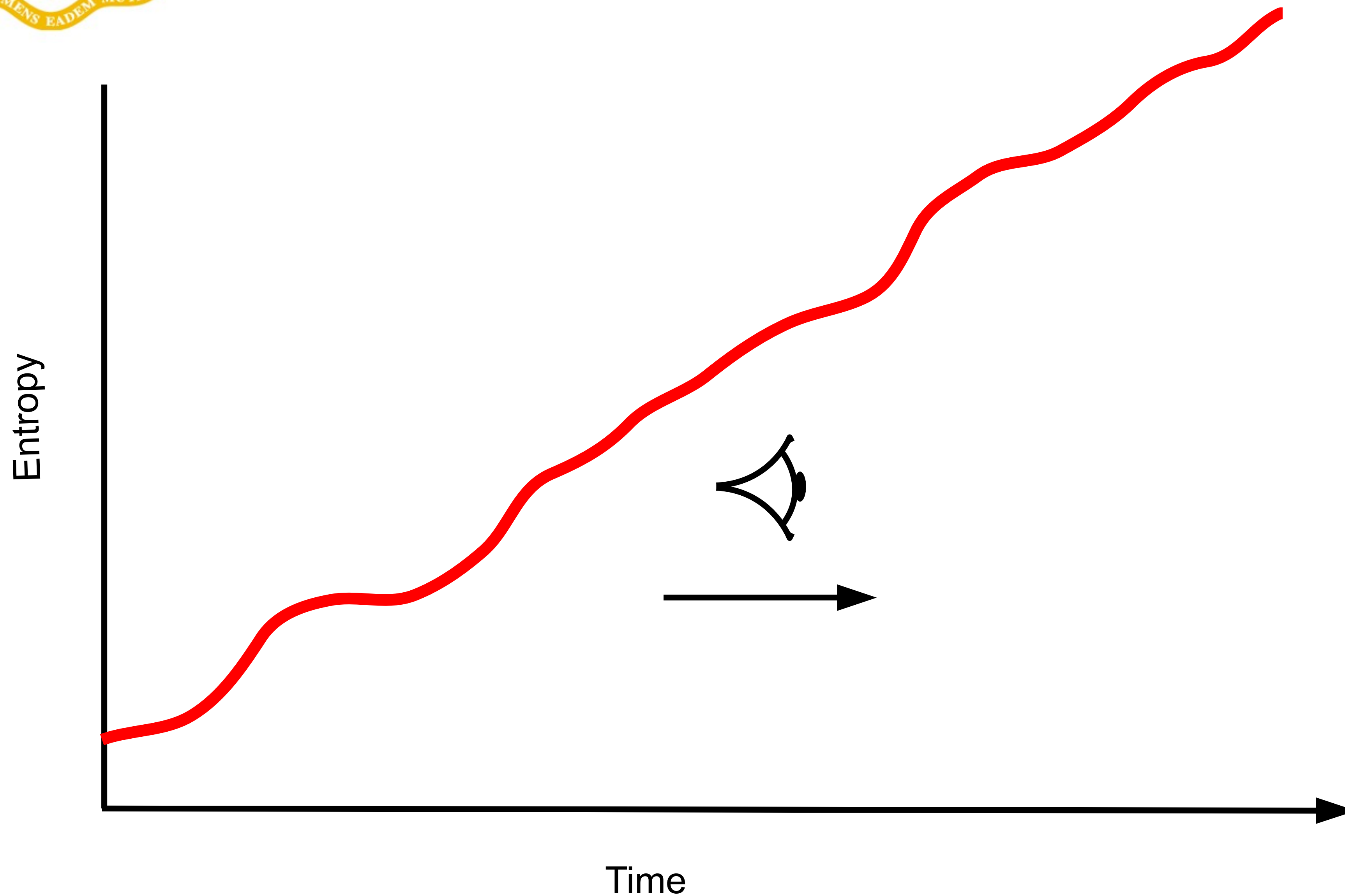
# Our World



# Entropy Increasing

- An entropy increasing universe:
  - A marked asymmetry in physical processes
    - The tendency for work to be irreversibly converted to heat.
  - An initial condition hypothesis
    - The universe started in a small, a priori unlikely, part of state space.
    - No equivalent future condition hypothesis (unless on a very large timescale in the future)
  - A present day statistical condition about interacting systems
    - No initial microscopic correlations between systems
    - Thermal systems are initially well described by the canonical distribution on the accessible state space.
    - No equivalent conditions on final statistical states.

# Different Arrows?



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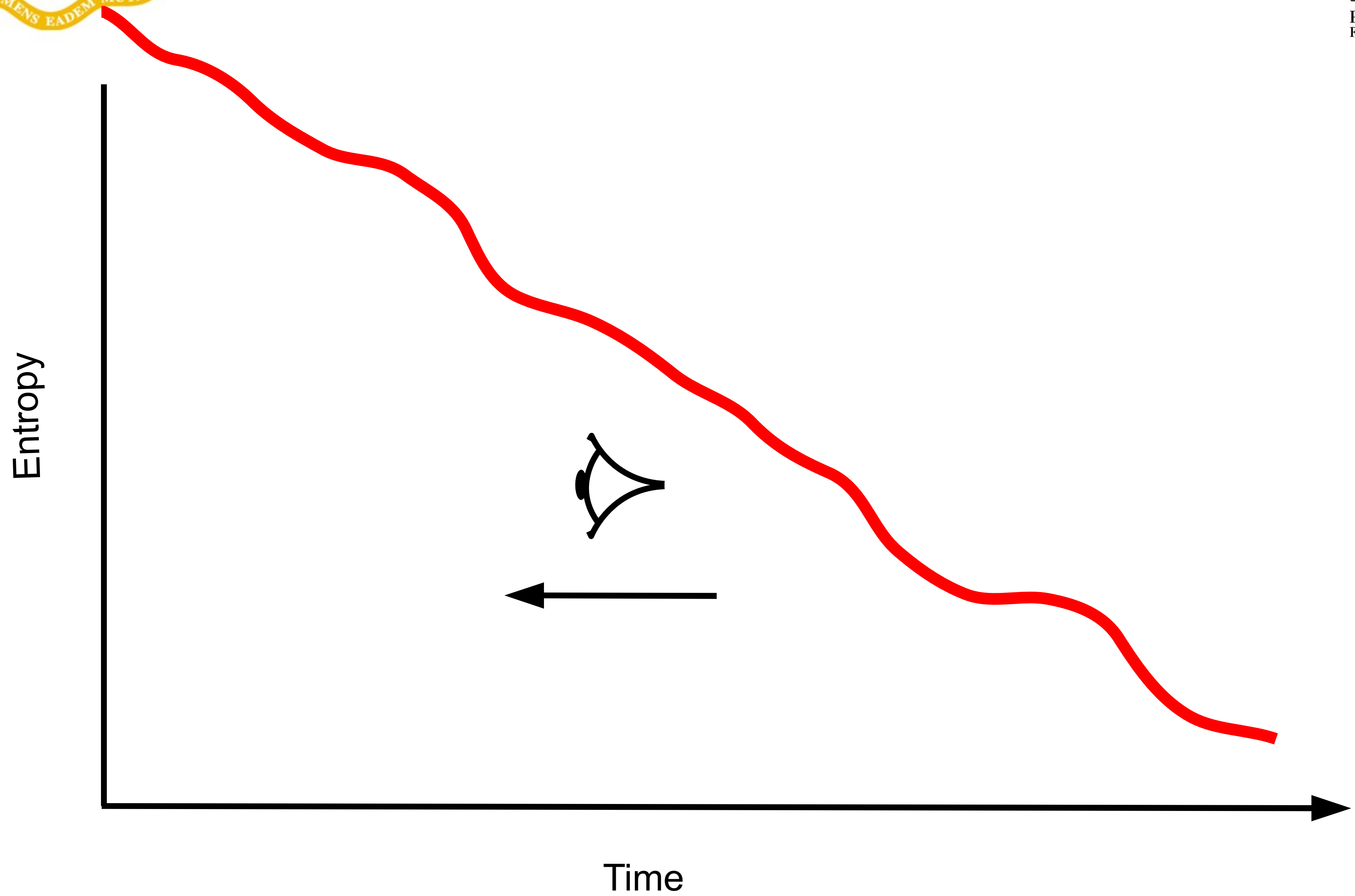

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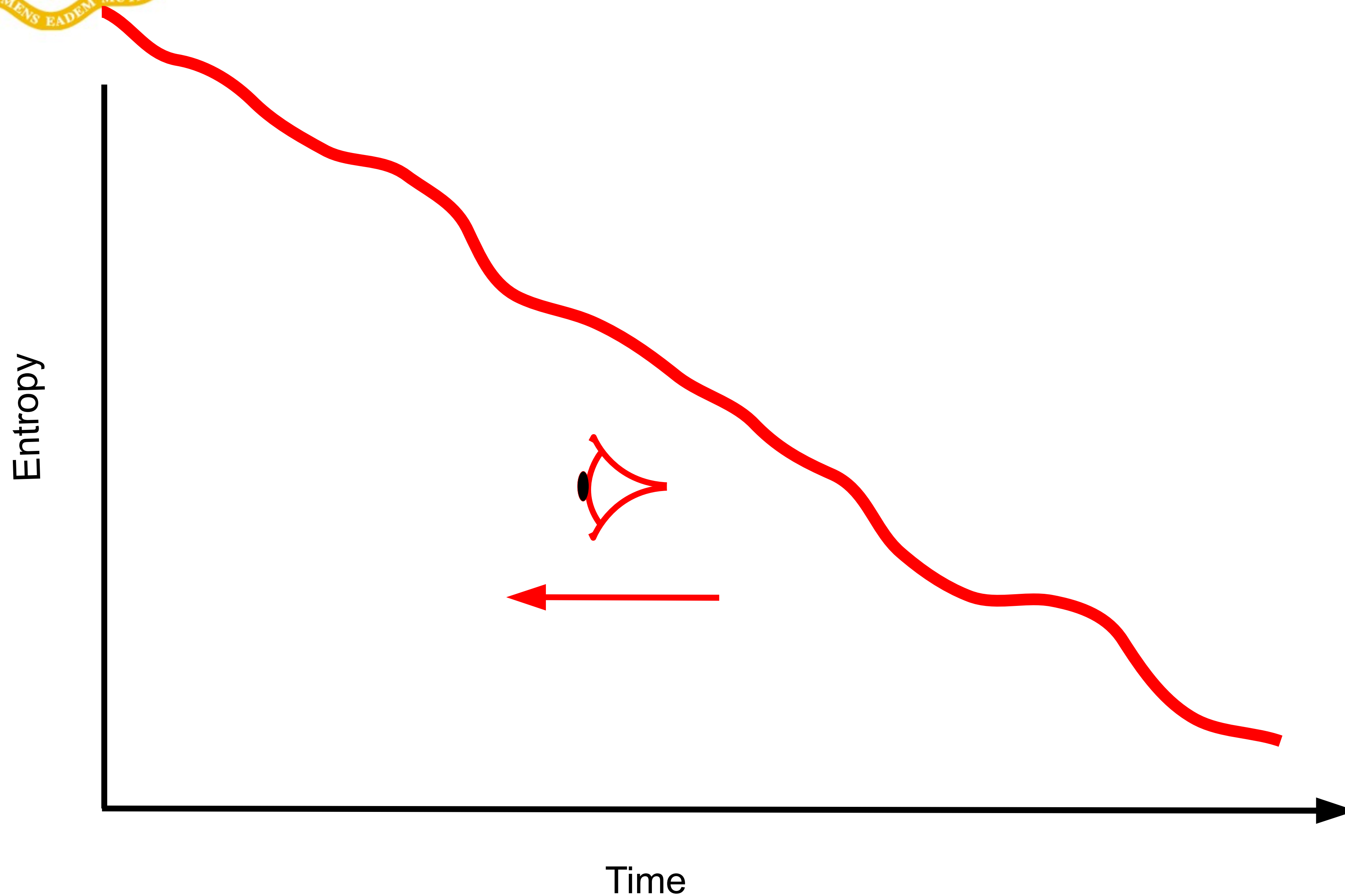
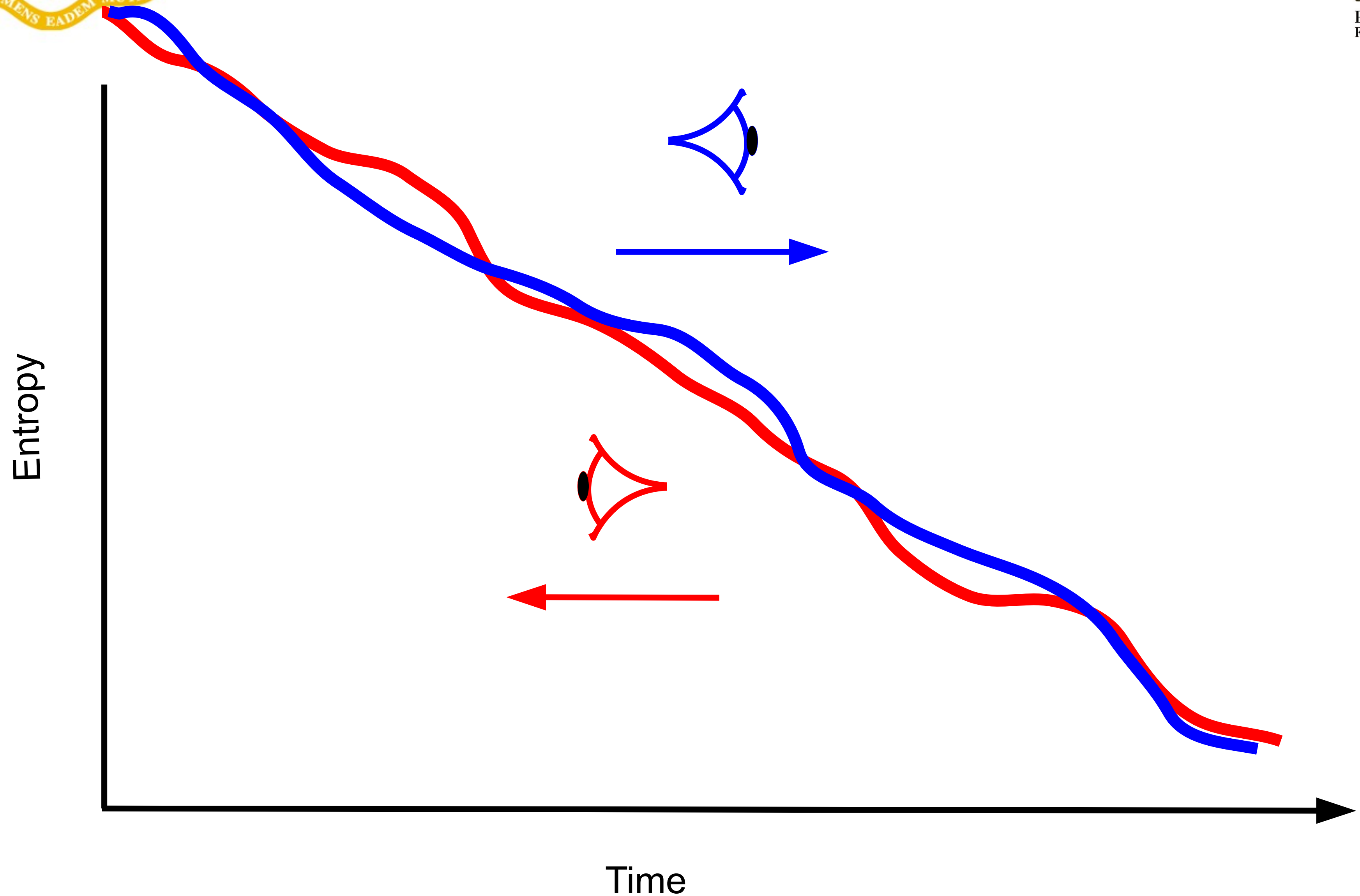



