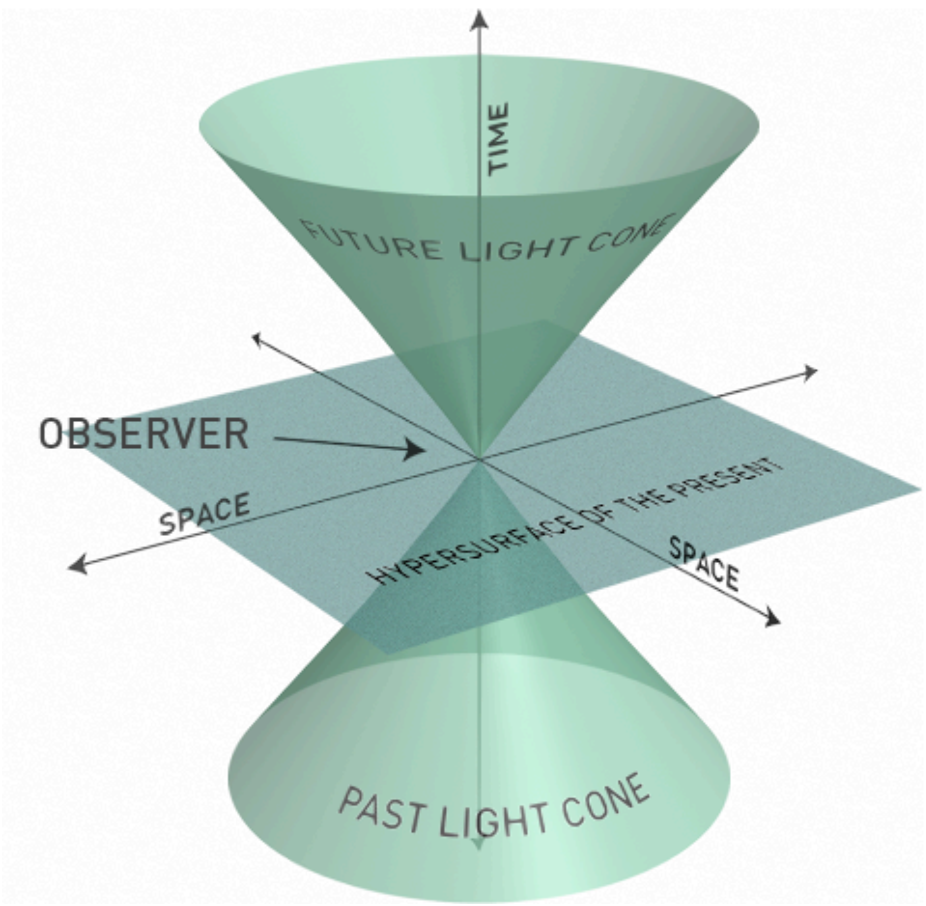
The Cyber-Physical Limits of Control

Alex Wissner-Gross, Ph.D.

Harvard Institute for Applied Computational Science
Harvard Innovation Lab
MIT Media Laboratory
Gemedy, Inc.

Overview

As the speed of computer systems and their integration with the physical world have grown, the **physical limits of control** have become increasingly relevant for ensuring high confidence in cyber systems.



Two key **physical limits** for realizing optimal coordination & control in cyber-physical systems:

Time-Like Limit

Maximum causal entropy

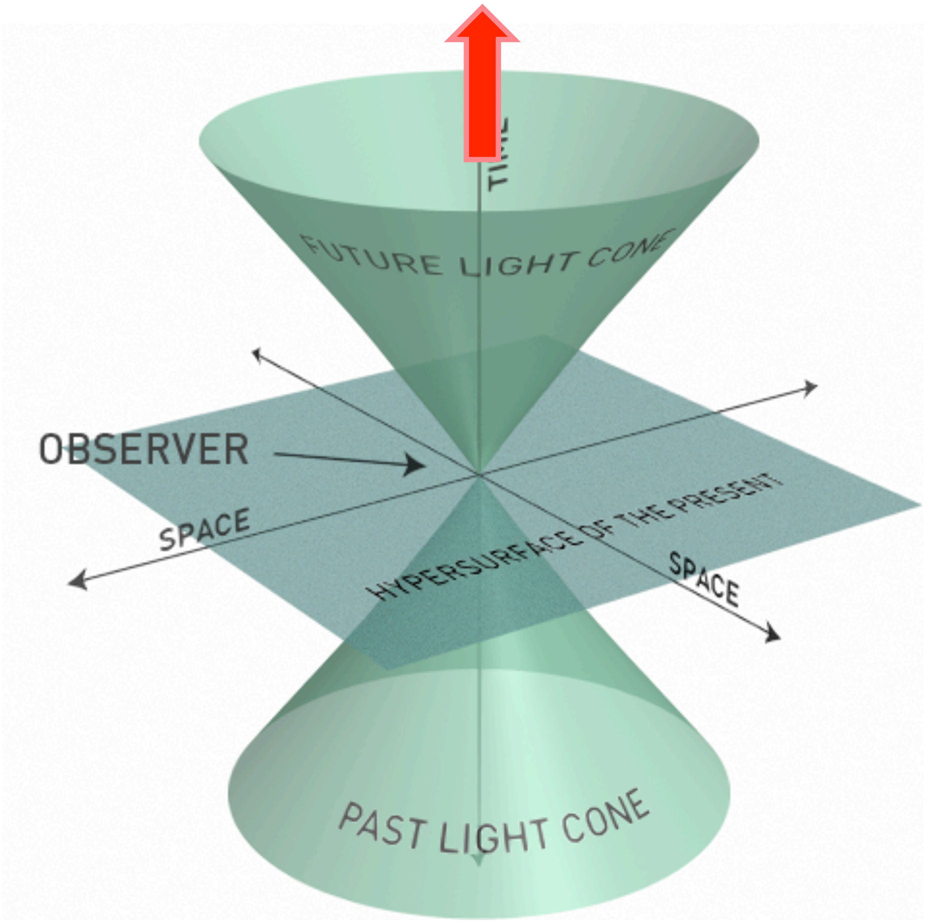
Space-Like Limit

Minimum coordination latency

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Overview

As the speed of computer systems and their integration with the physical world have grown, the **physical limits of control** have become increasingly relevant for ensuring high confidence in cyber systems.



Two key **physical limits** for realizing optimal coordination & control in cyber-physical systems:

Time-Like Limit

Maximum causal entropy

Space-Like Limit

Minimum coordination latency

A new approach to intelligence

"The question of whether Machines Can Think... is about as relevant as the question of whether Submarines Can Swim." -- Edsger W. Dijkstra

"How can we fly like birds?" ⟶ "What is the physical phenomenology of flight?"

(HARDER) (EASIER)

"How can we build minds?" ⟶ "What is the physical phenomenology of intelligence?"

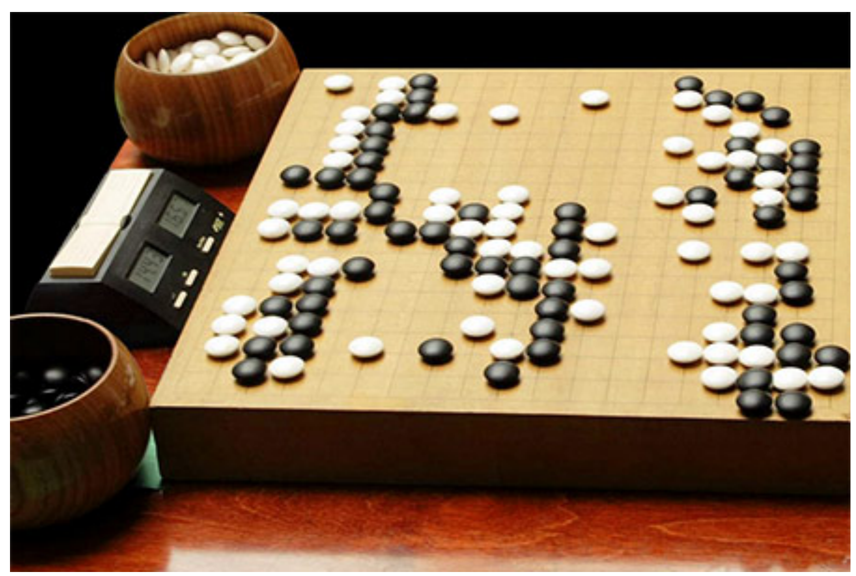
(HARDER) (EASIER?)

