Time as It Could Be Measured in Artificial Living Systems

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Time measurement as a function of memory

- Why study clock?
- Klyubin et. al (2007) ask an agent to find the goal
  - after reaching goal, analyze its memory
  - information about present time discovered in memory
- A generic phenomenon?
- **Hypothesis**: might be a general property of agent memories in dynamical environments
- **Goal**: understanding the “extreme” case of “pure” time measurement

Klyubin, A. S., Polani, D., and Nehaniv, C. L. (2007). Representations of space and time in the maximization of information flow in the perception-action loop. Neural Computation, 19(9):2387–2432.

How do we "study the measurement of time"?

- Focus on small clocks because:
  - easier to treat mathematically
  - Ockham's razor
  - evolution might minimise cost
- Here, clock complexity given by size of state space

What is a clock?

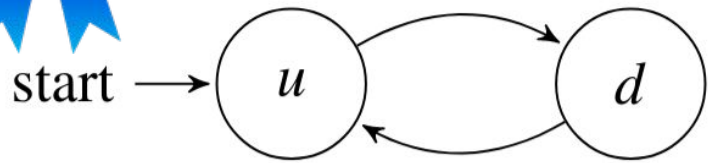
- A clock gives you information about time
- Our clocks are Markov processes P(S|T)
- Model time as (finite) sequence of integers
  - (i.e.: 1, 2, 3, 4, 5… N)
- Performance of clocks given by **I(*S*;*T*)**
  - (mutual information about time from the state of the clock)
  - Colloquially: “How much do I know about the present time T if I fall asleep and wake up and all I see is the state of the clock?”

The Computer Experiments

- Drop clock
  - Simplest clock
- Bag of Clocks
  - More of them
- Composite Clock
  - Put two clocks together

Examples of Minimal Clocks

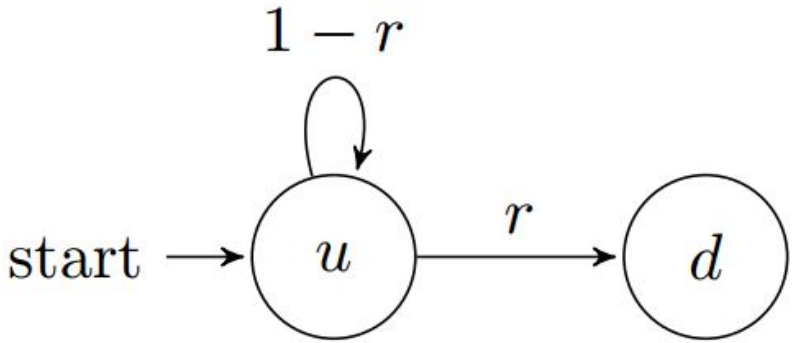
Alternator



Example:

- u d u d u d u d u d u d u d u d u d ....

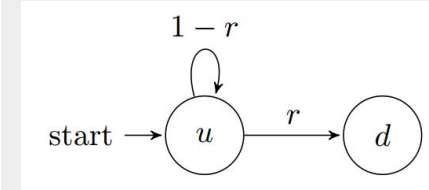
Drop Clock



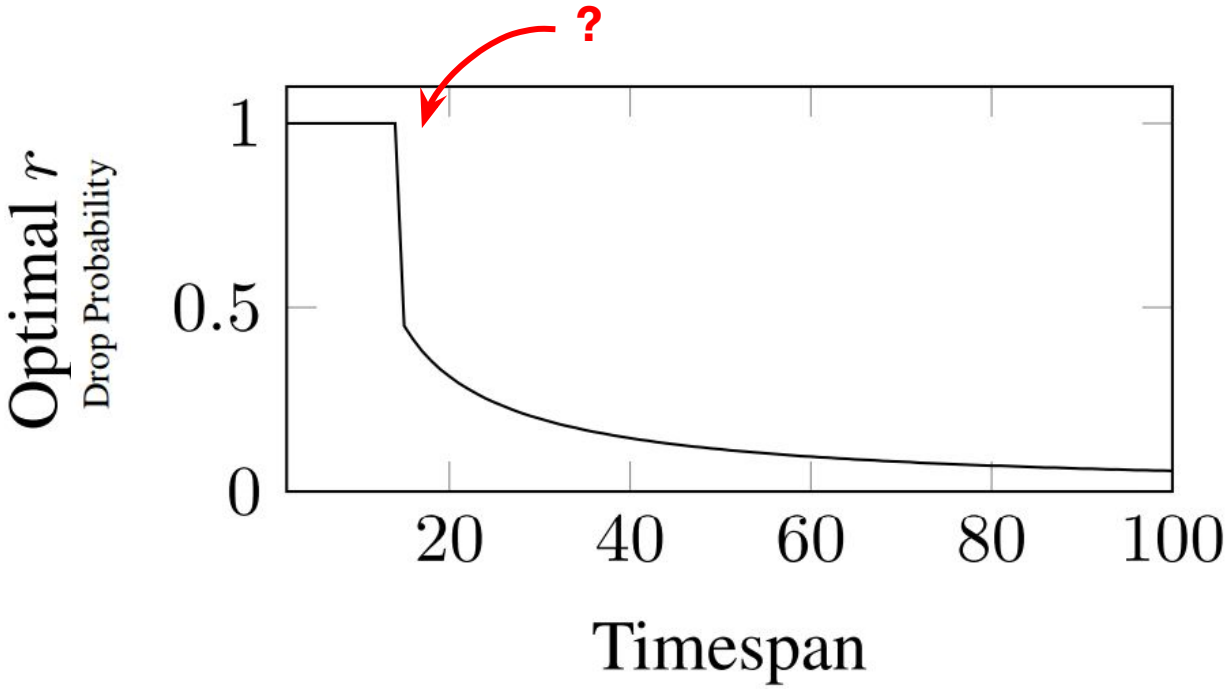
Examples:

- u u u u u u u u u u d d d d d d d d d ....
- u u u d d d d d d d d d d d d d d d d ...

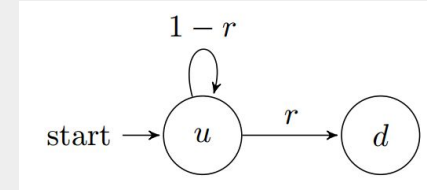
What is the best Drop Clock?

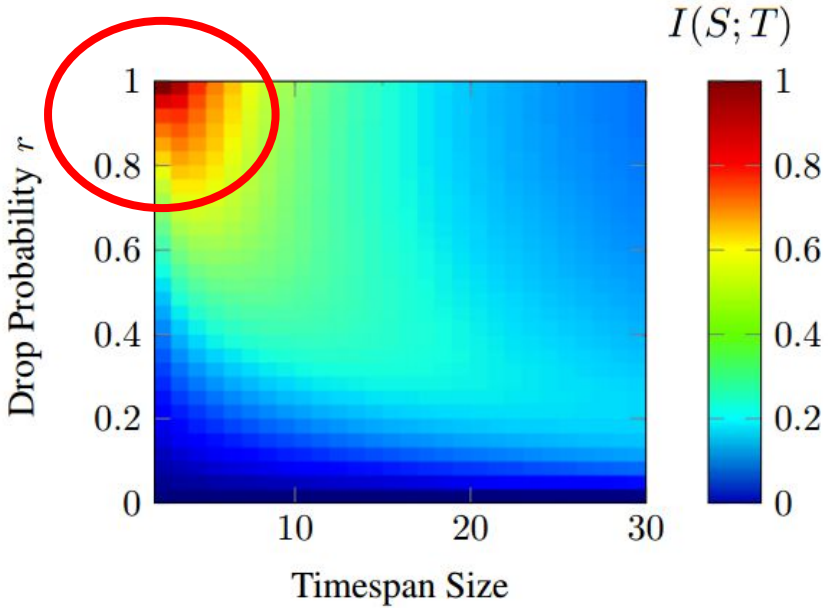


- Depends on the timespan.