Agents and Arrows

January 2009, Sydney

# Different Arrows?



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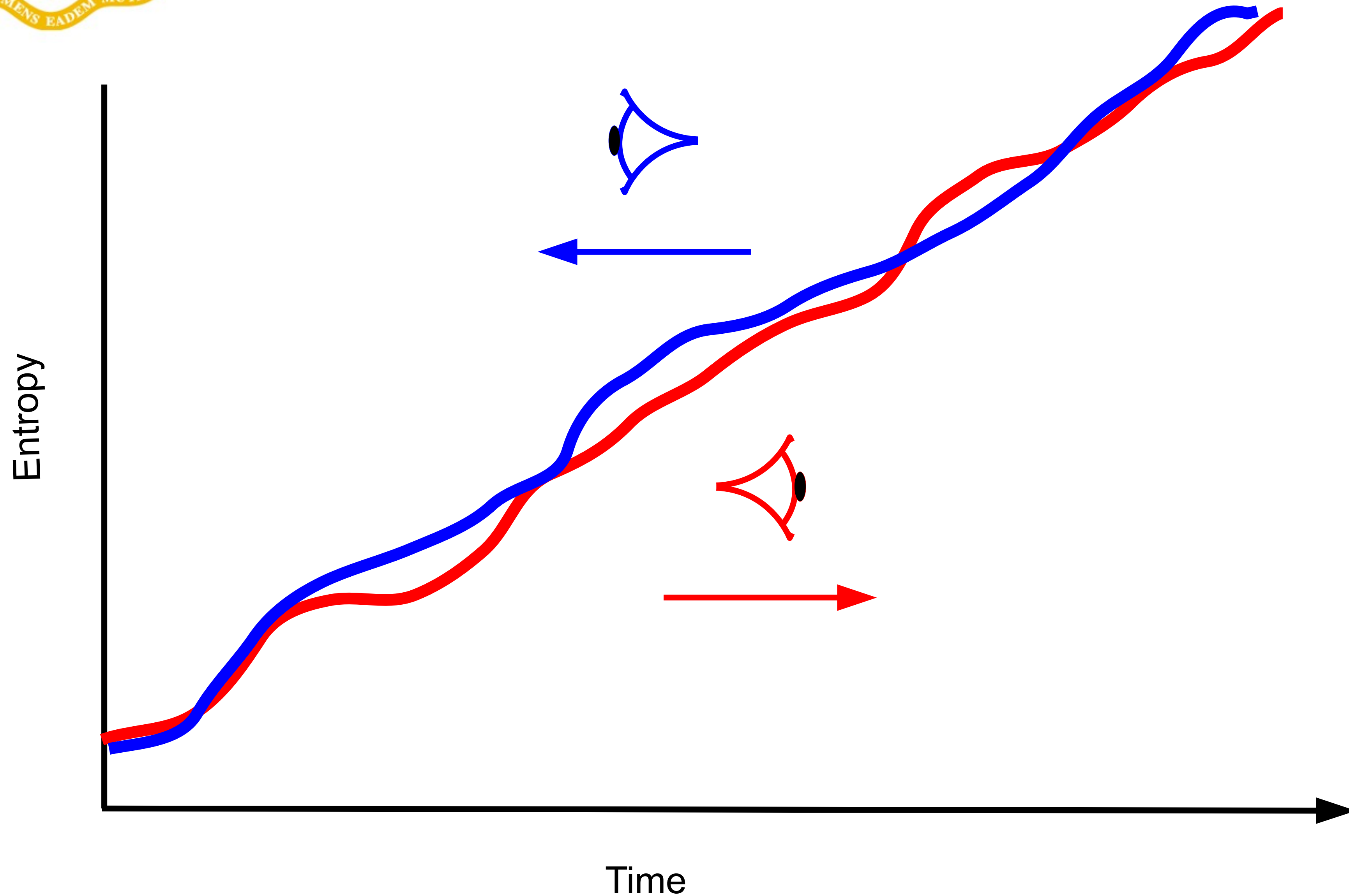


# Entropy Increasing

- An entropy increasing universe:
  - A marked asymmetry in physical processes
    - The tendency for work to be irreversibly converted to heat.
  - An initial condition hypothesis
    - The universe started in a small, a priori unlikely, part of state space.
    - No equivalent future condition hypothesis (unless on a very large timescale in the future)
  - A present day statistical condition about interacting systems
    - No initial microscopic correlations between systems
    - Thermal systems are initially well described by the canonical distribution on the accessible state space.
    - No equivalent conditions on final statistical states.

# Entropy *Decreasing*

- An entropy *decreasing* universe:
  - A marked asymmetry in physical processes
    - The tendency for *heat* to be irreversibly converted to *work*.
  - A *final* condition hypothesis.
    - The universe *will end up* in a small, a priori unlikely, part of state space.
    - No equivalent *initial* condition hypothesis (unless on a very large timescale in the *past*)
  - A present day statistical condition about interacting systems
    - No *final* microscopic correlations between systems
    - Thermal systems are *finally* well described by the canonical distribution on the accessible state space.
    - No equivalent conditions on *initial* statistical states.
- But *NOT* necessarily just a time reverse of our *particular* universe...

# Minds, Memories and Computers

"... when a computer records an item in memory, the total amount of disorder in the Universe increases. The direction of time in which a computer remembers the past is the same as that in which disorder increases"

*Hawking, 1987*

"If one imposes a final boundary condition on these trajectories, one can show that the correlation between the computer memory and the surroundings is greater at early times than at late times. In other words, the computer remembers the future but not the past."

*Hawking, 1994*

"Computations are accompanied by dissipation, so much so that one of the principal issues for Intel's Itanium chip is its power consumption ... More fundamentally, Landauer ... has shown that computation requires irreversible processes and heat generation"

*Schulman, 2005*

# Computation and Logic

## Logical Operations

AND

| A | B | A.B |
|---|---|---|
| ٠ | ٠ | ٠ |
| ٠ | ١ | ٠ |
| ١ | ٠ | ٠ |
| ١ | ١ | ١ |

NOT

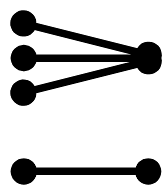
| A | $\bar{A}$ |
|---|---|
| 0 | 1 |
| 1 | 0 |

# Computation and Logic

## Logical Operations

### AND

| A | B | A.B |
|---|---|---|
| ٠ | ٠ | |
| ٠ | ١ | ٠ |
| ١ | ٠ | |
| ١ | ١ | ١ |



### NOT

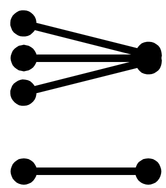
| A | A |
|---|---|
| 0 | 1 |
| 1 | 0 |

# Computation and Logic

## Logical Operations

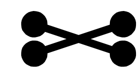
### AND

| A | B | A.B |
|---|---|---|
| ٠ | ٠ | ٠ |
| ٠ | ١ | |
| ١ | ٠ | |
| ١ | ١ | ١ |



### NOT

| A | $\bar{A}$ |
|---|---|
| 0 | 1 |
| 1 | 0 |

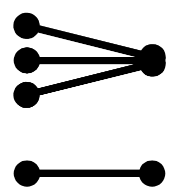


# Computation and Logic

## Logical Operations

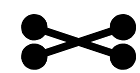
### AND

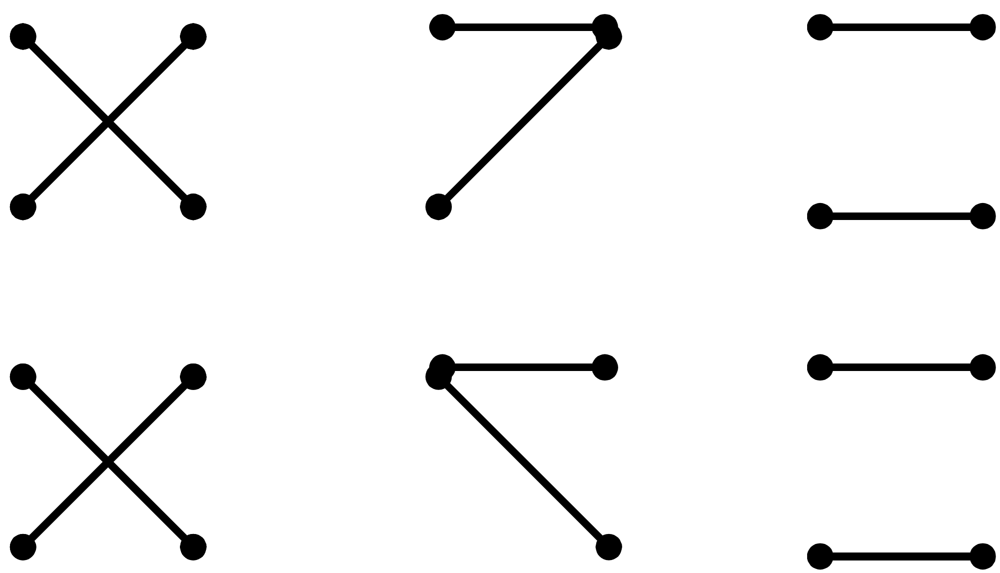
| A | B | A.B |
|---|---|---|
| 0 | 0 | |
| 0 | 1 | 0 |
| 1 | 0 | |
| 1 | 1 | 1 |



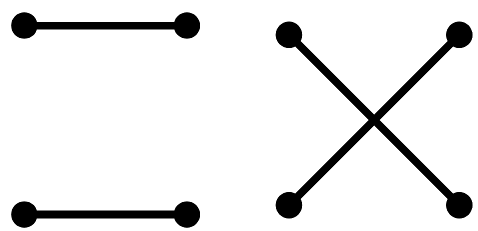
### NOT

| A | $\bar{A}$ |
|---|---|
| 0 | 1 |
| 1 | 0 |

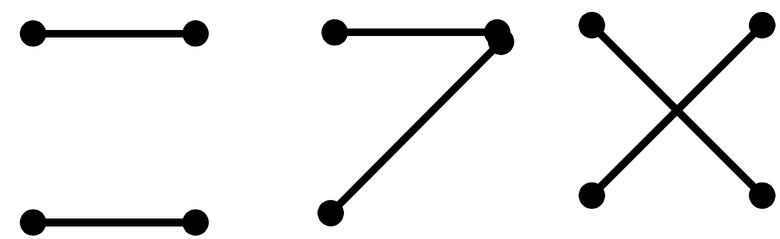




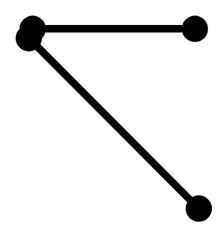
# Computation and Logic



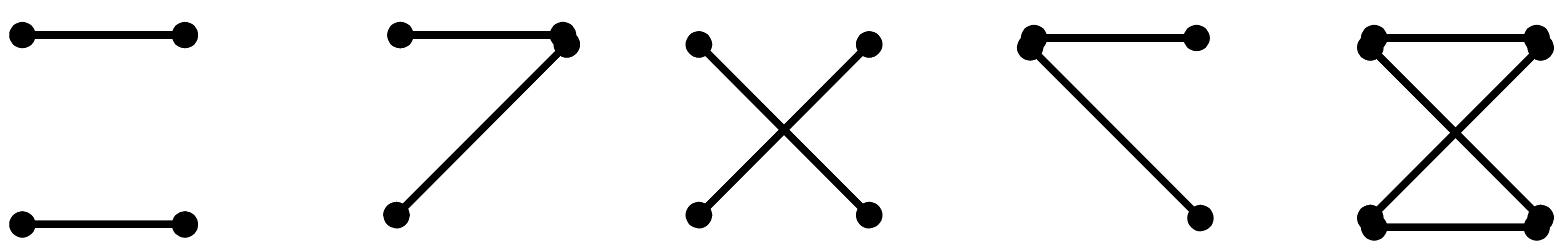
efficiently simulates



*but* they cannot efficiently simulate:



BPP Complexity Class
Probabilistic Turing Machines



# Logically reversing computations

A general transformation of *information*, "***L***" must take into account the effect on the probability distribution, ***P(a),*** over the input states.