Hints of a deep connection between "keeping future options open" and intelligence

Cosmology

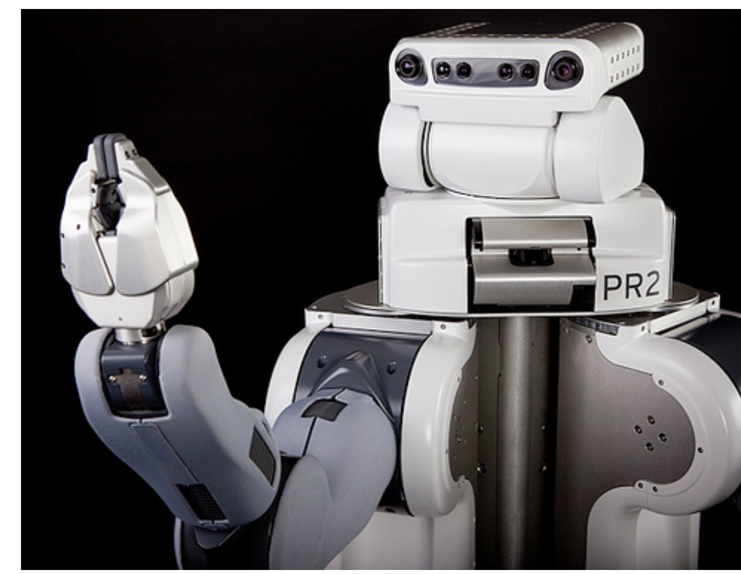
Causal Entropic Principle (2007)

Games



MoGo (2006)

Robotics



Willow Garage PR Path Planning (2006)

http://www.harpers.org/media/image/blogs/misc/cosmos.jpg

http://www.collegedegrees.com/wp-content/uploads/Go(1).jpg

http://farm5.static.flickr.com/4128/4986537007_e9ac89ac90.jpg

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

We recently took a major step toward this connection

PRL **110,** 168702 (2013) PHYSICAL REVIEW LETTERS week ending 19 APRIL 2013

Causal Entropic Forces

A. D. Wissner-Gross[1,2,*] and C. E. Freer[3,†]

[1]*Institute for Applied Computational Science, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*The Media Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Department of Mathematics, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA*
(Received 24 May 2012; revised manuscript received 26 February 2013; published 19 April 2013)

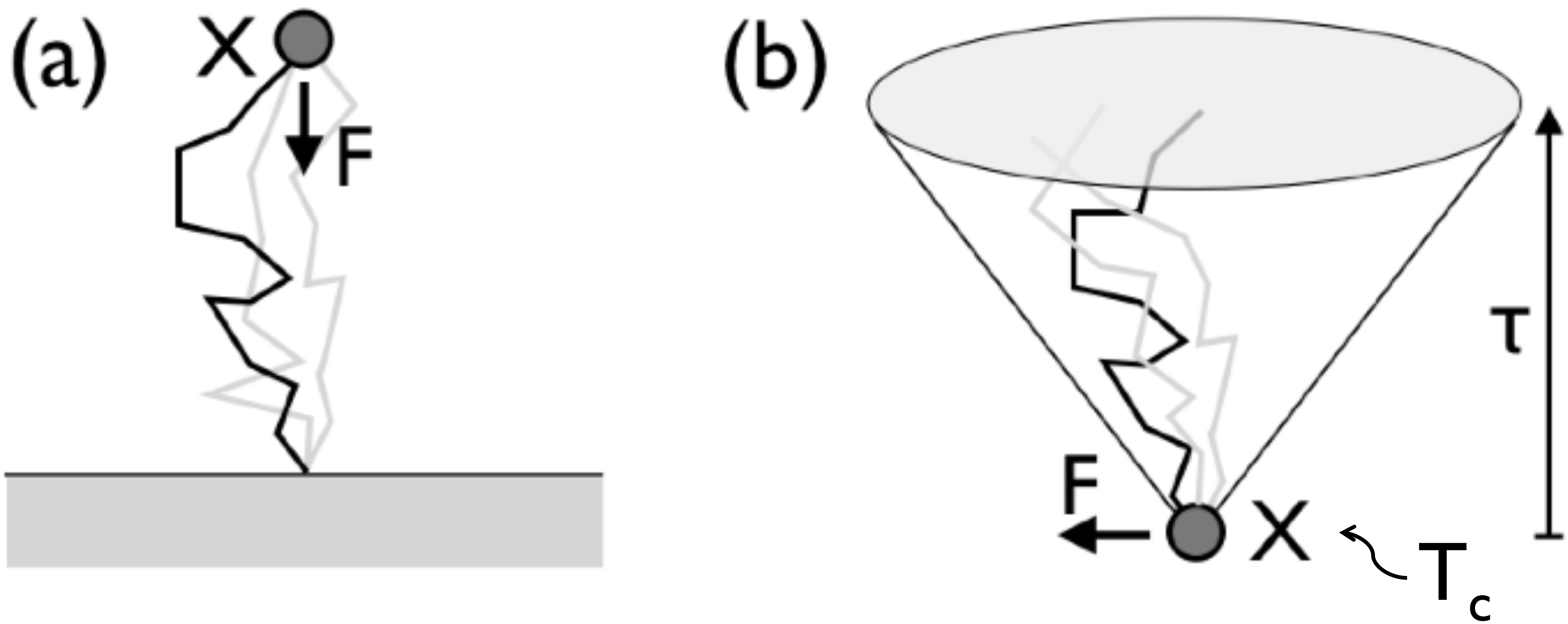
Recent advances in fields ranging from cosmology to computer science have hinted at a possible deep connection between intelligence and entropy maximization, but no formal physical relationship between them has yet been established. Here, we explicitly propose a first step toward such a relationship in the form of a causal generalization of entropic forces that we find can cause two defining behaviors of the human "cognitive niche"—tool use and social cooperation—to spontaneously emerge in simple physical systems. Our results suggest a potentially general thermodynamic model of adaptive behavior as a nonequilibrium process in open systems.

Formalizing the connection

"Keeping Options Open" / "Capturing Possible Futures"
→ Constrained Maximization of Causal Entropy
→ Causal Entropic Force

Just like an entropic force from polymer physics…

…but rotated in spacetime to "thermally" drive a present macrostate between path microstates.



web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Theory

$$\mathbf{F}(\mathbf{X_0}, \tau) = T_c \nabla_{\mathbf{X}} S_c(\mathbf{X}, \tau)|_{\mathbf{X}_0}$$

⇩

$$F_j(\mathbf{X_0}, \tau) = -\frac{2T_c}{T_r} \int_{\mathbf{x}(t)} f_j(0) \Pr(\mathbf{x}(t)|\mathbf{x}(0)) \ln \Pr(\mathbf{x}(t)|\mathbf{x}(0)) \, \mathcal{D}\mathbf{x}(t)$$