All drop clocks for all time spans

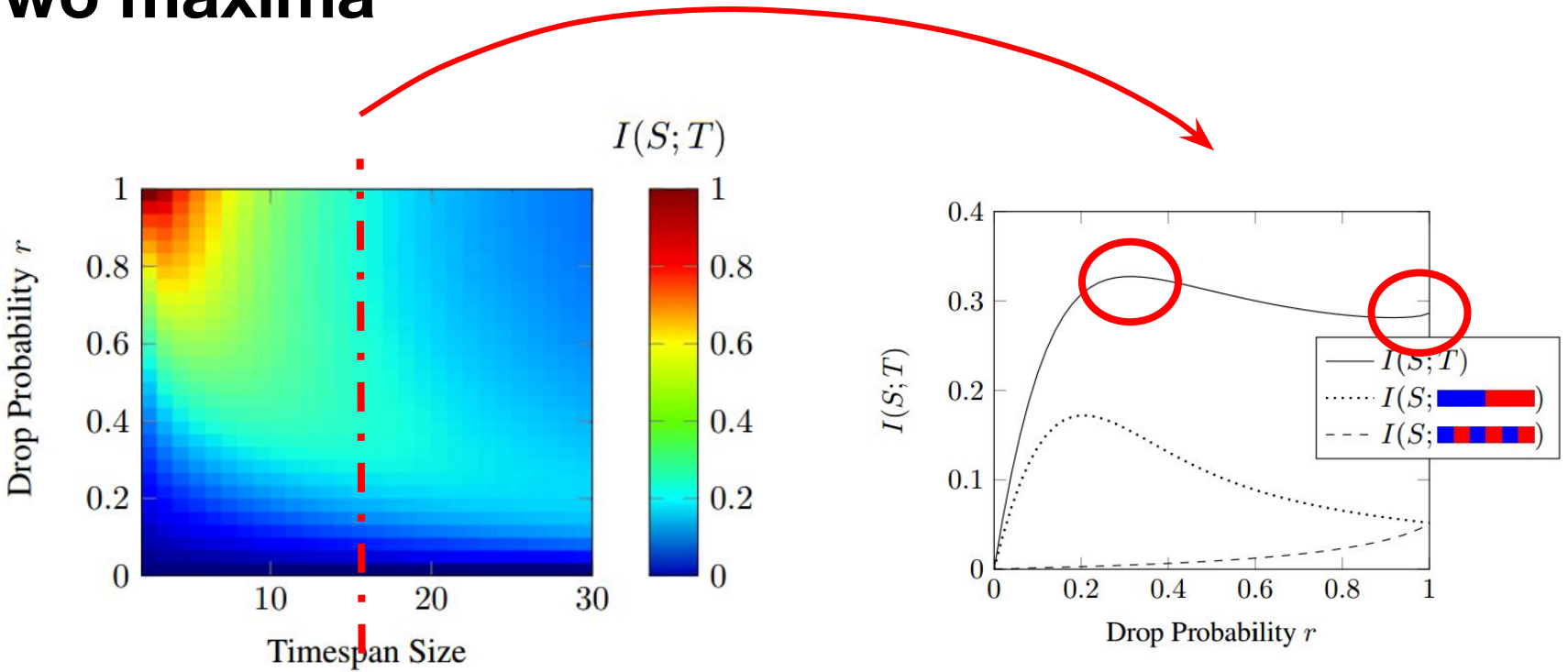




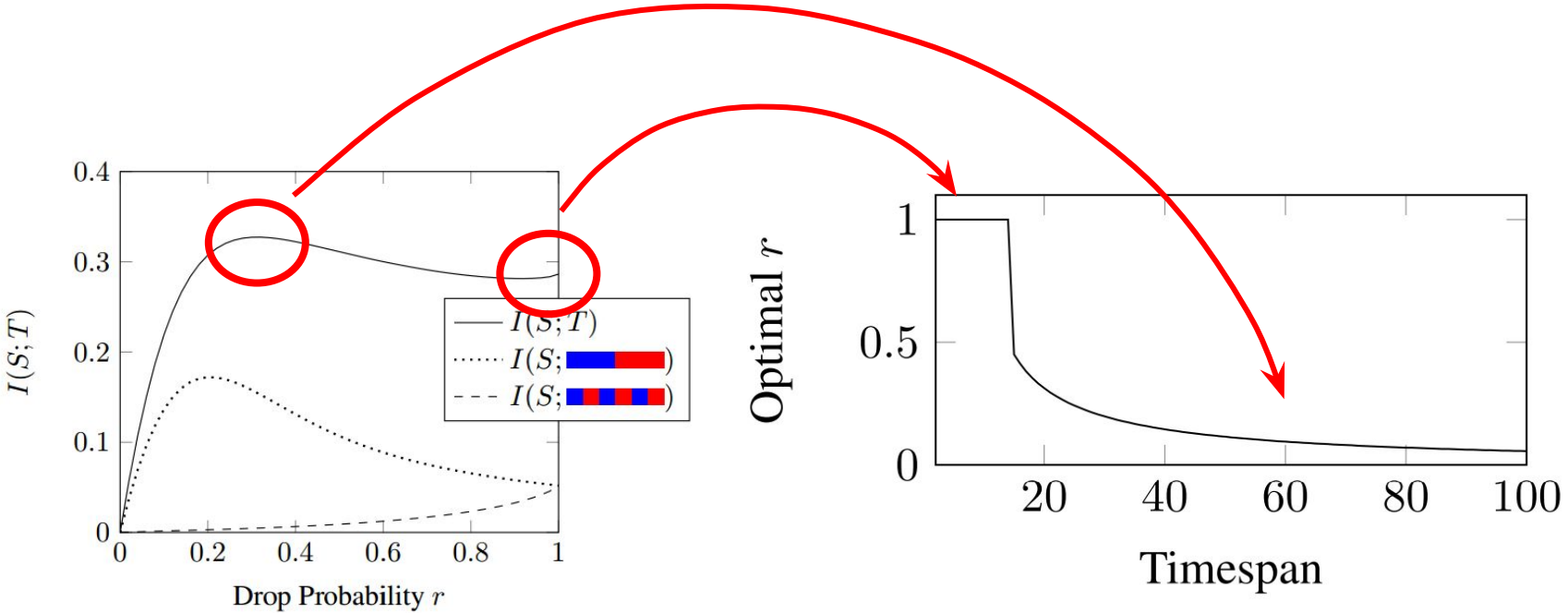
Red means high performance

Blue means low performance

Two maxima

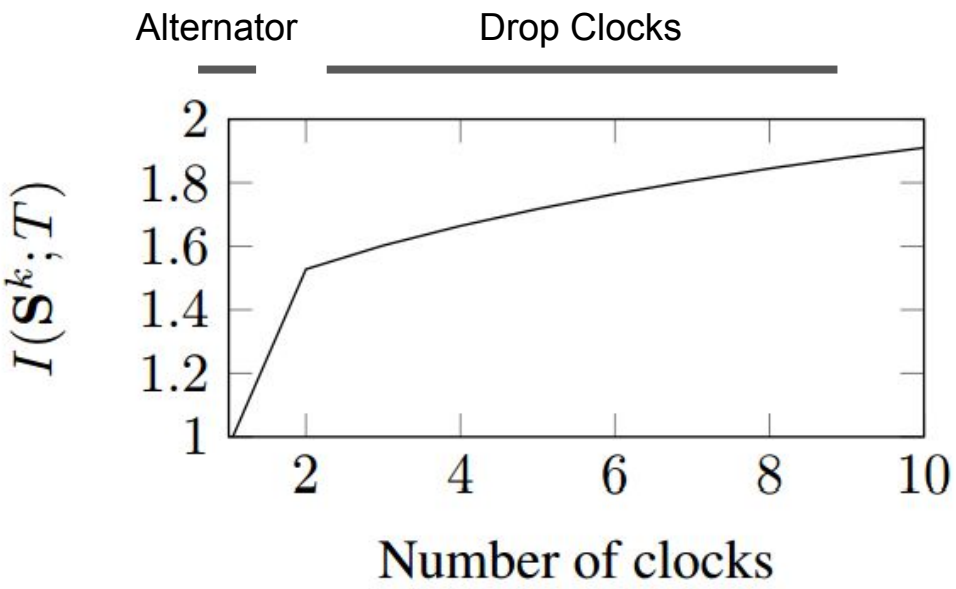

$I(S;T)$
Drop Probability r
Timespan Size
1
0.8
0.6
0.4
0.2
0
10
20
30
$I(S;T)$
Drop Probability r
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1