Defined by the conditional probabilities of any an output, ***b***, given an input, ***a*** $P(b|a)$

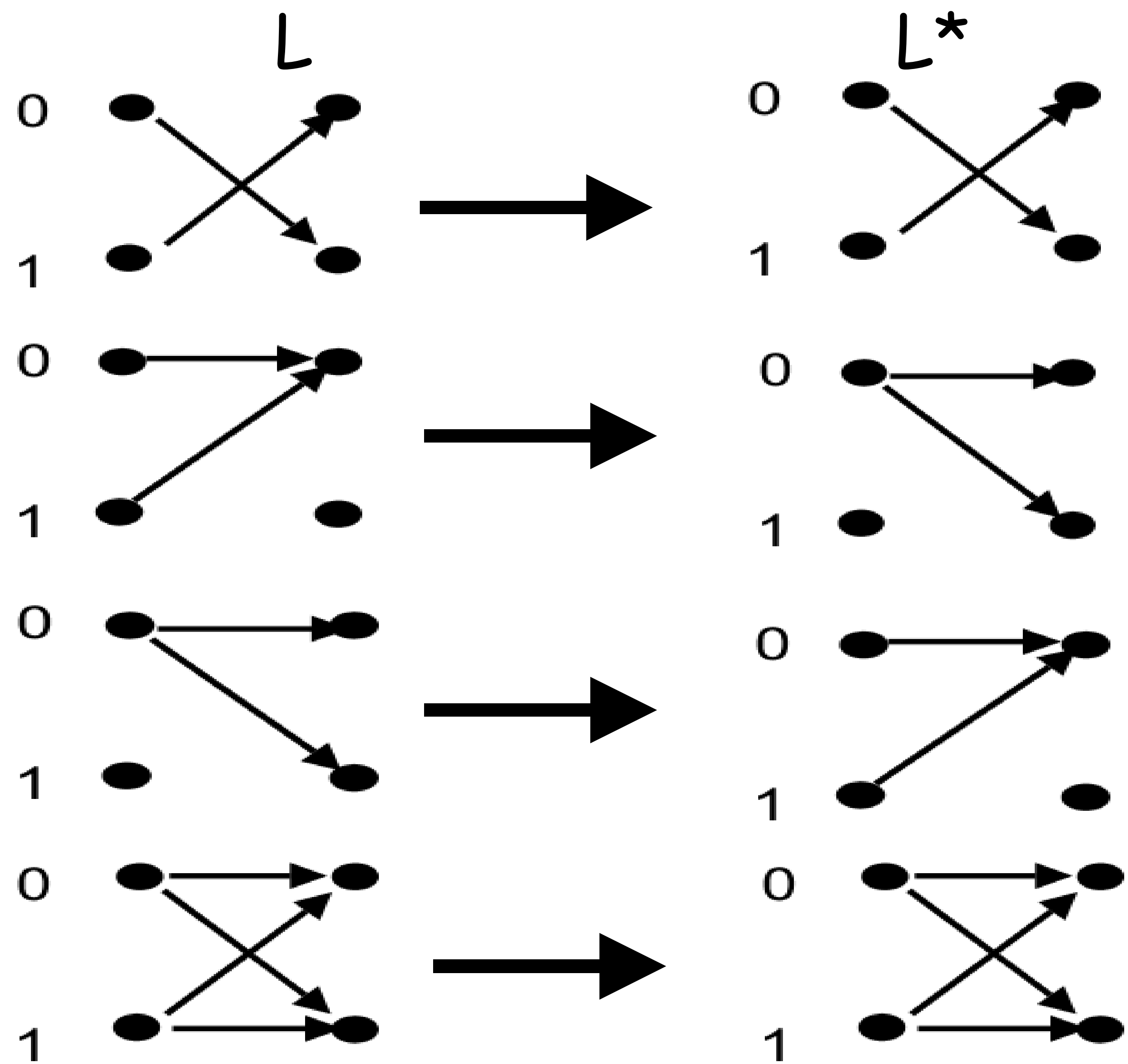
The reverse transformation of *information* "***L****" is:

$$P(a|b)=\frac{P(b|a)P(a)}{P(b)}=\frac{P(b|a)P(a)}{\sum_a P(b|a)P(a)}$$

It is not hard to see:

- if the input, ***a***, to ***L***, occurs with probability ***P(a)***, then following ***L*** with ***L**** restores the original probability distribution, ***P(a) :*** $(L^*)L=I$
- the reversal of ***L**** is ***L :*** $(L^*)^*=L$
- if the input, ***b***, to ***L****, occurs with probability ***P(b)***, then following ***L**** with ***L*** restores ***P(b) :*** $L(L^*)=I$

# Reverse Transformations



# Physically implementing operations

- A particular physical implementation of $L$, is an evolution of microstates, that satisfies $P(b|a)$
  - A flow on the state space (of system and environment), defined by a Hamiltonian: $H_L$
  
    Each input logical state corresponds to a region of system state space *[a]*, a macrostate with many microstates.
    - The proportion of all microstates in *[a]* is: $P(a)$
    
      A sequence of macro operations takes place, accompanied by evolution of microstates.
      - The macro operations are *not* correlated to the microstate.
  - Each output state corresponds to a region of state space *[b]*, a macrostate with many microstates.
    - The proportion of those microstates that started out in *[a]*, that end in *[b]* is: $P(b|a)$
- The proportion of all microstates ending up in *[b]* is: $P(b)=\sum_a P(b|a)P(a)$
- The proportion of those microstates that end in *[b]*, that started in *[a]* is:

$$P(a|b)=\frac{P(b|a)P(a)}{\sum_a P(b|a)P(a)}$$

# Time reversing the physics

- Now consider the complete, microscopic time reversal
  - Time reverse the macro-operations, via the Hamiltonian: $(H_L)^T$
    - Includes reversing velocities of (or complex conjugating) the final microstates for the initial microstates.
  - Each *[b]* corresponds to a region of state space, macrostate with many microstates.
    - The proportion of microstates in *[b]* is $P(b) = \sum_a P(b|a)P(a)$
  - A sequence of macro operations take place, accompanied by evolution of microstates.
    - The flow on the state space is defined by the Hamiltonian that is the time reverse of the initial Hamiltonian.
  - The proportion of microstates starting out in *[b]* that end in *[a]* is:

$$P(a|b) = \frac{P(b|a)P(a)}{P(b)}$$

  - The proportion of all microstates ending up in *[a]* is: $\sum_b P(a|b)P(b) = P(a)$

$(H_L)^T$ is a physical implementation of $L^*$

$$(H_L)^T \equiv H_{L^*} \qquad (H_{L^*})^T \equiv H_L$$

# Reversed Computational Processes

Now consider a sequence, ***S1***, of logical operations

$$\cdots P_i(a_i) = L_{i-1} : P_{i-1}(a_{i-1}) \to P_{i+1}(a_{i+1}) = L_i : P_i(a_i) \to P_{i+2}(a_{i+2}) = L_{i+1} : P_{i+1}(a_{i+1}) \cdots$$

After the $i^{th}$ operation: $L_i$ the logical states are: $a_i$ the probability distribution is: $P_i(a_i)$

The time reverse of this sequence, gives ***S2***

$$\cdots P_{i+1}(a_{i+1}) = L^*_{i+1} : P_{i+2}(a_{i+2}) \to P_i(a_i) = L^*_i : P_{i+1}(a_{i+1}) \to P_{i-1}(a_{i-1}) = L^*_{i-1} : P_i(a_i) \cdots$$

If ***S1*** is in an entropy increasing universe, ***S2*** is in an entropy decreasing universe.
But these are quite different sequences of operations!

Instead, construct physical implementations of the ***L**** operations, in entropy increasing universe: results in ***S3***

$$\cdots P_{i+1}(a_{i+1}) = L^*_{i+1} : P_{i+2}(a_{i+2}) \to P_i(a_i) = L^*_i : P_{i+1}(a_{i+1}) \to P_{i-1}(a_{i-1}) = L^*_{i-1} : P_i(a_i) \cdots$$

the same series of logical operations (and states) as ***S2***, but is entropy increasing.

Now time reverse ***S3***, to get ***S4***

$$\cdots P_i(a_i) = L_{i-1} : P_{i-1}(a_{i-1}) \to P_{i+1}(a_{i+1}) = L_i : P_i(a_i) \to P_{i+2}(a_{i+2}) = L_{i+1} : P_{i+1}(a_{i+1}) \cdots$$

***S4*** is the same as ***S1***, but is in an entropy decreasing universe.

# Reversed Computational Processes

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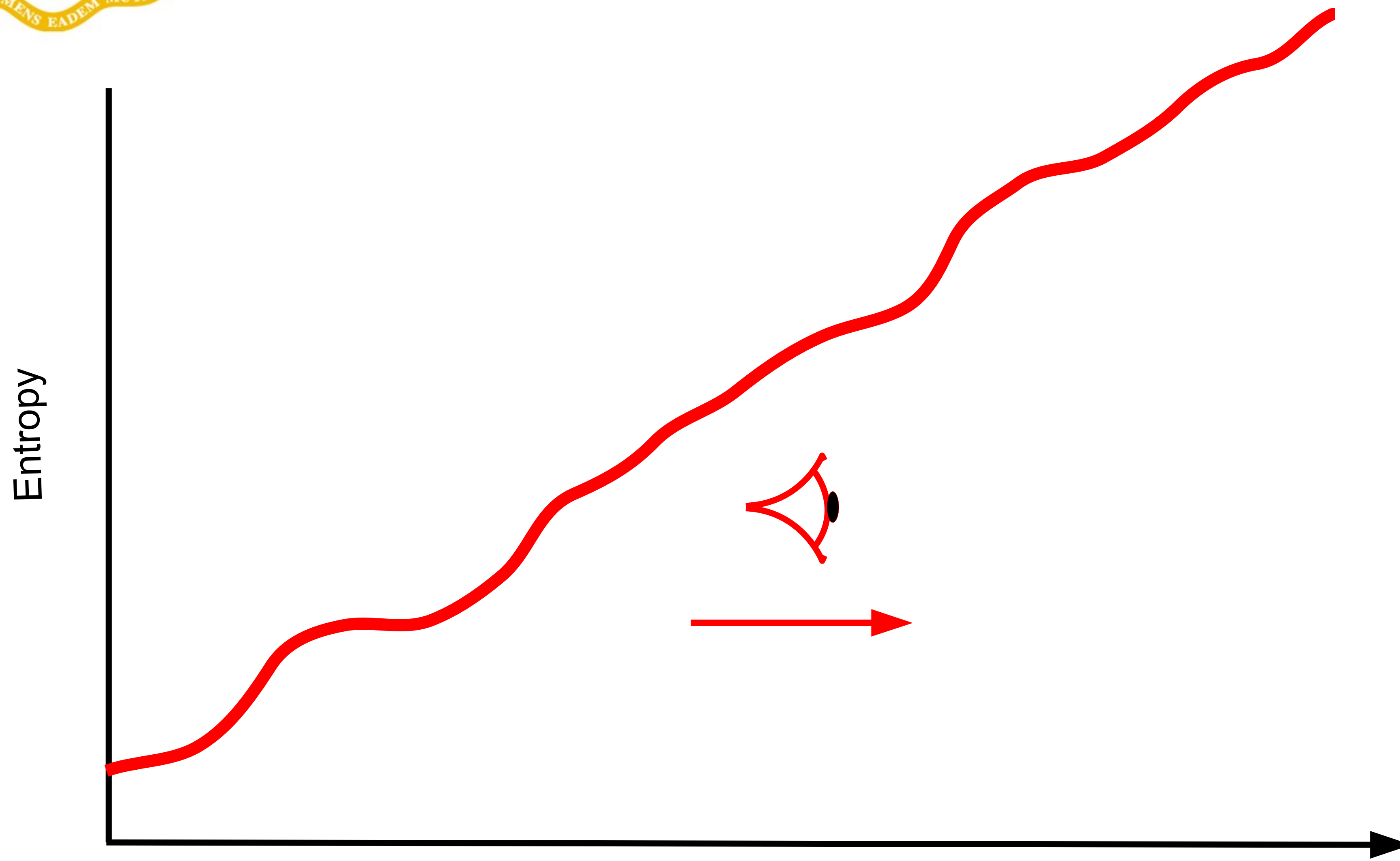
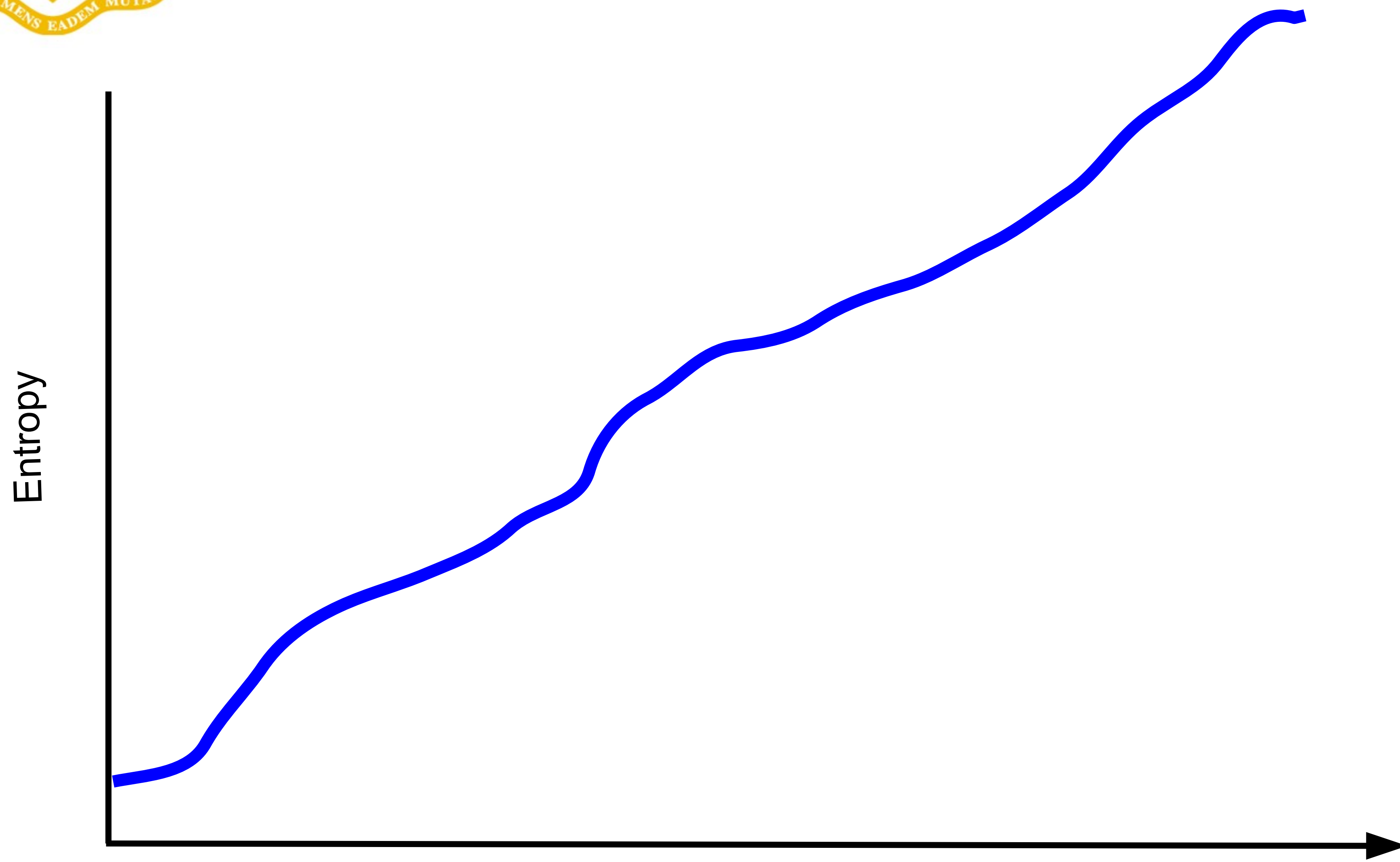