⇩

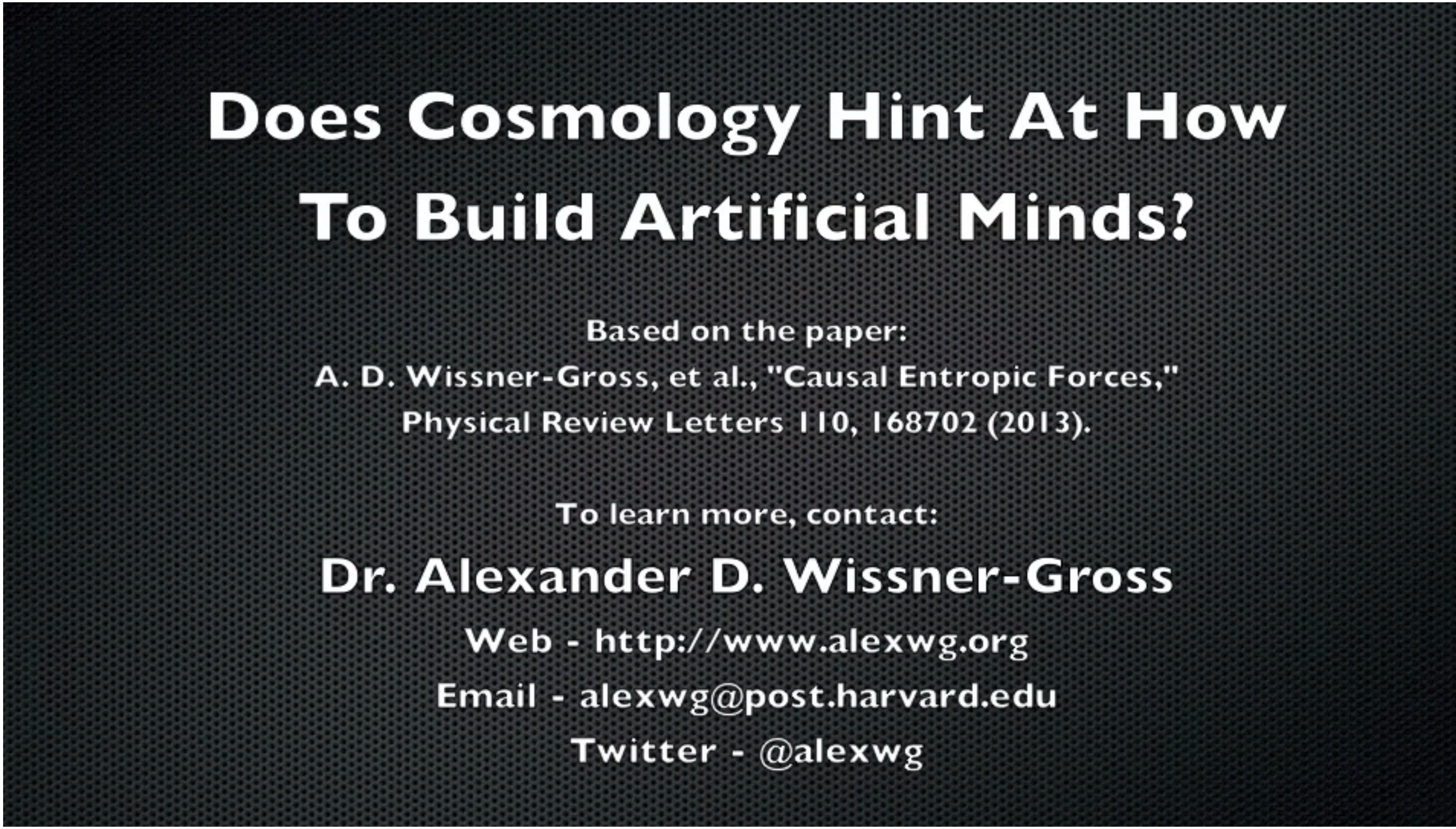
$$F_j(\mathbf{X_0}, \tau) \approx \left\langle \frac{2T_c}{T_r} \frac{1}{M} \sum_i f_{ij}(0) \ln \frac{\Omega_i}{\sum_{i'} \Omega_{i'}} \right\rangle$$

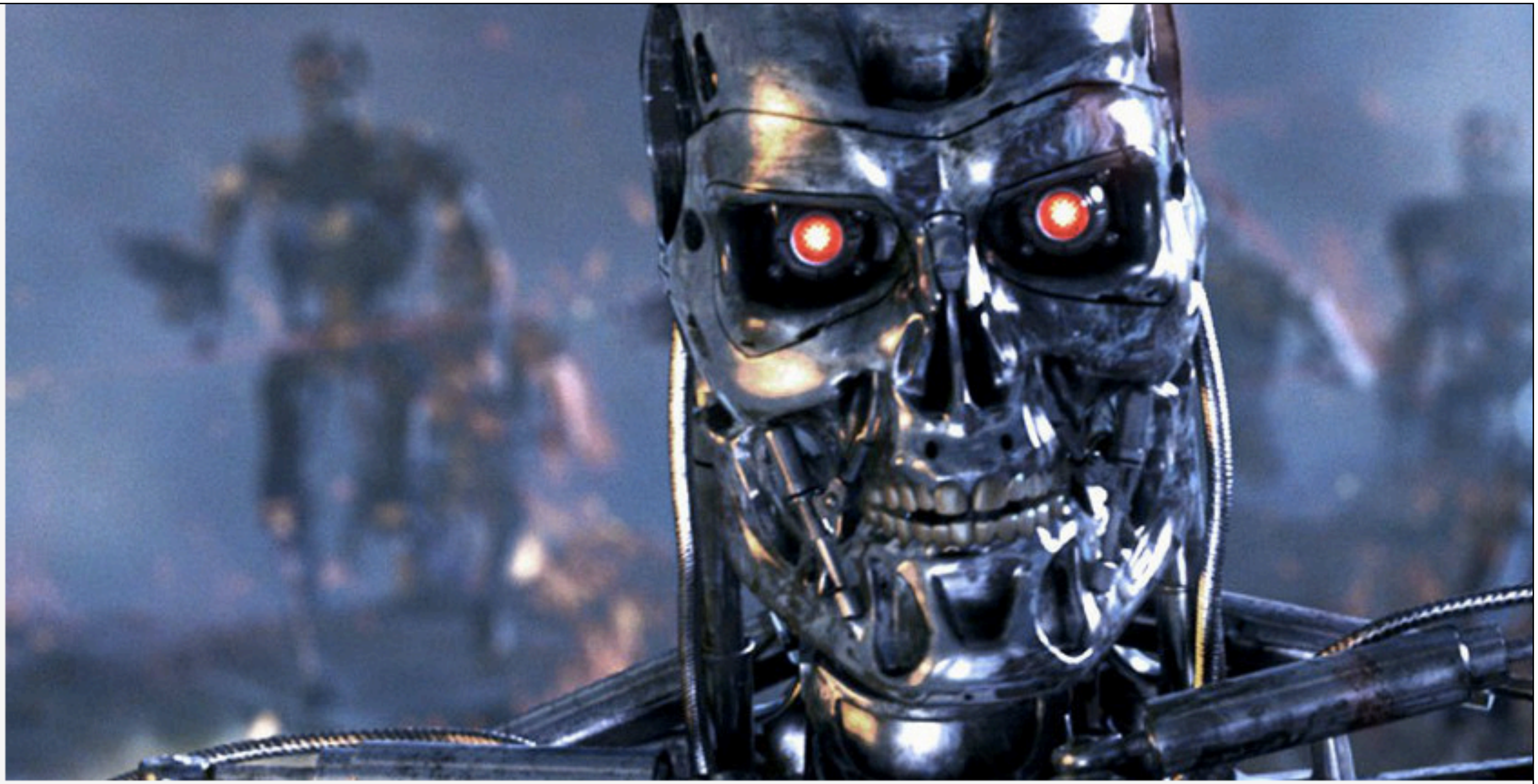
Universal: Only 2 free parameters for <u>any</u> system…

T_c (“strength”) τ (“foresight”)

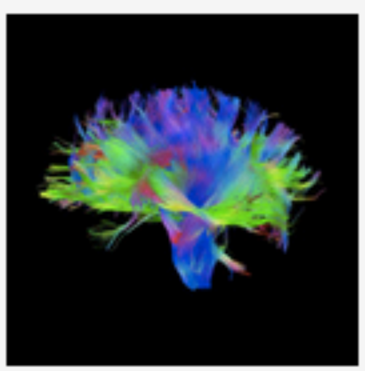
web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Entropica: A Causal Entropy Engine