Discontinuity reason



Bag of Clocks

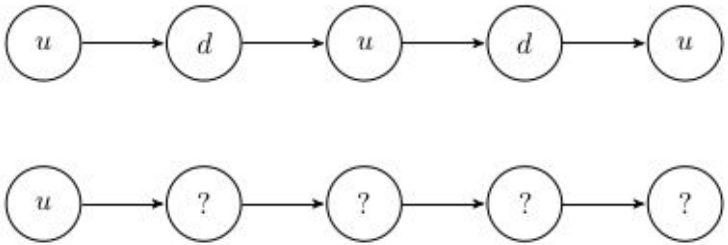
- And if you can afford more?
- How does time information grow with more parallel small clocks?



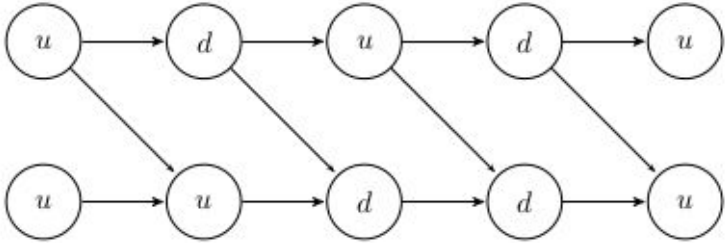
Composite Clock

- We "connect" the bottom clock to the upper one
  - Now the lower clock can read the upper one
- What if you connect them perfectly? You simply get a counter.