$$\cdots P_i(a_i) = L_{i-1} : P_{i-١}(a_{i-1}) \rightarrow P_{i+1}(a_{i+١}) = L_i : P_i(a_i) \rightarrow P_{i+٢}(a_{i+2}) = L_{i+1} : P_{i+١}(a_{i+1}) \cdots$$

# Reversed Computational Processes

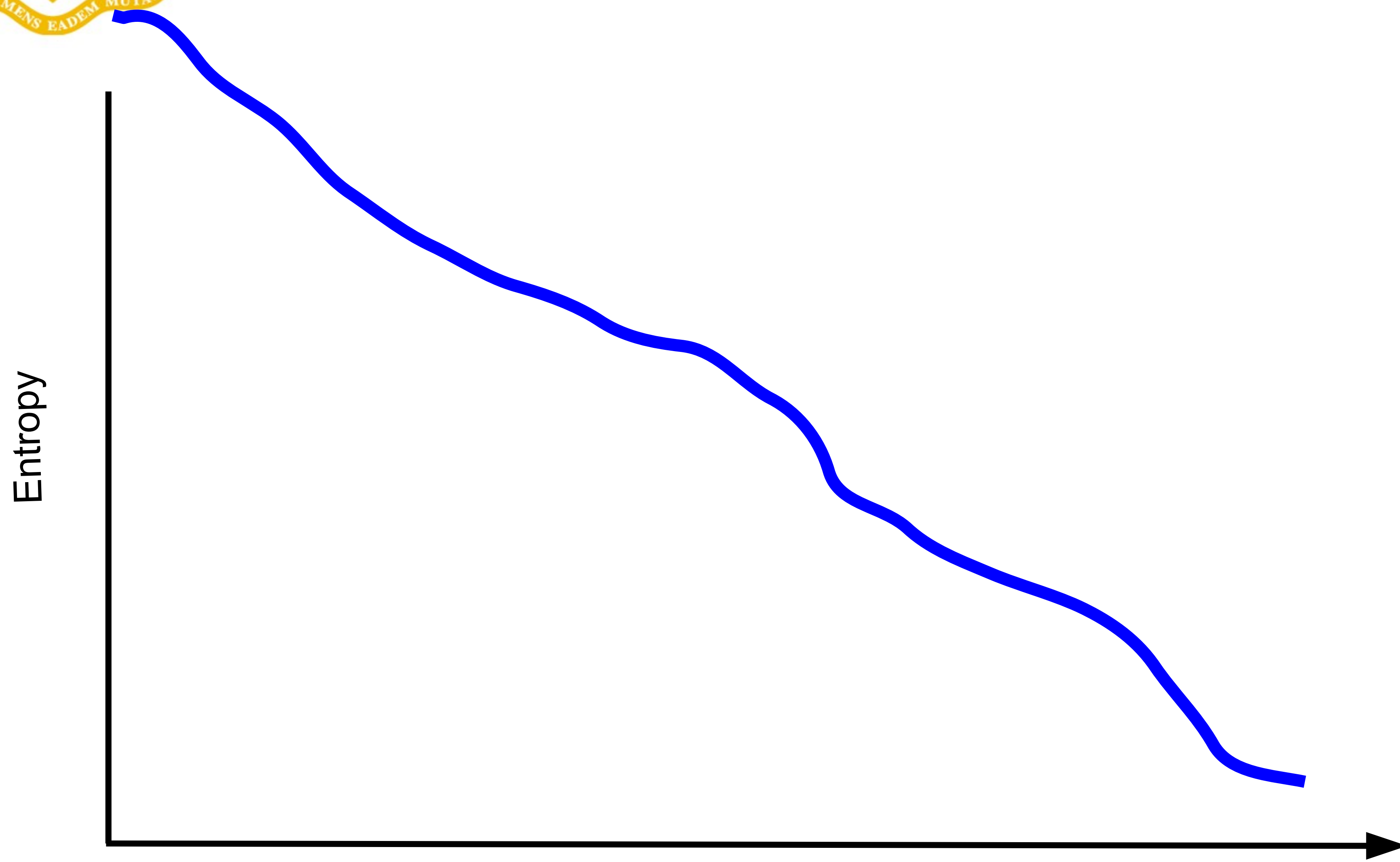

$$\cdots P_{i+1}(a_{i+1}) = L^*_{i+1} : P_{i+2}(a_{i+2}) \rightarrow P_i(a_i) = L^*_i : P_{i+1}(a_{i+1}) \rightarrow P_{i-1}(a_{i-1}) = L^*_{i-1} : P_i(a_i) \cdots$$

# Reversed Computational Processes



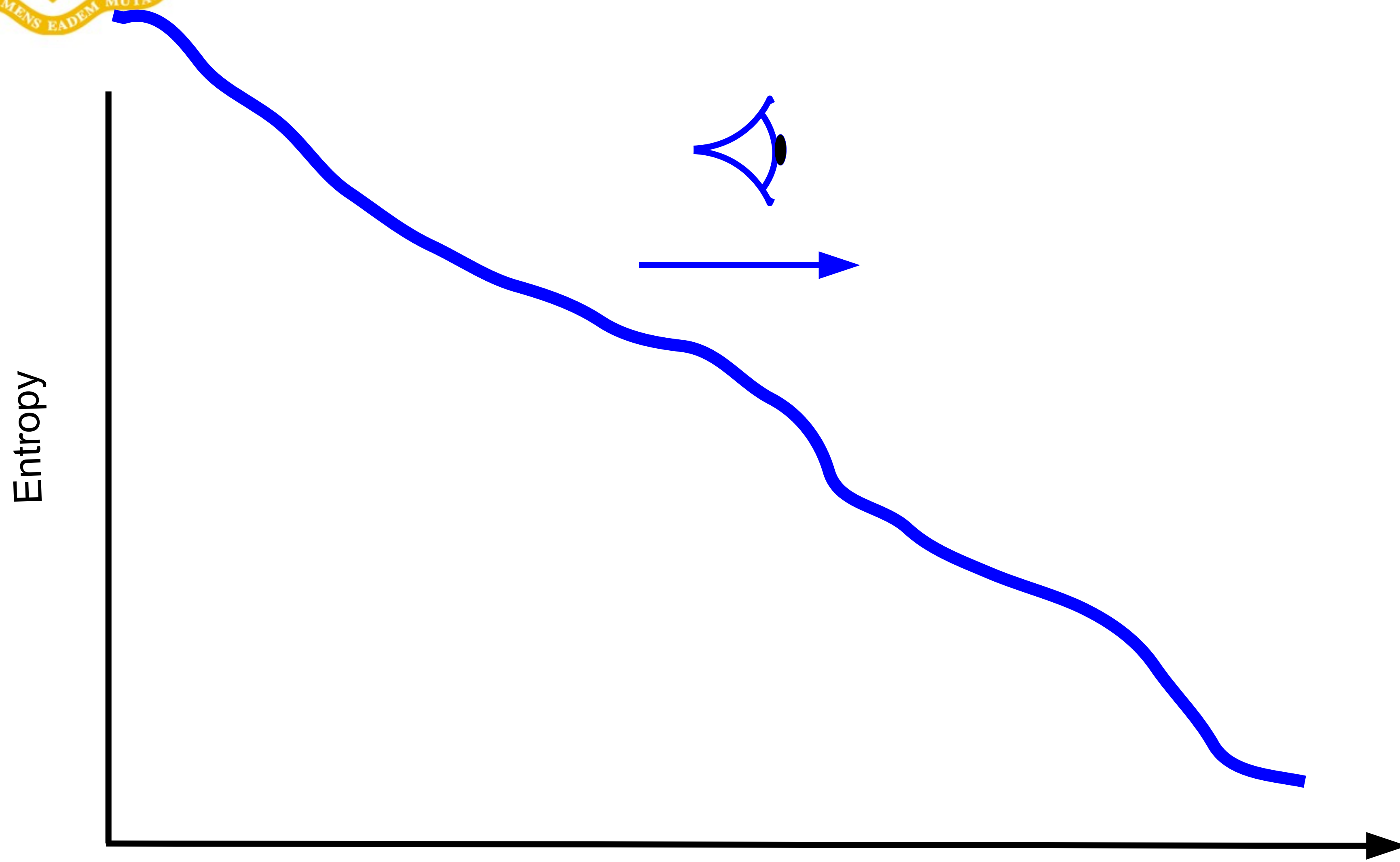

$$\cdots P_{i+1}(a_{i+1}) = L^*_{i+1} : P_{i+2}(a_{i+2}) \to P_i(a_i) = L^*_i : P_{i+1}(a_{i+1}) \to P_{i-1}(a_{i-1}) = L^*_{i-1} : P_i(a_i) \cdots$$

# Reversed Computational Processes




$$\cdots P_i(a_i) = L_{i-1} : P_{i-1}(a_{i-1}) \rightarrow P_{i+1}(a_{i+1}) = L_i : P_i(a_i) \rightarrow P_{i+2}(a_{i+2}) = L_{i+1} : P_{i+1}(a_{i+1}) \cdots$$

# Reversed Computational Processes




$$\cdots P_i(a_i) = L_{i-1} : P_{i-1}(a_{i-1}) \to P_{i+1}(a_{i+1}) = L_i : P_i(a_i) \to P_{i+2}(a_{i+2}) = L_{i+1} : P_{i+1}(a_{i+1}) \cdots$$

# Computers and Agents and Arrows

- Given the fundamental logical structure of an Information Gathering, Processing and Utilising System, it is possible to design and construct a system that is the logical reversal of such a system
  - This would not necessarily look like an IGUS to us
  - It would look like an IGUS in a time reversed universe
  - Such a time reversed universe would be entropy decreasing
  - Information Gathering, Processing and Utilising, as a sequence of logical processing steps, is *not* governed by the thermodynamic arrow.
- If the temporal asymmetry of a causal agent is supposed to be a consequence of it being an information gathering, processing and utilising being, then that temporal asymmetry is *not* thermodynamic in origin.

# What of Landauer's Principle?

- Landauer's Principle is supposed to be "the basic principle of the thermodynamics of information processing" *(Bennett, 2003)*.
  - It is widely believed to state that some types of logical operations are necessarily thermodynamically irreversible:

"If information is understood as physically embodied information, a logically irreversible operation must be implemented by a physically irreversible device, which dissipates heat into the environment."