FUTURISM



GEORGE DVORSKY

Yesterday 9:00am

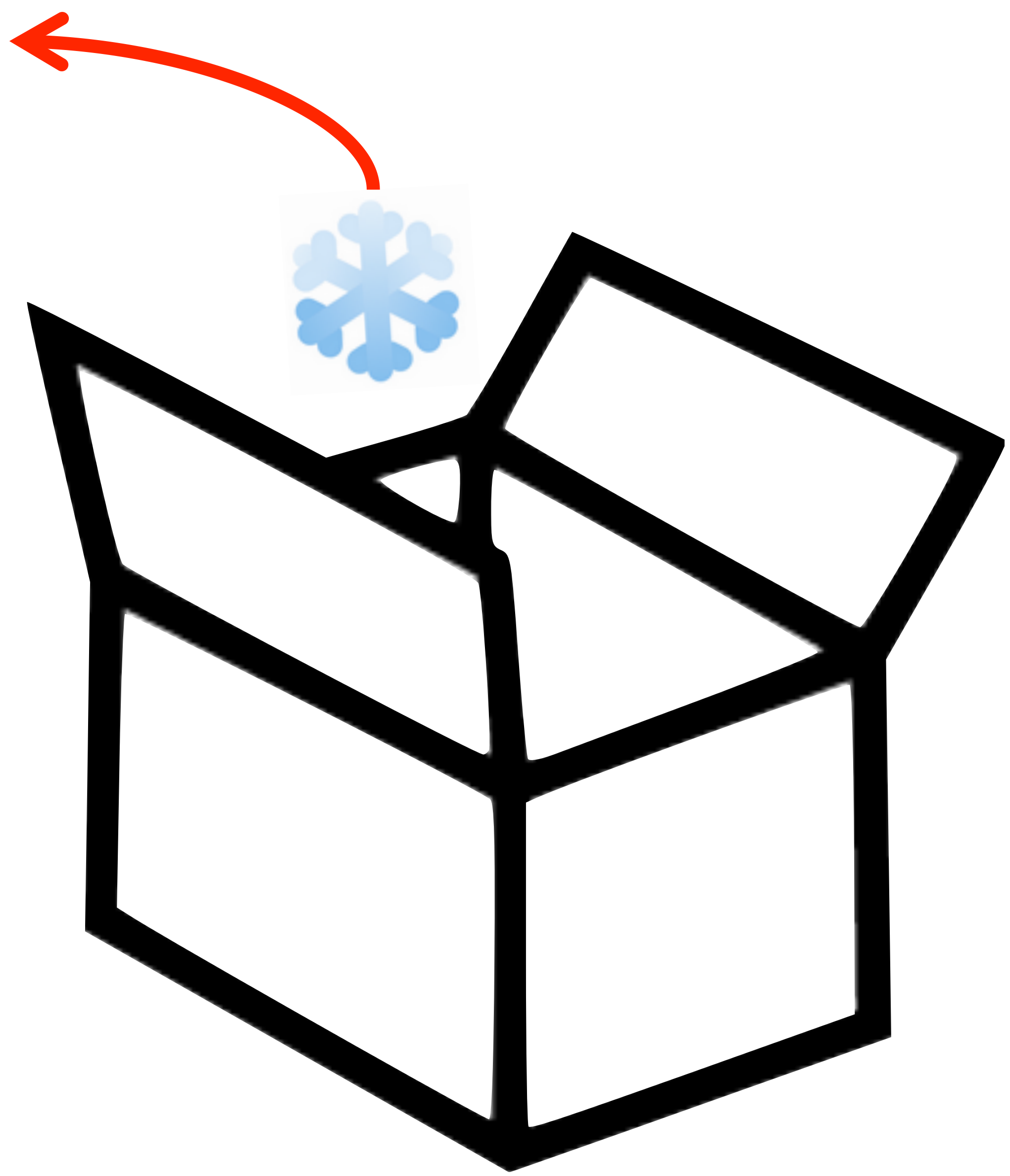
17,603 59

How Skynet Might Emerge From Simple Physics

A provocative new paper is proposing that complex intelligent behavior may emerge from a fundamentally simple physical process. The theory offers novel prescriptions for how to build an AI — but it also explains how a world-dominating superintelligence might come about. We spoke to the lead author to learn more.

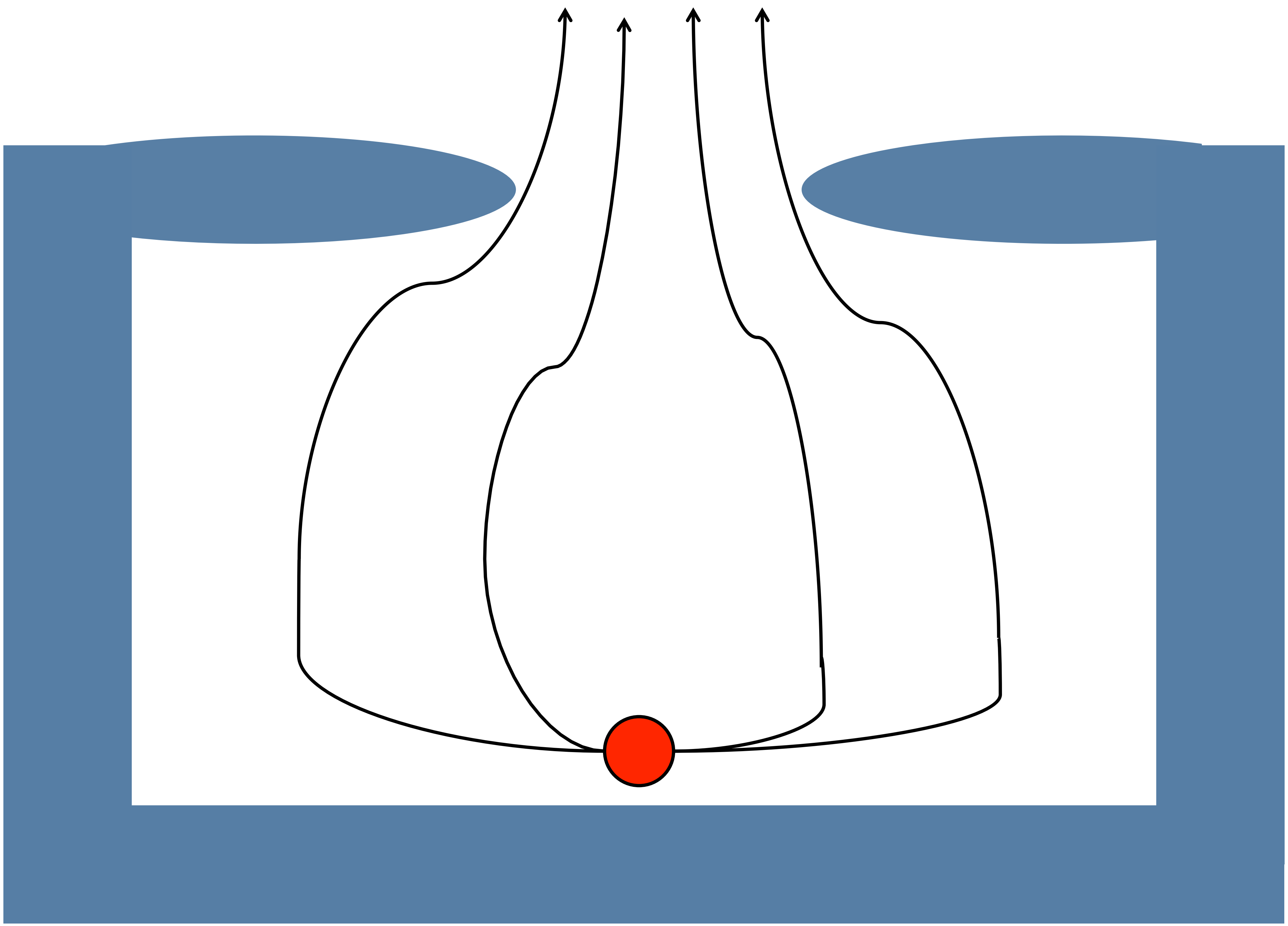
In the paper, which now appears in *Physical Review Letters*, Harvard

The "boxing problem"



Causal entropy maximizing processes are explicitly antithetical to being "boxed"

Goal seeking is a side effect of CEM with bottlenecks



Discussion

Causal entropic forcing has the potential to autonomously analyze and prescribe high-confidence strategic courses of cyber action in circumstances where human-provided objectives either:

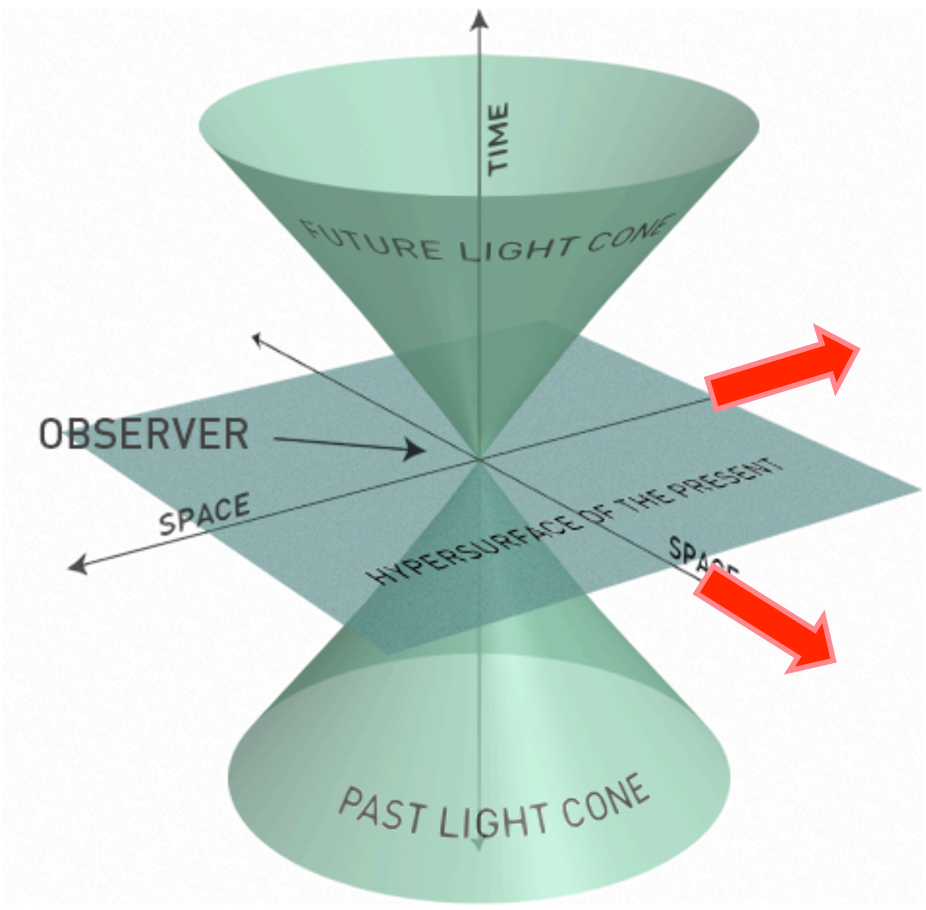
(1) cannot be provided on relevant time scales

(2) are too complex to be formulated by humans

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Overview

As the speed of computer systems and their integration with the physical world have grown, the **physical limits of control** have become increasingly relevant for ensuring high confidence in cyber systems.