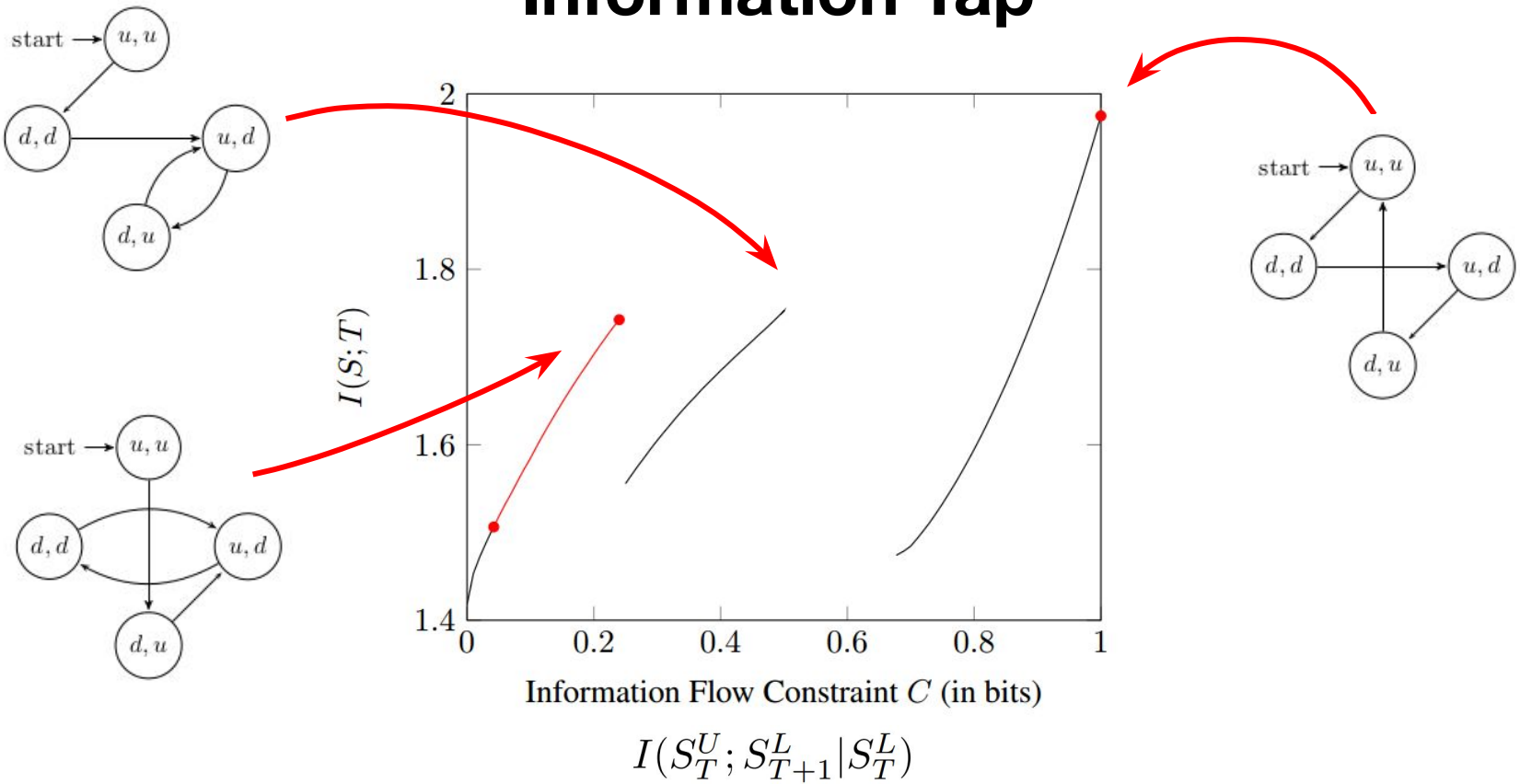
No connection



Full connection



Information Tap



$$I(S_T^U; S_{T+1}^L | S_T^L)$$

Final Comments and Future Work

- We studied the ability of minimal clocks to measure time
  - even 1 bit clocks can provide some "global" time information.
- connecting two clock modules with a cap on information exchange
  - found different types of clocks along the tradeoff curve
- some clocks appear more fundamental (drop and alternator)
  - of course, oscillators and counters are ubiquitous
- using discrete time means “global ticks” shared by all clocks
- we have not yet studied how “ticks” could be “agreed” upon across clocks