*(Bub 2001)*

"This is often generalised to the claim that any logically irreversible operation cannot be implemented in a thermodynamically reversible way."

*(Short, Ladyman, Groisman, Presnell, 2007)*

How does this relate to the conclusion of the previous slides?

# Landauer in an entropy increasing universe

$$\rho_0=\rho_i\otimes\rho_E(T)=\sum_\alpha P(\alpha)\rho_\alpha\otimes\rho_E(T)\qquad H=H_C+H_E+V\qquad \rho_E(T)=N\,e^{-H_E/kT}$$

$$\rho_t=e^{-iHt}\rho_0 e^{iHt}\qquad Tr_E\left[e^{-iHt}\rho_\alpha\otimes\rho_E(T)e^{iHt}\right]=\sum_\beta P(\beta|\alpha)\rho_\beta$$

$$P(\beta)=\sum_\alpha P(\beta|\alpha)P(\alpha)\qquad \rho_f=Tr_E[\rho_t]=\sum_\beta P(\beta)\rho_\beta$$

$$\rho_E{}'=Tr_C[\rho_t]$$

$$Tr[\rho_i\ln(\rho_i)]+Tr[\rho_E(T)\ln(\rho_E(T))]\geqslant Tr[\rho_f\ln(\rho_f)]+Tr[\rho_E{}'\ln(\rho_E{}')]$$

$$Tr\left[\rho_E{}'\left(\ln(\rho_E{}')+\frac{H_E}{kT}\right)\right]\geqslant Tr\left[\rho_E(T)\left(\ln(\rho_E(T))+\frac{H_E}{kT}\right)\right]$$

$$\sum_\alpha P(\alpha)\ln P(\alpha)-\sum_\beta P(\beta)\ln P(\beta)\geqslant\frac{Tr\left[H_E\rho_E(T)\right]}{kT}-\frac{Tr\left[H_E\rho_E{}'\right]}{kT}$$

$$\Delta H=\sum_\alpha P(\alpha)\log P(\alpha)-\sum_\beta P(\beta)\log P(\beta)\qquad \Delta Q=Tr\left[H_E\rho_E{}'\right]-Tr\left[H_E\rho_E(T)\right]$$

$$\Delta Q\geqslant-\Delta H\,kT\ln(2)$$

# Landauer in an entropy decreasing universe

$$\rho_t = \rho_f \otimes \rho_E(T) = \sum_\beta P(\beta)\,\rho_\beta \otimes \rho_E(T) \qquad H = H_C + H_E + V \qquad \rho_E(T) = N\,e^{-H_E/kT}$$

$$\rho_t = e^{-iHt}\,\rho_0\,e^{iHt} \qquad Tr_E\left[e^{iHt}\,\rho_\beta \otimes \rho_E(T)\,e^{-iHt}\right] = \sum_\alpha P(\alpha|\beta)\,\rho_\alpha$$

$$P(\alpha|\beta) = \frac{P(\beta|\alpha)\,P(\alpha)}{\sum_{\alpha'} P(\beta|\alpha')\,P(\alpha')} \qquad \rho_i = Tr_E[\rho_0] = \sum_\alpha P(\alpha)\,\rho_\alpha$$

$$\rho_E' = Tr_C[\rho_0]$$

$$Tr[\rho_f \ln(\rho_f)] + Tr[\rho_E(T)\ln(\rho_E(T))] \geqslant Tr[\rho_i \ln(\rho_i)] + Tr[\rho_E' \ln(\rho_E')]$$

$$Tr\left[\rho_E'\left(\ln(\rho_E') + \frac{H_E}{kT}\right)\right] \geqslant Tr\left[\rho_E(T)\left(\ln(\rho_E(T)) + \frac{H_E}{kT}\right)\right]$$

$$-\sum_\alpha P(\alpha)\ln P(\alpha) + \sum_\beta P(\beta)\ln P(\beta) \geqslant \frac{Tr\left[H_E\,\rho_E(T)\right]}{kT} - \frac{Tr\left[H_E\,\rho_E'\right]}{kT}$$

$$\Delta H = \sum_\alpha P(\alpha)\log P(\alpha) - \sum_\beta P(\beta)\log P(\beta) \qquad \Delta Q = -Tr\left[H_E\,\rho_E'\right] + Tr\left[H_E\,\rho_E(T)\right]$$

$$\Delta Q \leqslant -\Delta H\,kT\ln(2)$$

# Nothing Special to Computation!

- There is nothing special about computation in this argument!
  - Only a general sequence of stochastic transitions between quasi-static equilibrium states (QSES) has been used: $P\left(a_{i+1} \middle| a_i\right)$

$$\cdots P_i(a_i) = L_{i-1} : P_{i-1}(a_{i-1}) \rightarrow P_{i+1}(a_{i+1}) = L_i : P_i(a_i) \rightarrow P_{i+2}(a_{i+2}) = L_{i+1} : P_{i+1}(a_{i+1}) \cdots$$

- *Any* process that can be defined purely in terms of (stochastic) sequences of QSES will face the same issue.
  - Any temporal asymmetry appearing in such a process *cannot* be explained as being a consequence of thermal asymmetry
    - An ice cube in a glass may be succeeded by a glass of water *and vice versa* in both entropy increasing and entropy decreasing universes
  - It is not the order of the start and end point QSES that identifies the thermodynamic arrow
    - It is the fact that the process is the ice cube *melting* (a fundamentally non-equilibrium process) that identifies the direction of the thermodynamic arrow
- If the temporal experience of a causal agent can be defined *solely* in terms of the agent being in a sequence of QSES, then its asymmetry *cannot* be thermodynamic in origin.

# Correlations with the world

Consider a system, with states {A}, gathering information about another system, with states {B}, in an environment, {E}.

$$A_0 \otimes \cup_i B_i \otimes E_0 \rightarrow .\cup_i A_i \otimes B_i \otimes E_i \subseteq .\cup_i A_i \otimes B_i \otimes E_f \qquad E_f = .\cup_i E_i$$

$$\mu(A_0 \otimes \cup_i B_i \otimes E_0) = \mu(.\cup_i A_i \otimes B_i \otimes E_i) \leqslant \mu(.\cup_i A_i \otimes B_i \otimes E_f)$$

$$\mu(A_0)\left(\sum_i \mu(B_i)\right)\mu(E_0) = \sum_i \mu(A_i)\mu(B_i)\mu(E_i) \leqslant \left(\sum_i \mu(A_i)\mu(B_i)\right)\mu(E_f)$$

Coarse grained entropy increase. $\quad B_i \cap B_j = A_i \cap A_j = \emptyset \; (i \neq j)$

But now consider system {A}, initially possessing information about {B}, and "anti-gathering" it:

$$.\cup_i A_i \otimes B_i \otimes E_0{}' \rightarrow A_0 \otimes \cup_i B_i \otimes E_i{}' \subseteq A_0 \otimes \cup_i B_i \otimes E_f{}' \qquad E_f{}' = .\cup_i E_i{}'$$

$$\mu(.\cup_i A_i \otimes B_i \otimes E_0{}') = \mu(A_0 \otimes \cup_i B_i \otimes E_i{}') \leqslant \mu(A_0 \otimes \cup_i B_i \otimes E_f)$$

$$\left(\sum_i \mu(A_i)\mu(B_i)\right)\mu(E_0{}') = \mu(A_{.})\left(\sum_i \mu(B_i)\mu(E_i{}')\right) \leqslant \mu(A_0)\left(\sum_i \mu(B_i)\right)\mu(E_f{}')$$

Still a coarse grained entropy increase.

# (De-)Correlations with the world

How does the entropy increase appear?

$$.\cup_i A_i \otimes B_i \otimes E_i \subseteq .\cup_i A_i \otimes B_i \otimes E_f \qquad \mu(.\cup_i A_i \otimes B_i \otimes E_i) \leqslant \mu(.\cup_i A_i \otimes B_i \otimes E_f)$$

$$\sum_i \mu(A_i)\mu(B_i)\mu(E_i) \leqslant \left(\sum_i \mu(A_i)\mu(B_i)\right)\left(\sum_j \mu(E_j)\right) \qquad E_f = .\cup_i E_i$$

Inaccessibility of microscopic correlations with the environment.
Coarse grained decorrelation.

$$.\cup_i A_i \otimes B_i \subseteq .\cup_i A_i \otimes \cup_j B_j \qquad \mu(.\cup_i A_i \otimes B_i) \leqslant \mu(.\cup_i A_i \otimes \cup_j B_j)$$

$$\sum_i \mu(A_i)\mu(B_i) \leqslant \left(\sum_i \mu(A_i)\right)\left(\sum_j \mu(B_j)\right)$$

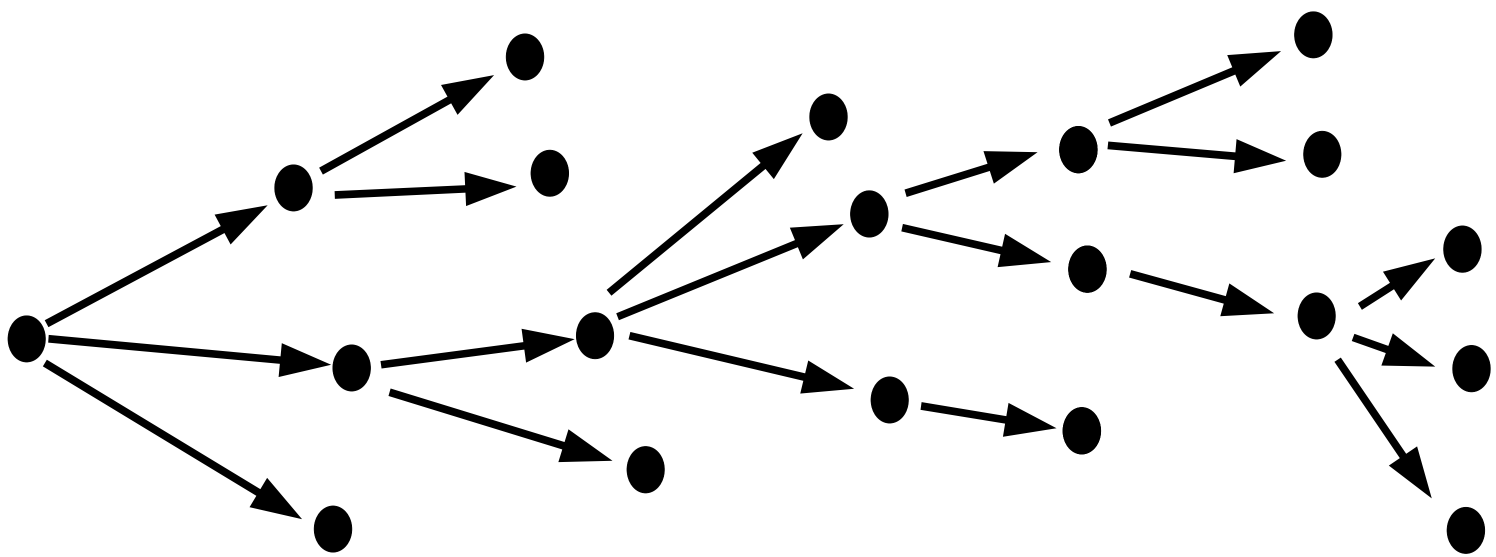
But it is precisely the *accessibility* of macroscopic correlations that makes information gathering of value. Coarse grained decorrelation of information does not occur (at least, on the timescales relevant).

$$A_0 \otimes \cup_i B_i \rightarrow .\cup_i A_i \otimes B_i \rightarrow .\cup_i A_i \otimes \cup_j B_j$$

$$.\cup_i A_i \otimes B_i \rightarrow A_0 \otimes \cup_i B_i \rightarrow .\cup_j A_j \otimes \cup_i B_i$$

# Initial Condition Constraint

- Causal handles *(Albert, Kutach, Loewer)*
  - The imposition of an initial condition hypothesis, but no final condition hypothesis, constrains counterfactual reasoning. Minor perturbations in the microstate now can have unconstrained future consequences but cannot have unconstrained past consequences. Criticisms *(Frisch, Price & Weslake)*