Two key **physical limits** for realizing optimal coordination & control in cyber-physical systems:

Time-Like Limit

Maximum causal entropy

Space-Like Limit

Minimum coordination latency

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Global data fusion is driving a latency arms race

Chicago - New York

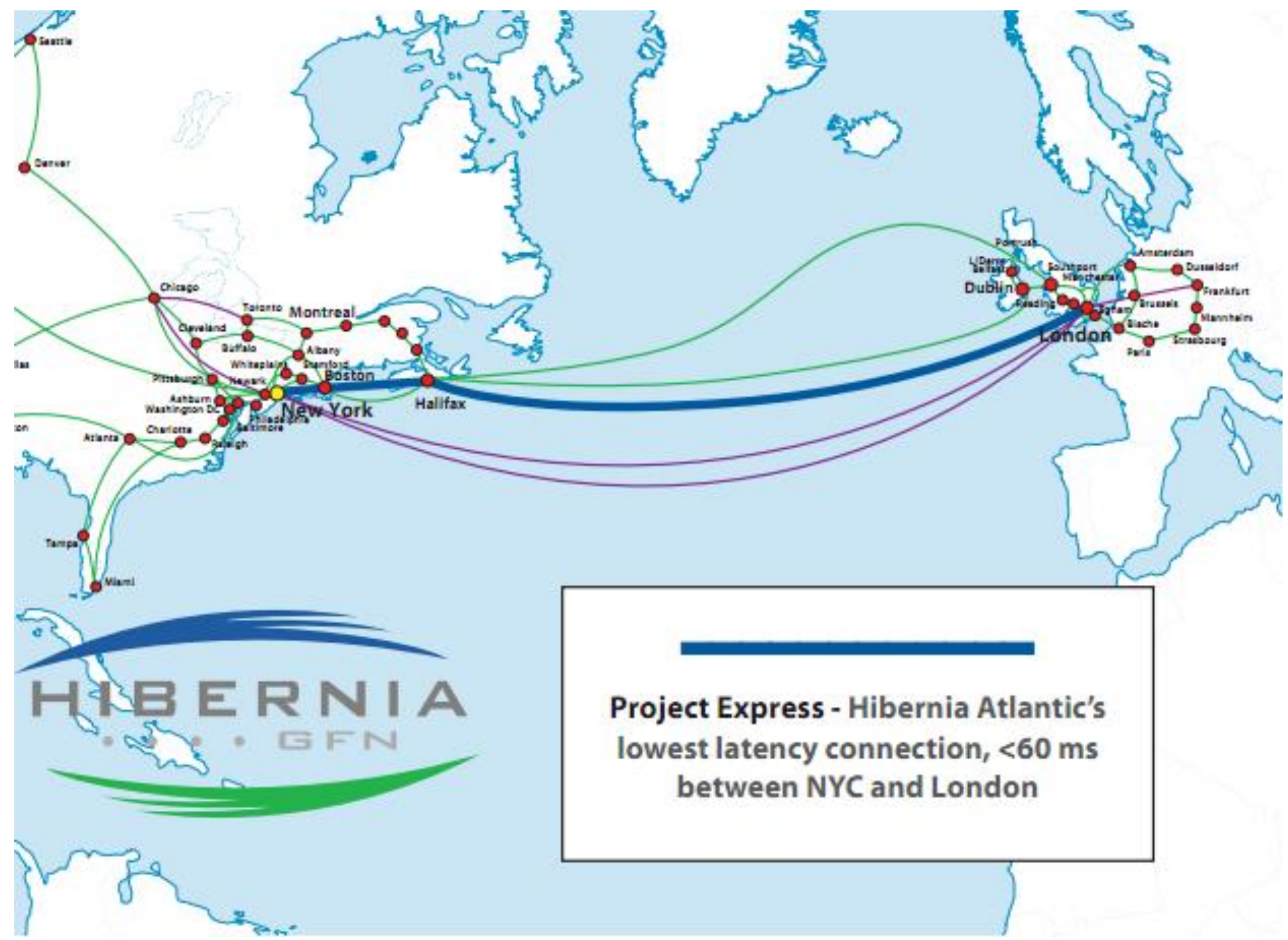
<13.33 ms RTD
(Spread Networks, 2010)

http://www.thewhir.com/web-hosting-news/010511_Hibernia_Atlantic_Secures_250M_Investment_for_New_York_to_London_Connection_Project_Express

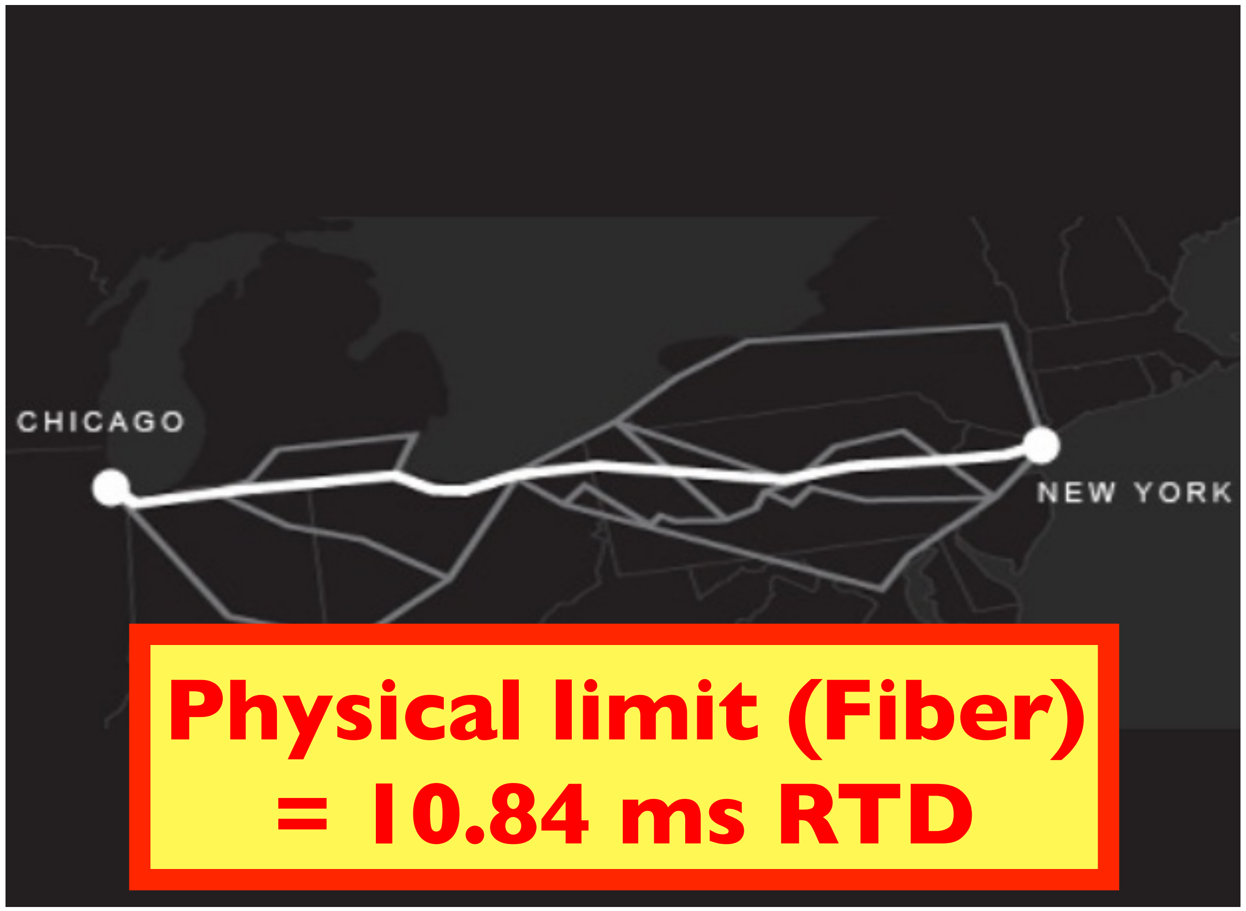
http://www.thewhir.com/web-hosting-news/011111_Spread_to_Connect_Fiber_Network_to_Equinix_New_York_Data_Center