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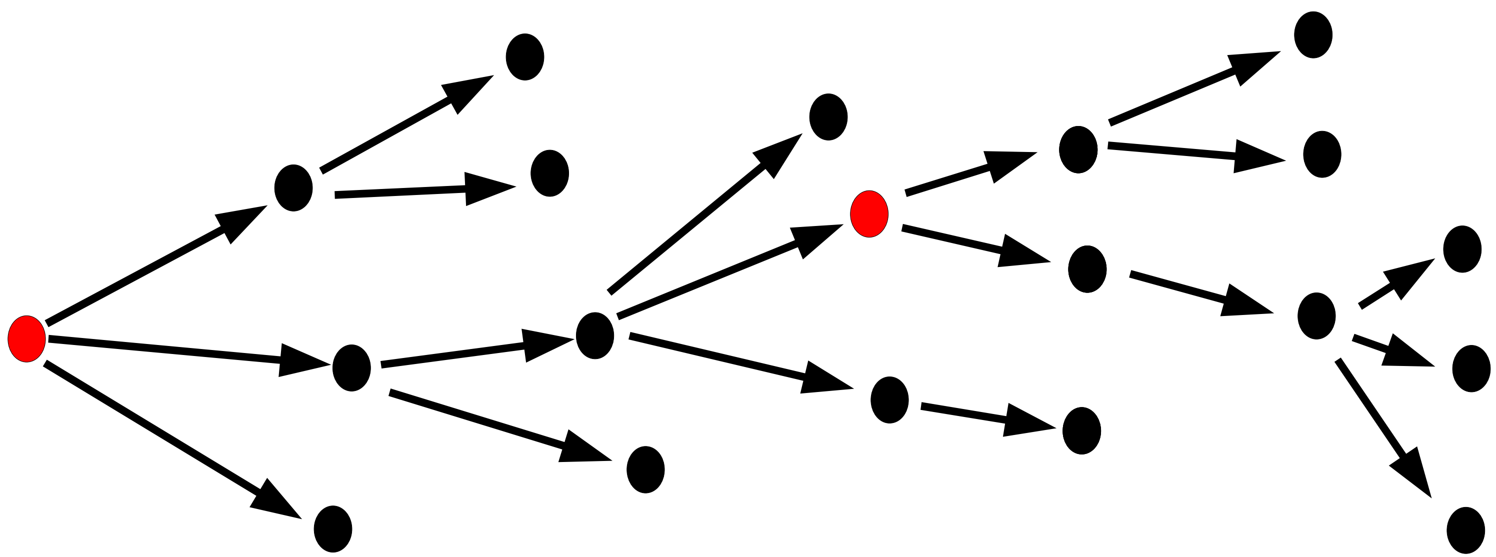

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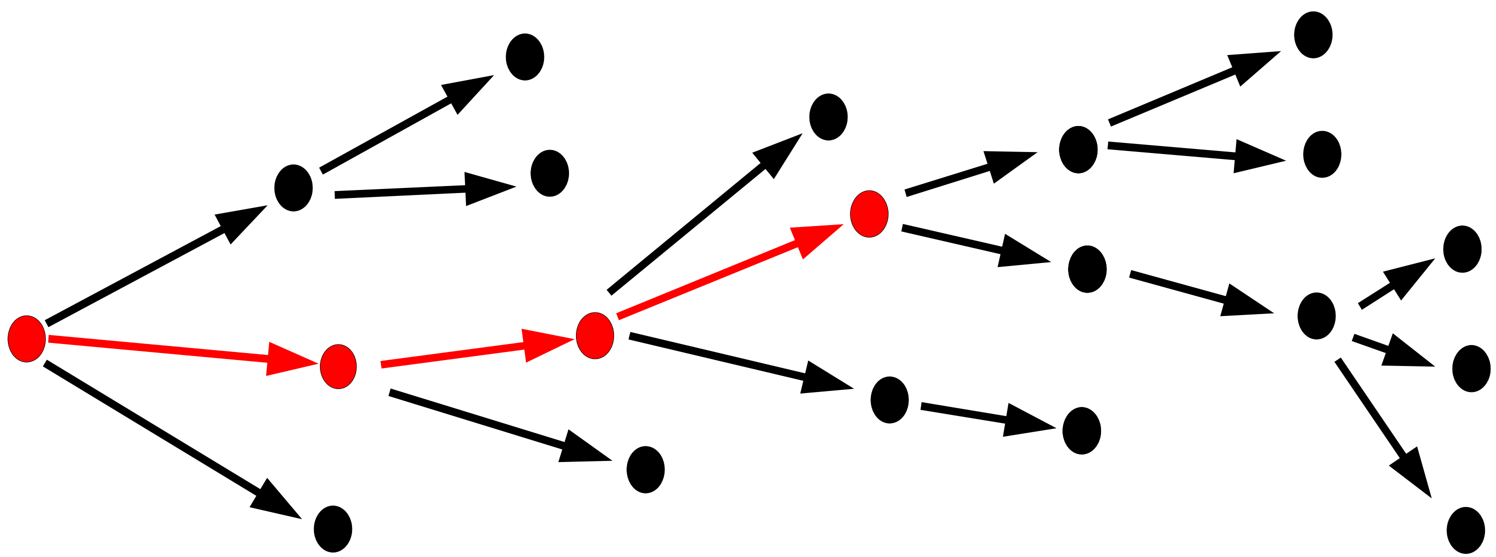

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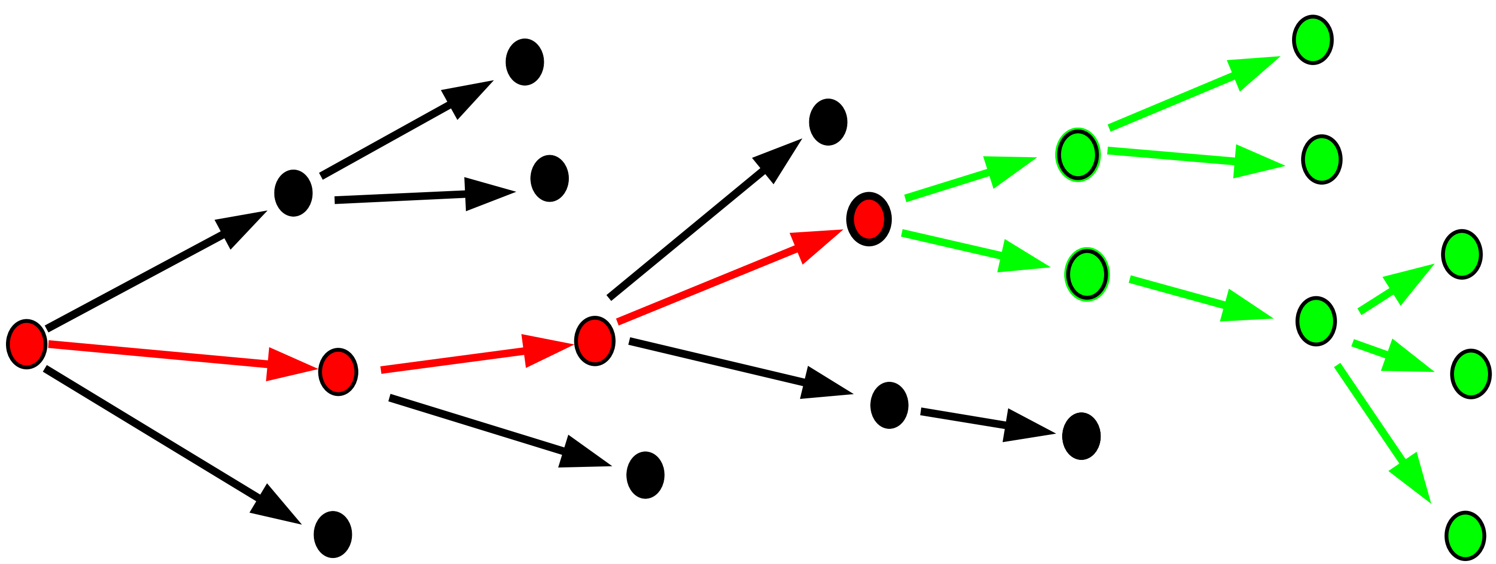

# Tree or Web?

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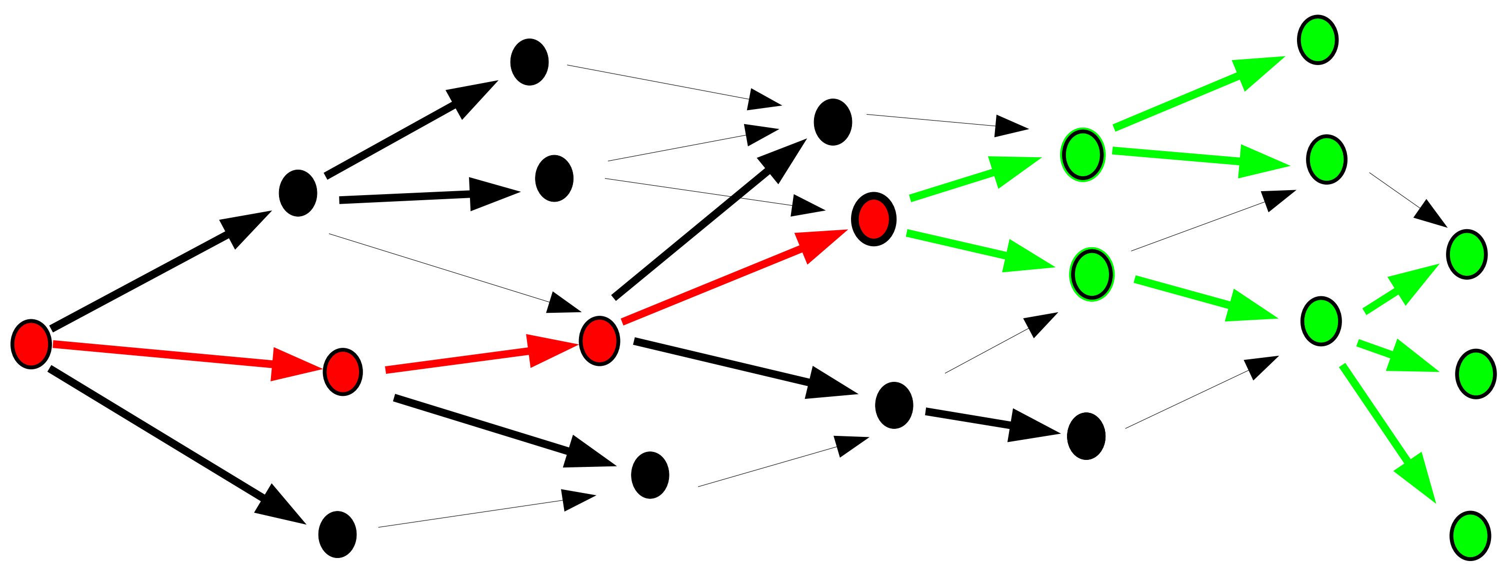

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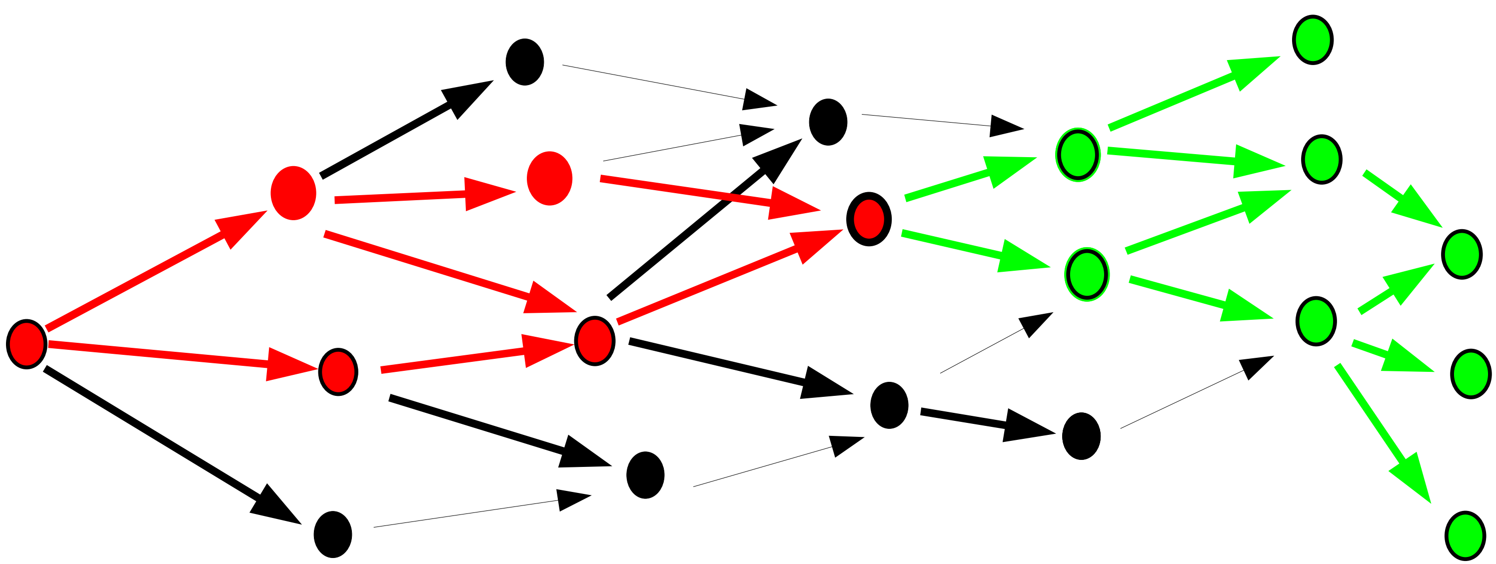

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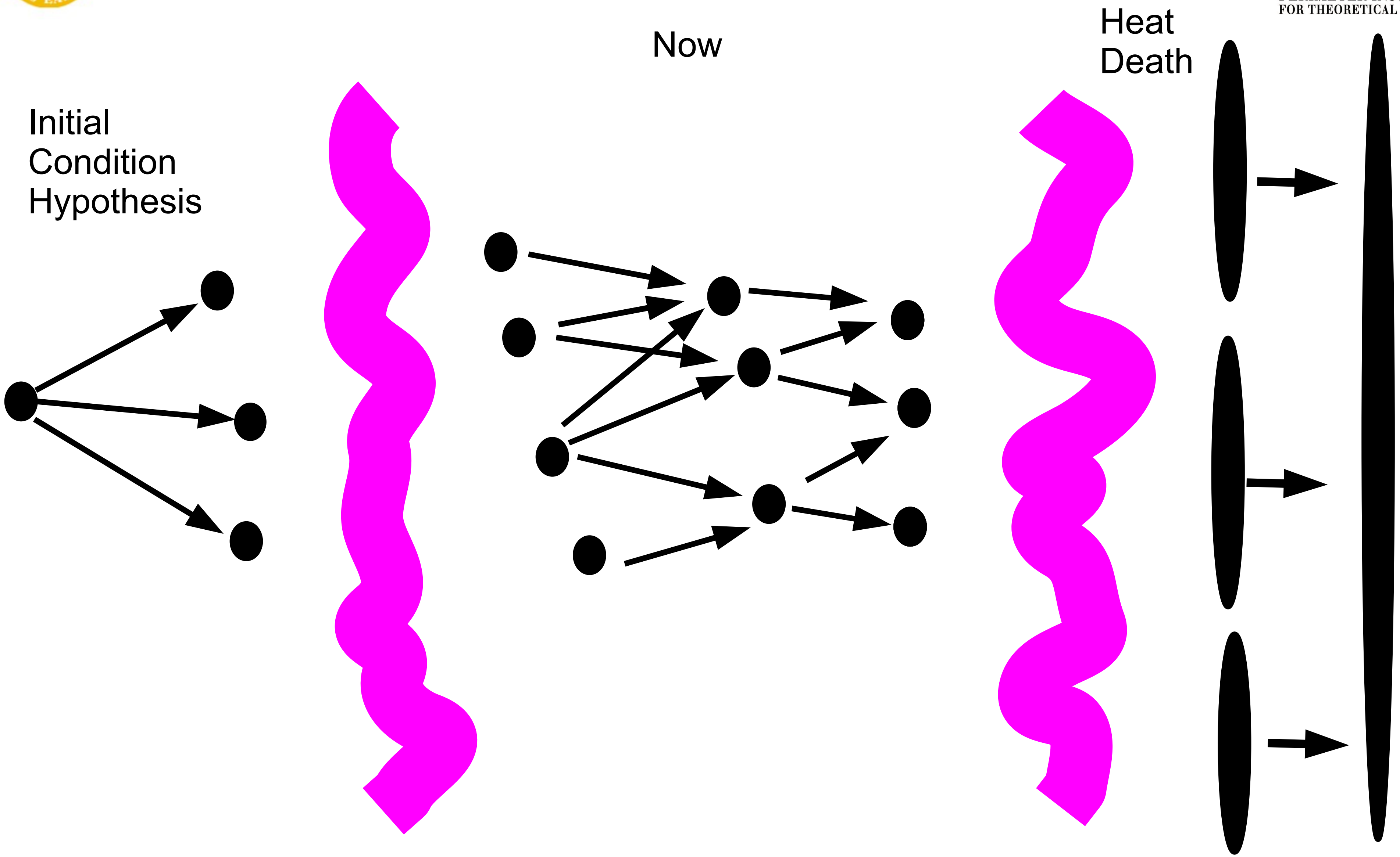

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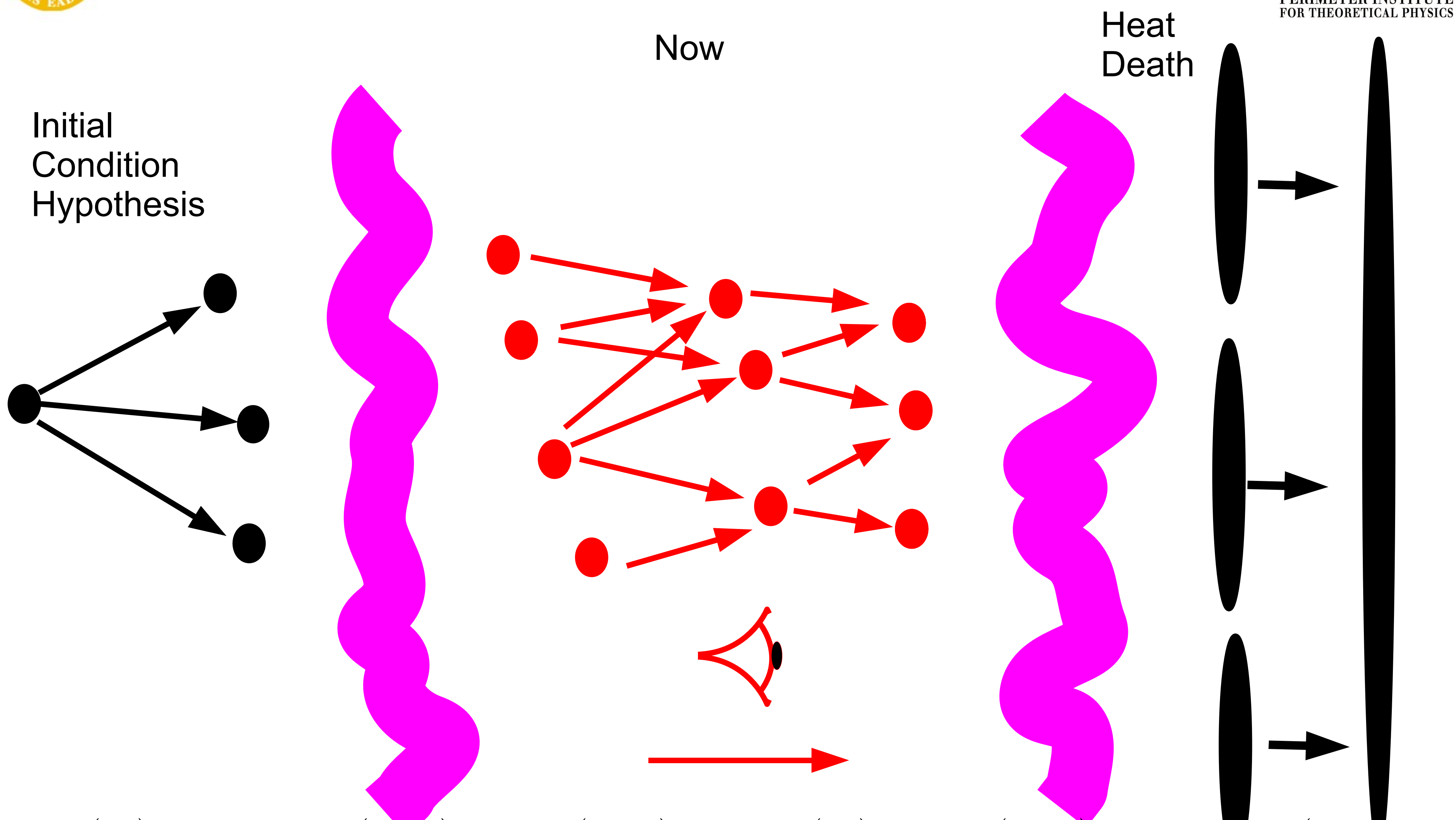


$$\cdots P_i(a_i) = L_{i-1} : P_{i-1}(a_{i-1}) \rightarrow P_{i+1}(a_{i+1}) = L_i : P_i(a_i) \rightarrow P_{i+2}(a_{i+2}) = L_{i+1} : P_{i+1}(a_{i+1}) \cdots$$

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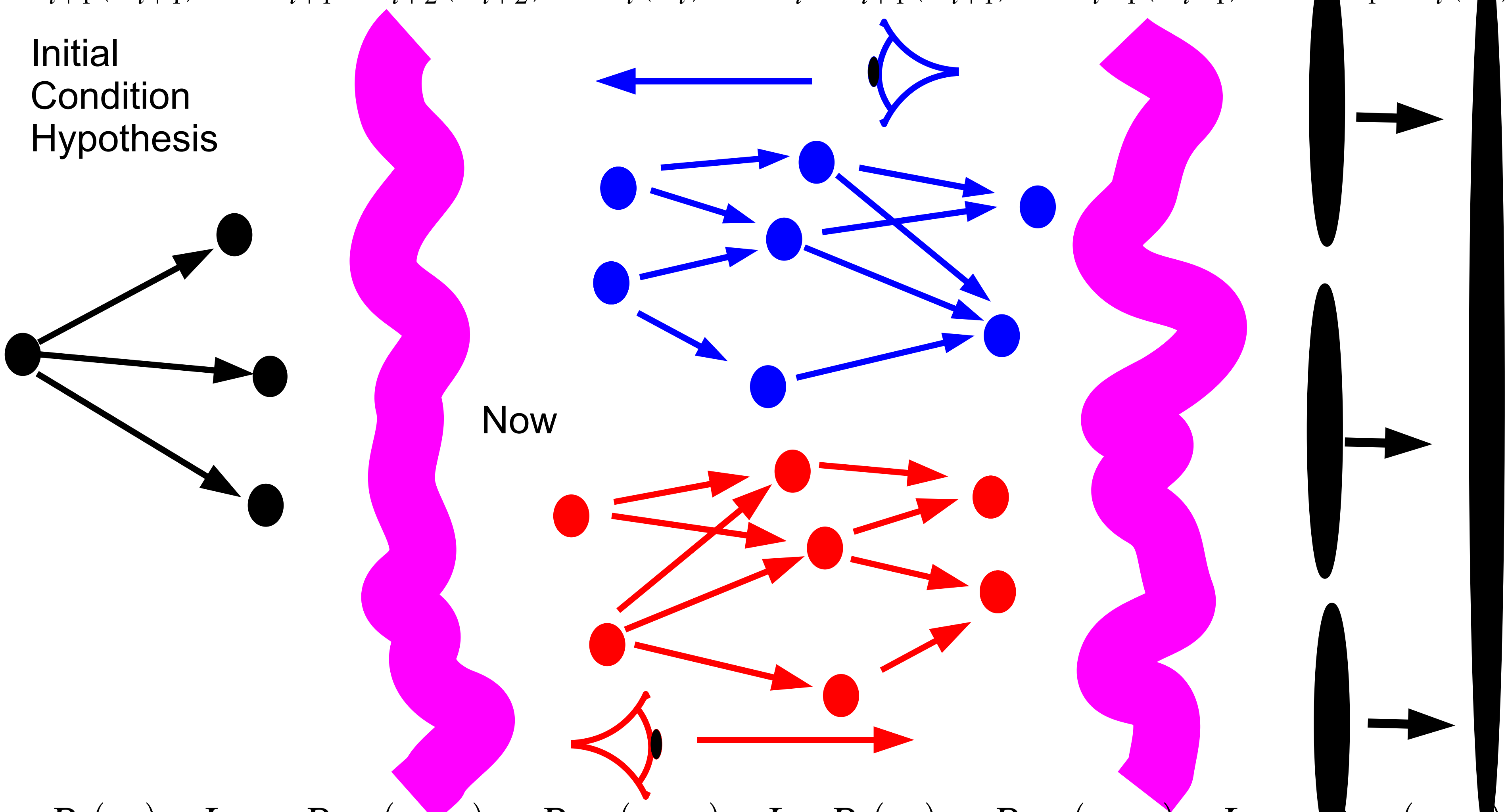


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# Tree or Web?

Heat Death

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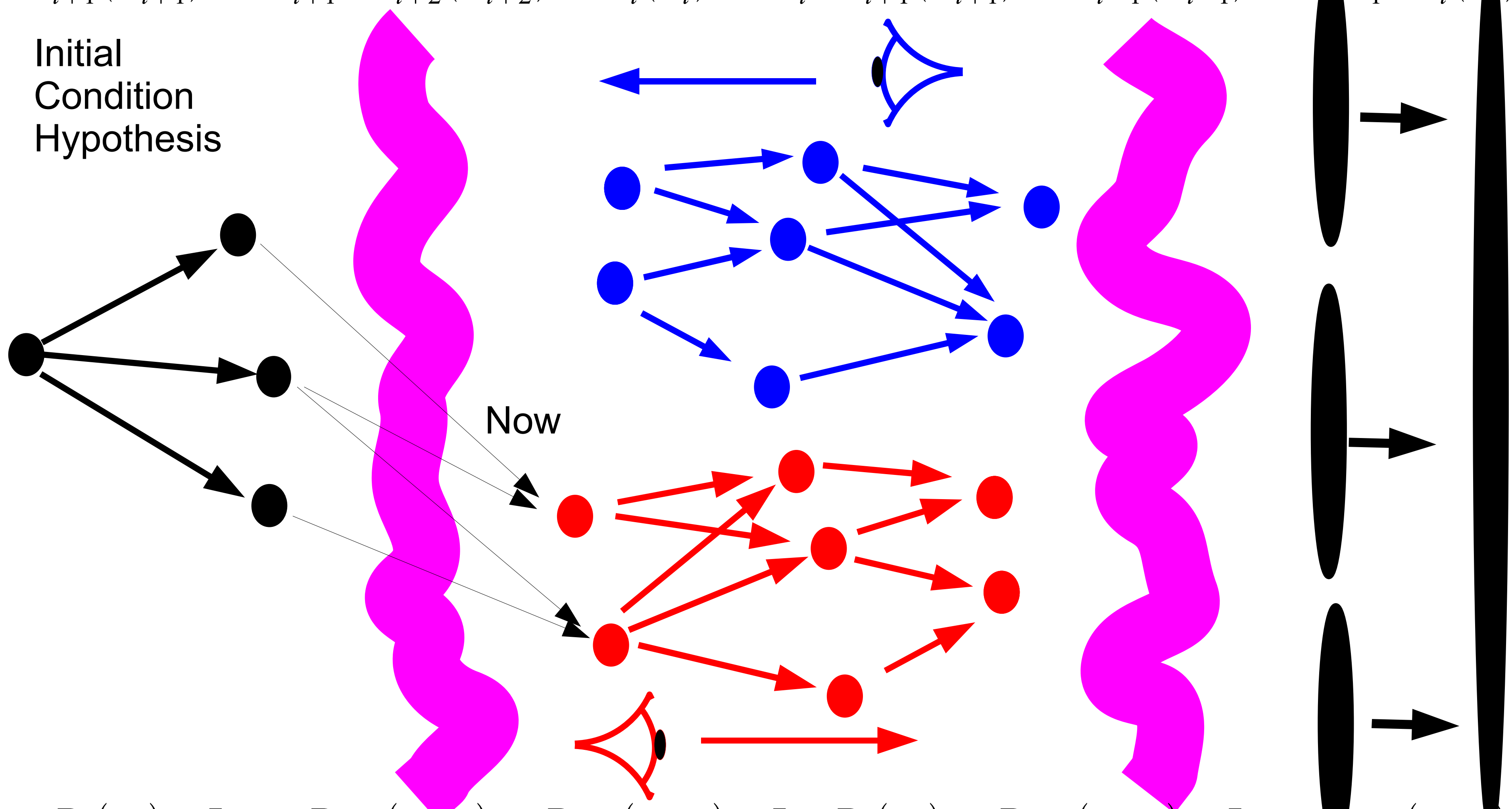