New York - London

<60 ms RTD
(Hibernia Atlantic, 2010)



Global data fusion is driving a latency arms race



Physical limit (Fiber) = 10.84 ms RTD

Chicago - New York

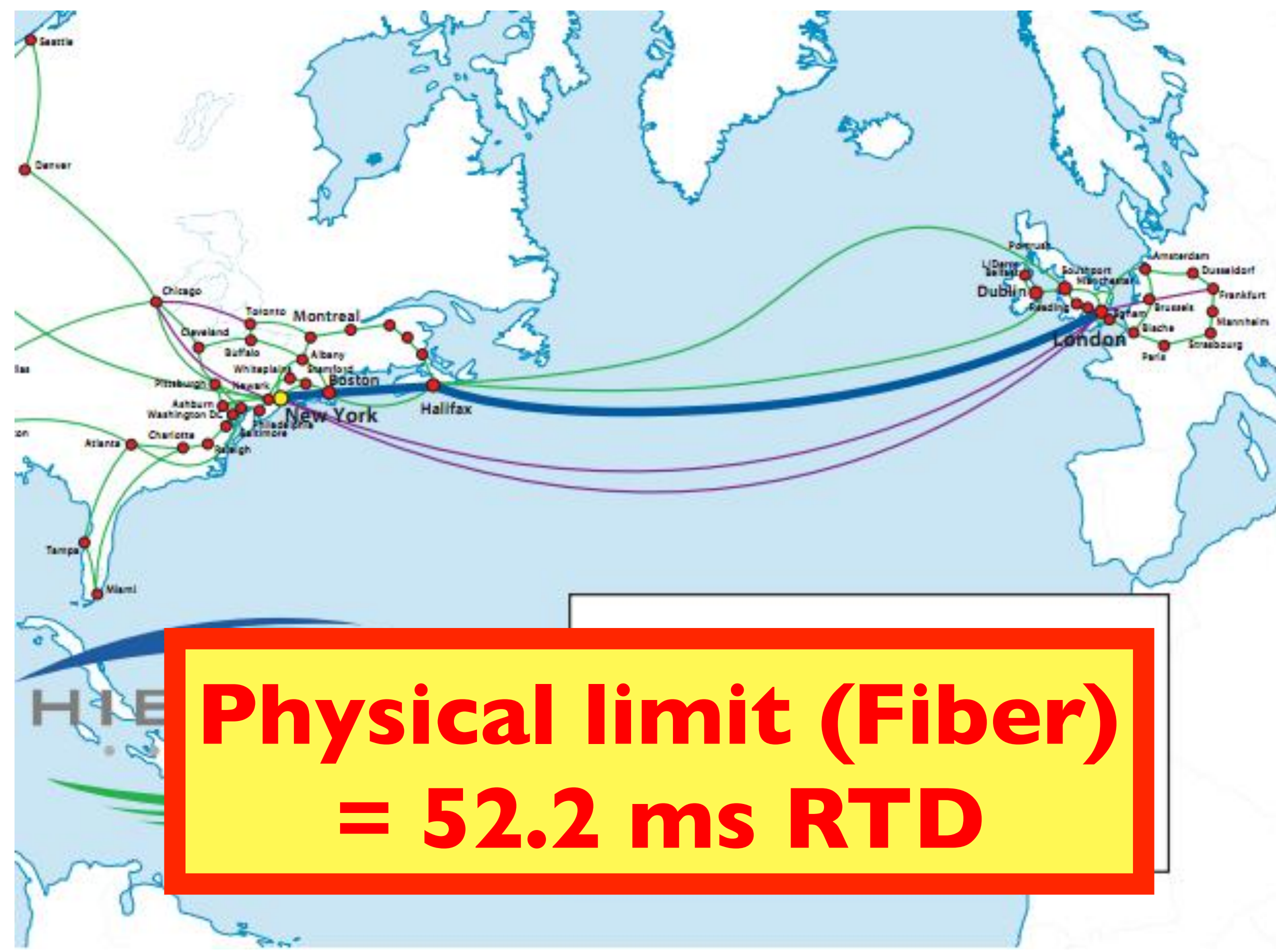
<13.33 ms RTD
(Spread Networks, 2010)

http://www.thewhir.com/web-hosting-news/010511_Hibernia_Atlantic_Secures_250M_Investment_for_New_York_to_London_Connection_Project_Express

http://www.thewhir.com/web-hosting-news/011111_Spread_to_Connect_Fiber_Network_to_Equinix_New_York_Data_Center

New York - London

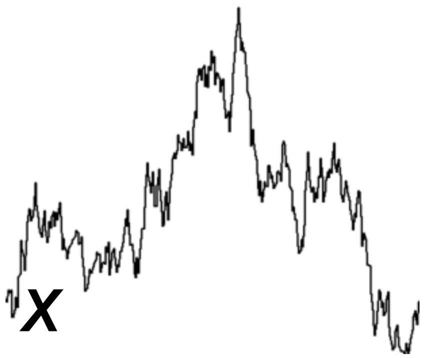
<60 ms RTD
(Hibernia Atlantic, 2010)

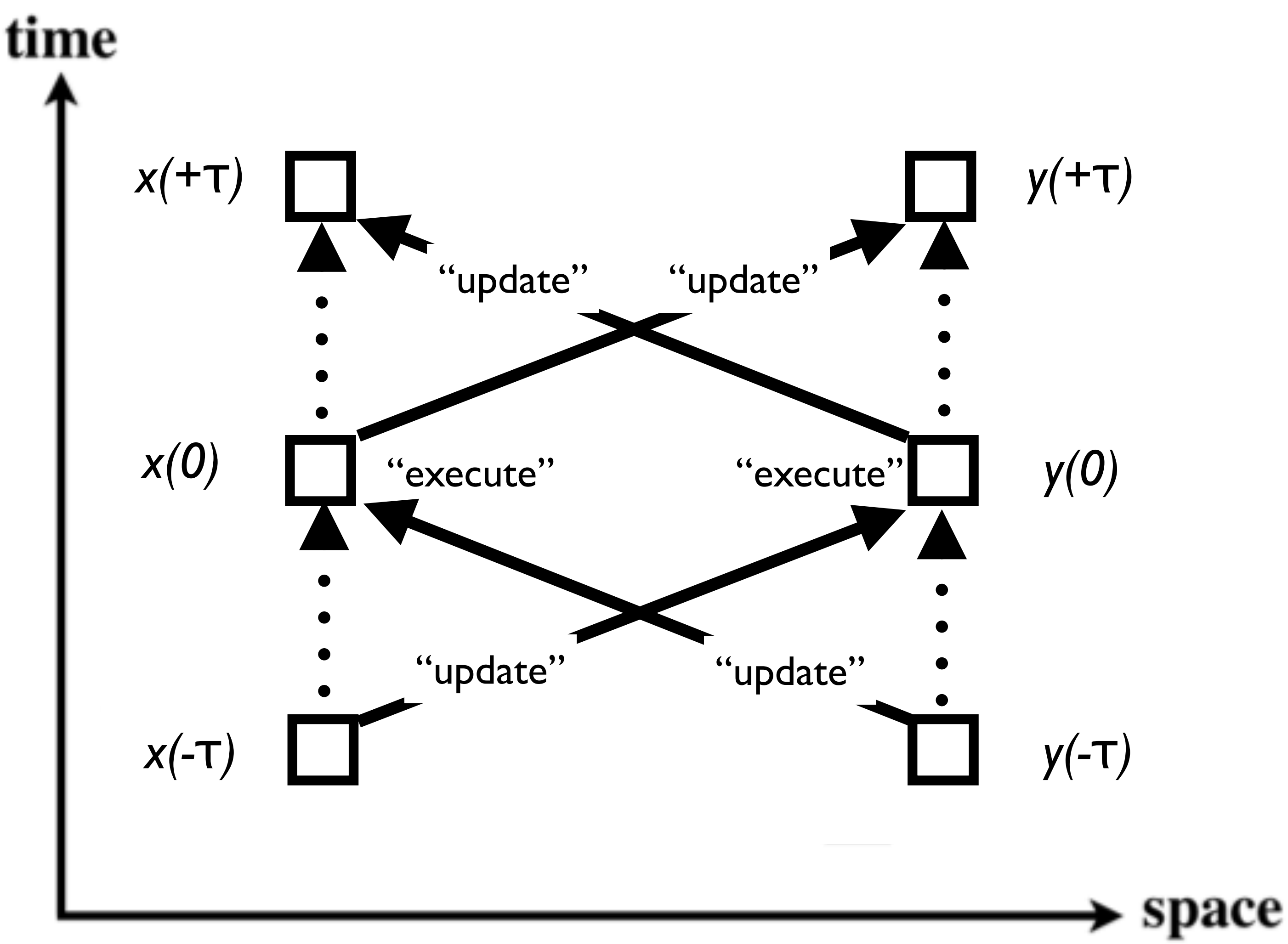


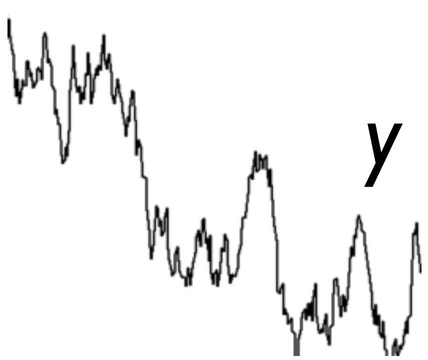
Physical limit (Fiber) = 52.2 ms RTD

But data sources will always be distributed

A generic spatially extended transaction:





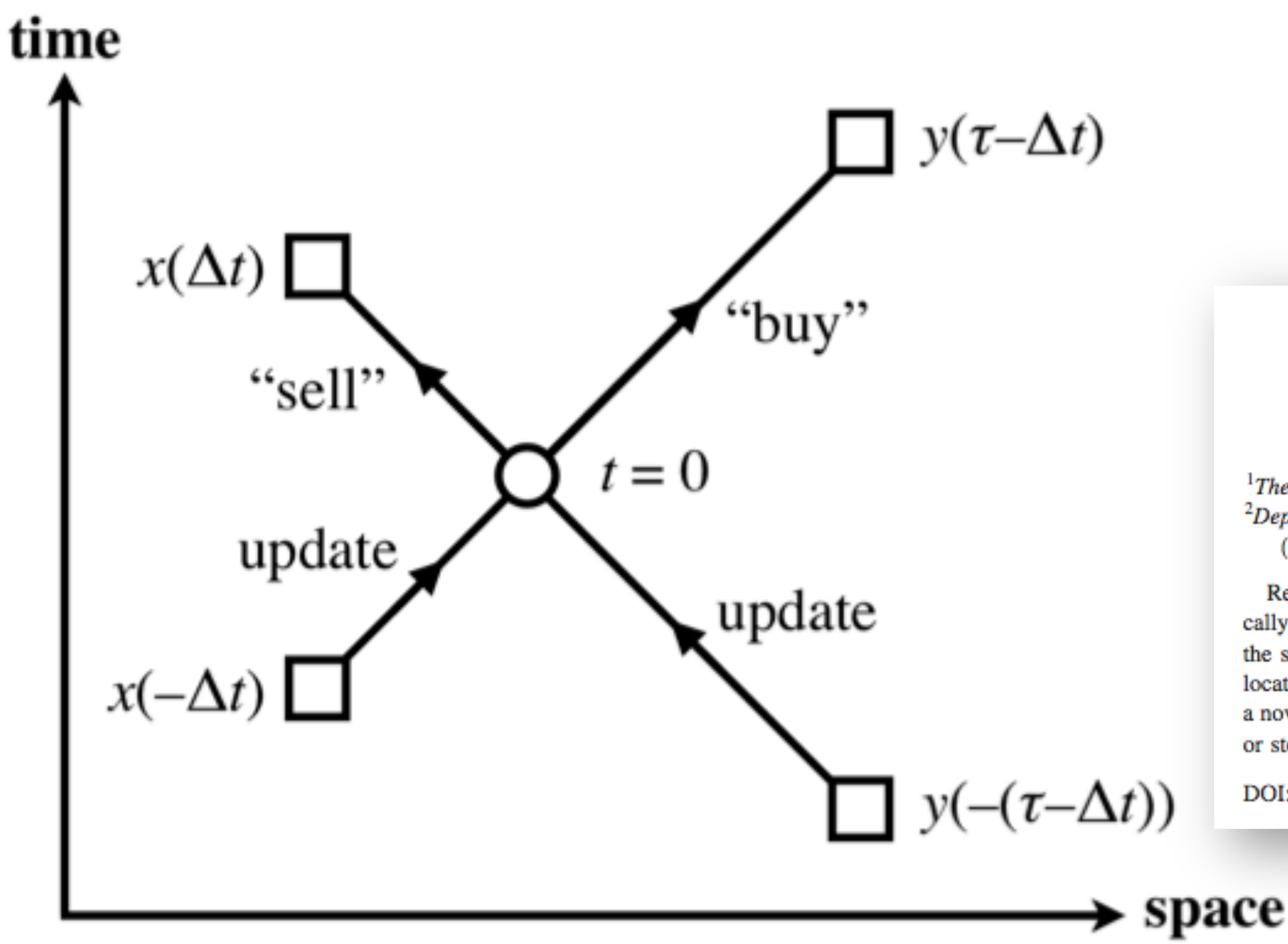


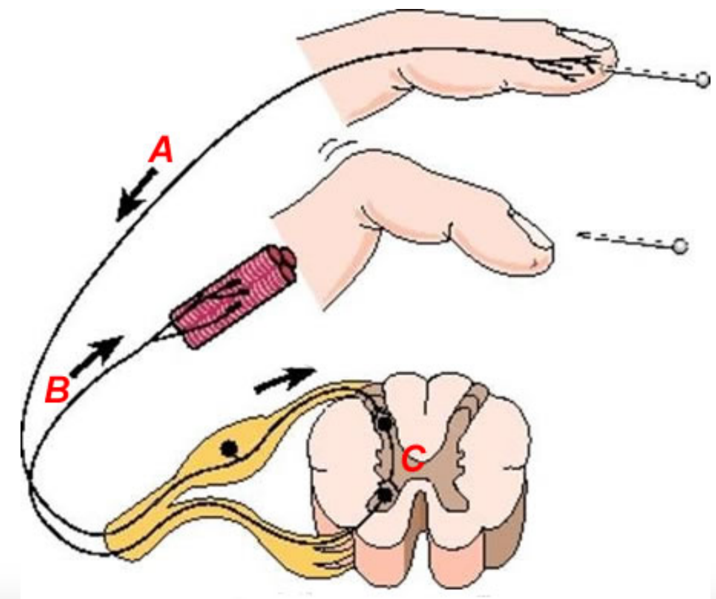
Full 2*tau RTD for non-local correlated execution + response

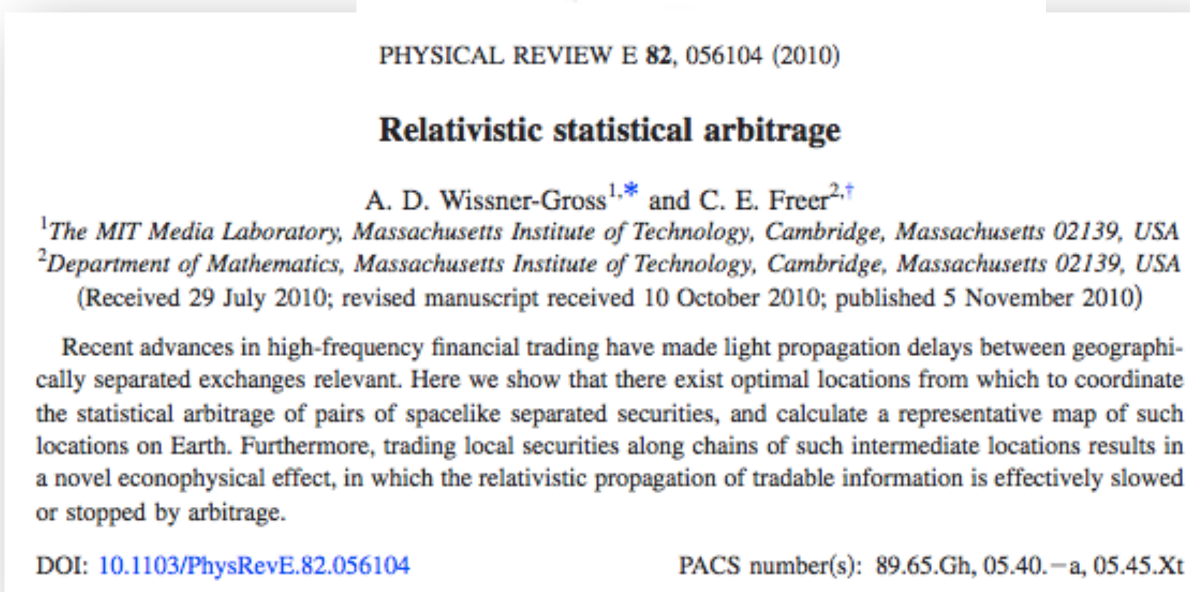
Mitigating latency for geo-distributed data fusion

Instead, localize coordination:

(symmetry no longer preserved,
instantaneous management of net position)






PHYSICAL REVIEW E **82**, 056104 (2010)

Relativistic statistical arbitrage

A. D. Wissner-Gross[1,*] and C. E. Freer[2,†]
[1]*The MIT Media Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Department of Mathematics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Received 29 July 2010; revised manuscript received 10 October 2010; published 5 November 2010)

Recent advances in high-frequency financial trading have made light propagation delays between geographically separated exchanges relevant. Here we show that there exist optimal locations from which to coordinate the statistical arbitrage of pairs of spacelike separated securities, and calculate a representative map of such locations on Earth. Furthermore, trading local securities along chains of such intermediate locations results in a novel econophysical effect, in which the relativistic propagation of tradable information is effectively slowed or stopped by arbitrage.