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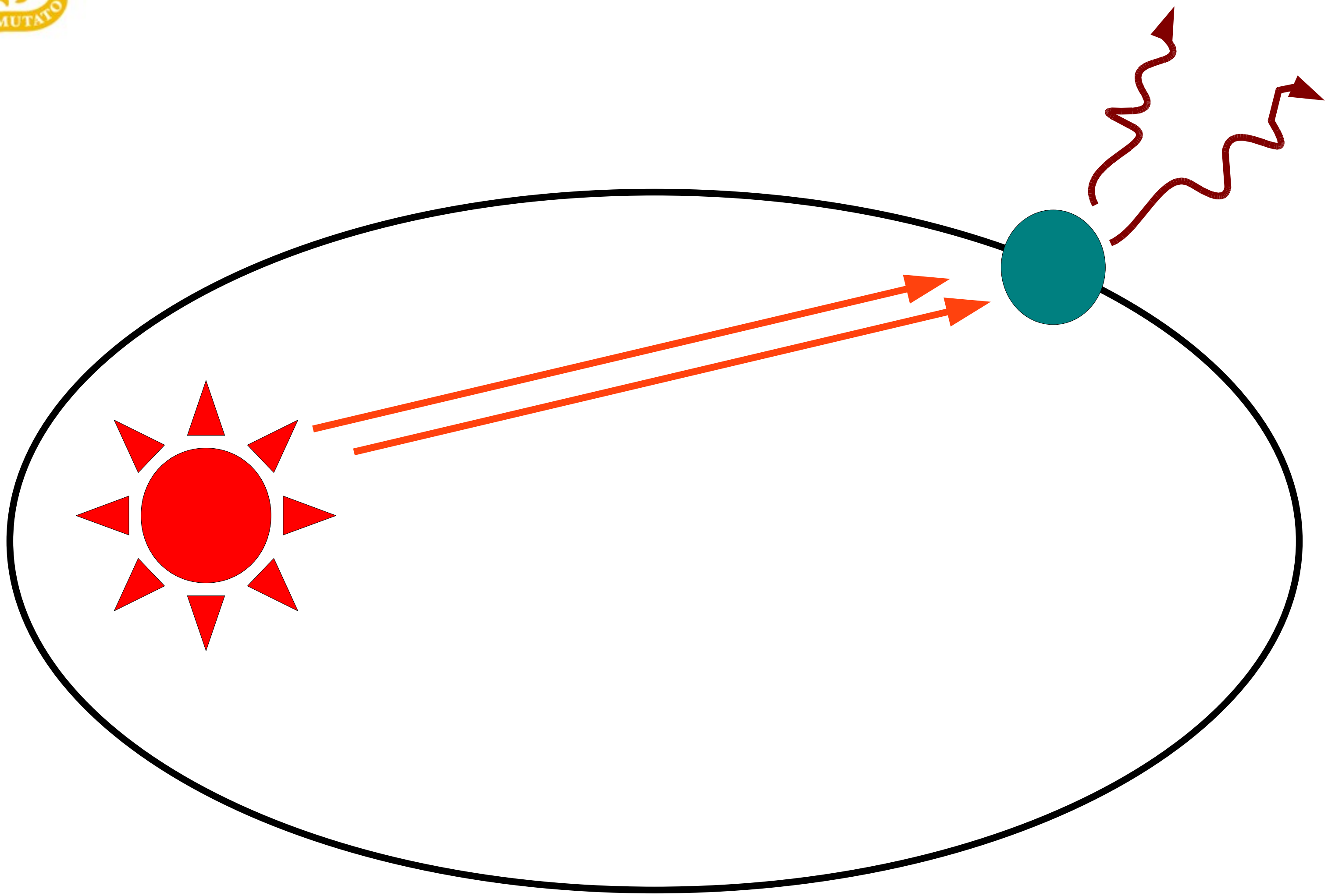
# Entropy increase without ICH



Agents and Arrows

January 2009, Sydney

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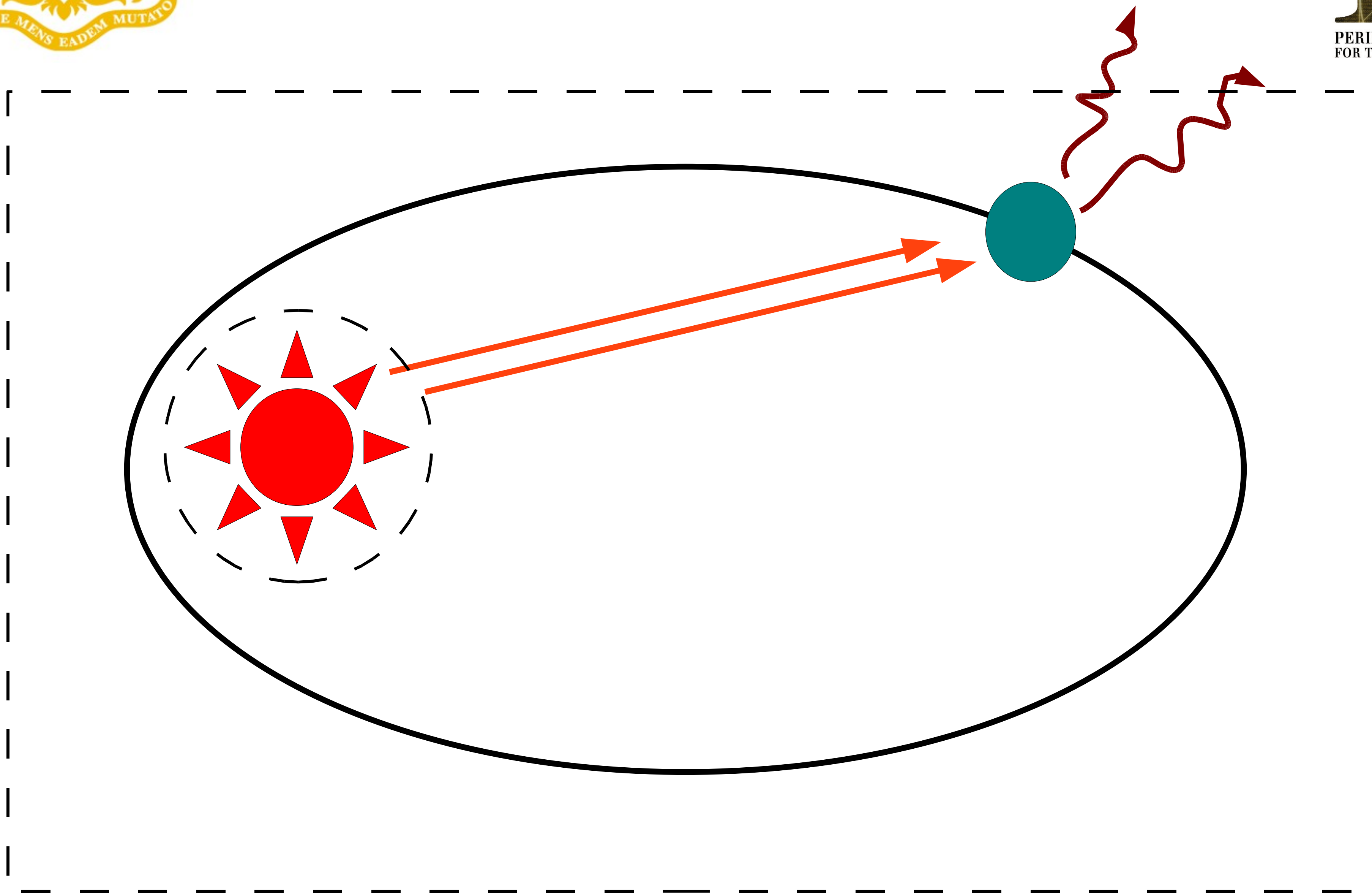

Agents and Arrows

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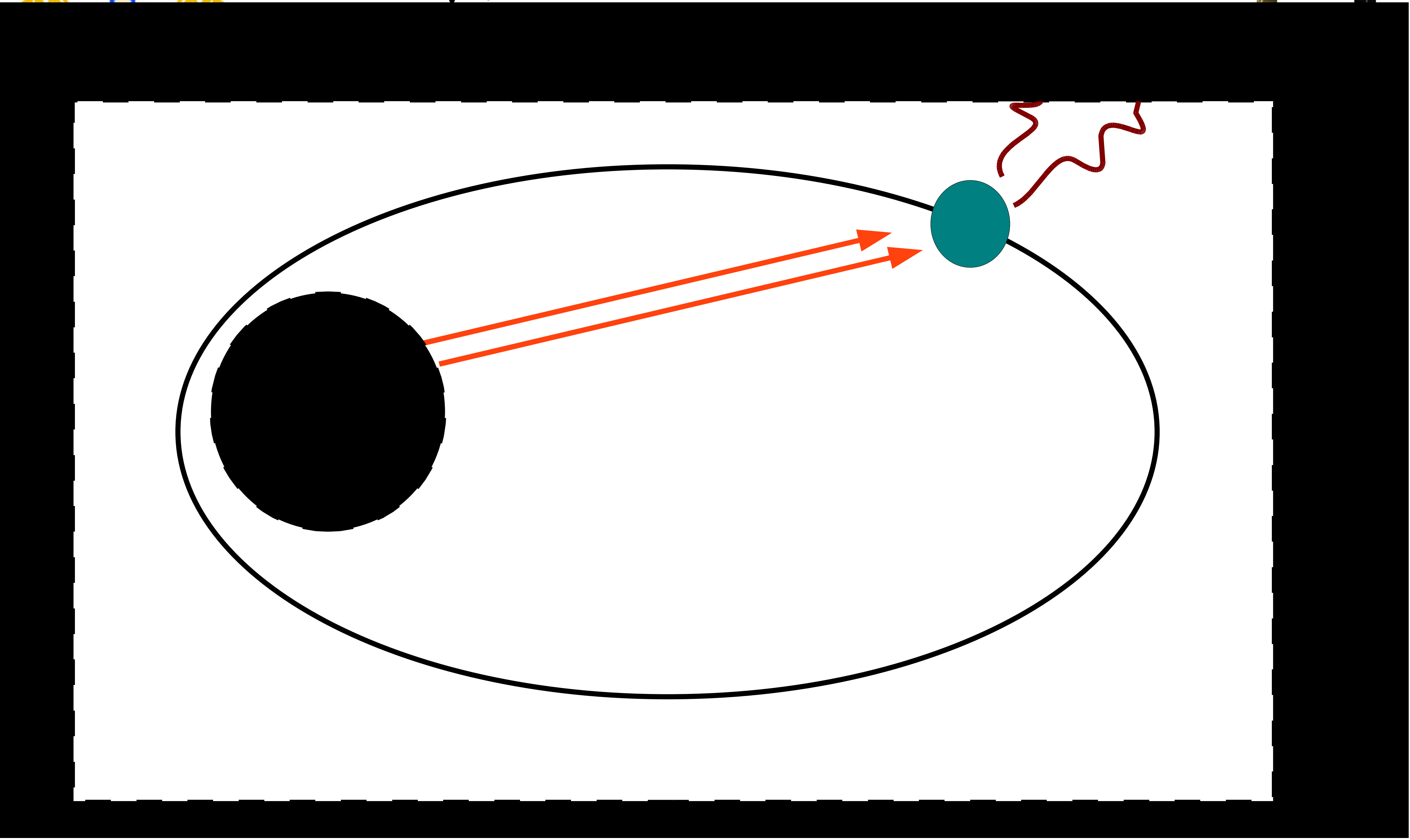

# Conclusion

- Information processing does *not* have an intrinsic alignment to the thermodynamic arrow of time
  - The logical reverse of any computational process may be constructed in an entropy increasing universe. From a reverse time direction, this looks like the original computational process in an entropy decreasing universe.
  - The same goes for *any* type of process that can be instantiated solely in terms of sequences of quasi-static equilibrium states.
- The initial condition hypothesis seems too remote in the past to adequately constrain the actions of causal agents in the present
  - It would need to constrain actions in a way that is not screened off by the local entropy gradient
- This does not mean that the asymmetry of temporal experience is definitely *not* a consequence of the statistical mechanical asymmetry
  - There may be more *evolutionary advantage* to the development of IGUS which utilise information that *has been* gathered, in an entropy increasing, rather than decreasing, universe. (Entropy increasing universes have a macroscopic predictability, entropy decreasing universes have an unpredictability)
- Or just an additional condition?
  - Causal agents agree on the direction of the causal arrow (for self consistency) but the fact that it is entropy increasing, not decreasing, may be just a contingent fact about this universe, and it could have been otherwise.