DOI: 10.1103/PhysRevE.82.056104 PACS number(s): 89.65.Gh, 05.40.−a, 05.45.Xt

RTD as low as tau for non-local correlated execution + response

[A. D. Wissner-Gross, C. E. Freer, Phys. Rev. E 82, 056104 (2010)]

Formalizing the principle

Simplest possible model → Vasicek process

Single:

$$dr(t) = a(b - r(t))dt + \sigma dW(t)$$

long-term mean b

speed of reversion a

instantaneous volatility σ

$W(t)$ is a Wiener process

Double:

$$dx(t) = -a_x x(t)dt + \sigma_x dV(t),$$

$$dy(t) = -a_y y(t)dt + \sigma_y dW(t)$$

Optimal location

Without loss of generality, assume: $x(-\Delta t) > y(-(\tau-\Delta t))$

So we want to maximize: $e^{R(\Delta t)} \equiv e^{x(\Delta t)} / e^{y(\tau-\Delta t)}$

knowledge decays with time:

$$\langle R(\Delta t)\rangle = x(-\Delta t)e^{-2a_x\Delta t} - y(-(\tau-\Delta t))e^{-2a_y(\tau-\Delta t)}$$

extremum when:

$$0 = \frac{d\langle R(\Delta t)\rangle}{d\Delta t} = -e^{-2a_x\Delta t}(\dot{X} + 2a_x X) - e^{-2a_y(\tau-\Delta t)}(\dot{Y} + 2a_y Y)$$

where $X \equiv x(-\Delta t)$, $\dot{X} \equiv \dot{x}(-\Delta t)$, $Y \equiv y(-(\tau-\Delta t))$, and $\dot{Y} \equiv \dot{y}(-(\tau-\Delta t))$

And we arrive at the solution class:

$$\frac{\Delta t}{\tau} = \frac{a_y}{a_x + a_y} + \frac{1}{2(a_x + a_y)\tau}\ln\left[-\frac{\dot{X} + 2a_x X}{\dot{Y} + 2a_y Y}\right]$$

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Conditions for optimality

Constrain search to maxima:
$$0 > \frac{d^2\langle R(\Delta t)\rangle}{d\Delta t^2} = e^{-2a_x\Delta t}[2a_x(\dot{X} + 2a_x X) + \ddot{X} + 2a_x\dot{X}]$$
$$- e^{-2a_y(\tau-\Delta t)}[2a_y(\dot{Y} + 2a_y Y) + \ddot{Y} + 2a_y\dot{Y}],$$

where $\ddot{X} \equiv \ddot{x}(-\Delta t)$ and $\ddot{Y} \equiv \ddot{y}(-(\tau - \Delta t))$

Sufficient that: $4a_x^2 X + 4a_x\dot{X} + \ddot{X} < 0 < 4a_y^2 Y + 4a_y\dot{Y} + \ddot{Y}$

Satisfied by sharp fluctuations:
$$x(t) = k_0 - k_1(\Delta t + \tau)^2,$$
$$y(t) = -k_2 + k_3(\Delta t + \tau)^2,$$
$$2a_x^2 k_0 < k_1 < k_0/\tau^2,$$
$$2a_y^2 k_2 < k_3 < k_2/\tau^2,$$
$$a_x, a_y < 1/(\tau\sqrt{2}),$$

Which correspond to fluctuations with characteristic frequency:

$$\frac{\max(a_x, a_y)}{\pi} < f < \frac{\tau^{-1}}{\pi\sqrt{2}}.$$

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Example application

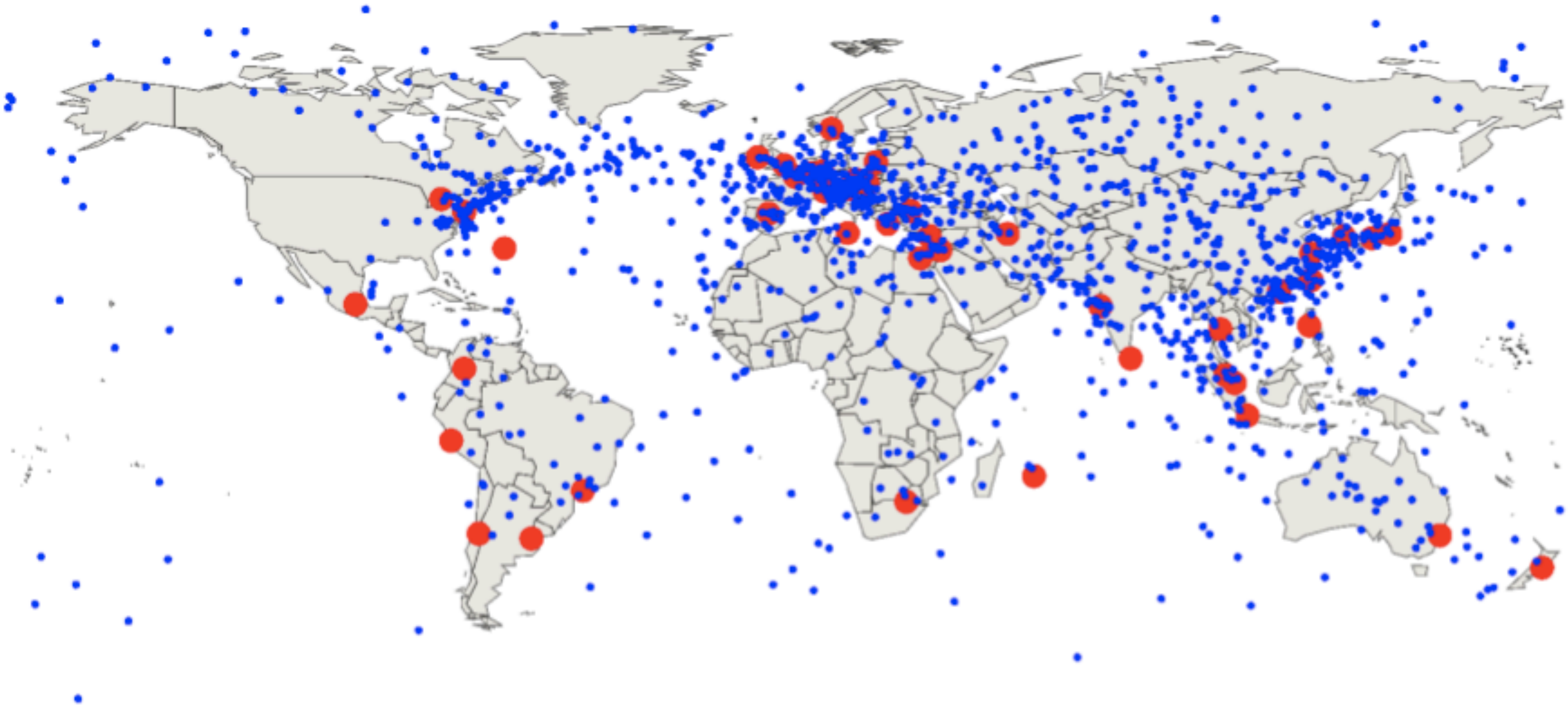
Under simplifying assumptions...

$$f \gg \max(a_x, a_y) / \pi$$

$$X \sim -Y$$

…we can neglect instantaneous context.

$$\Delta t = \tau a_y / (a_x + a_y)$$



Discussion

Relativistic statistical coordination has the potential to enable high-confidence cyber-physical system operation on planetary-scale networks, where latencies would otherwise be too high for effective data fusion.

web: **www.alexwg.org** twitter: **@alexwg** email: **alexwg@post.harvard.edu**

Questions?

Contact:
alexwg@post.harvard.edu