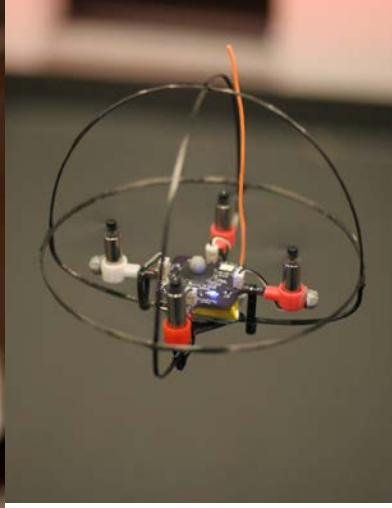
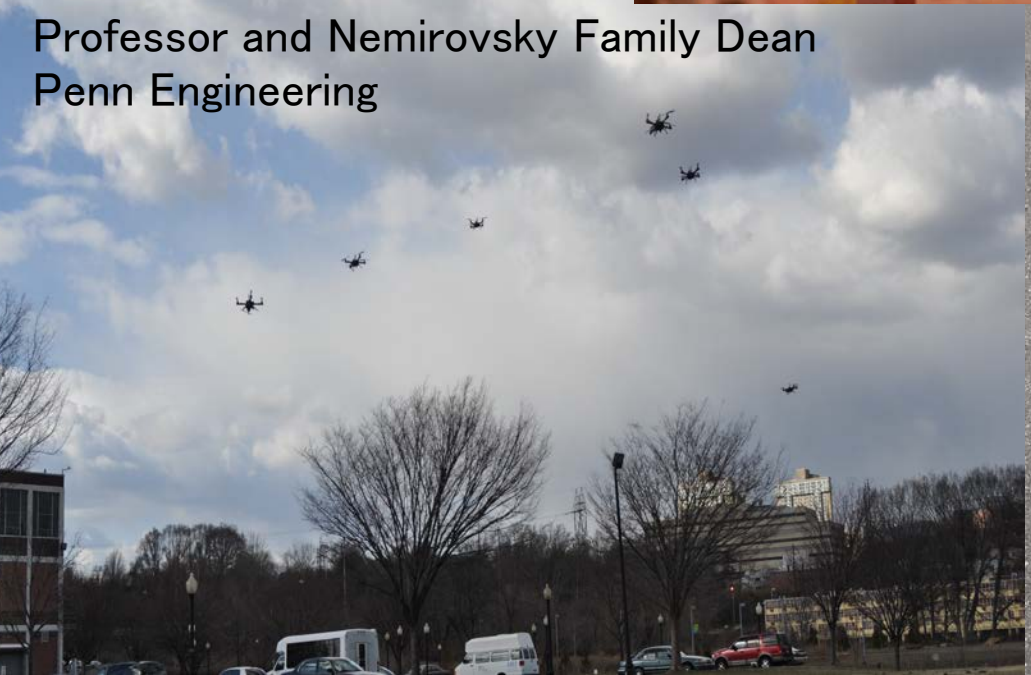
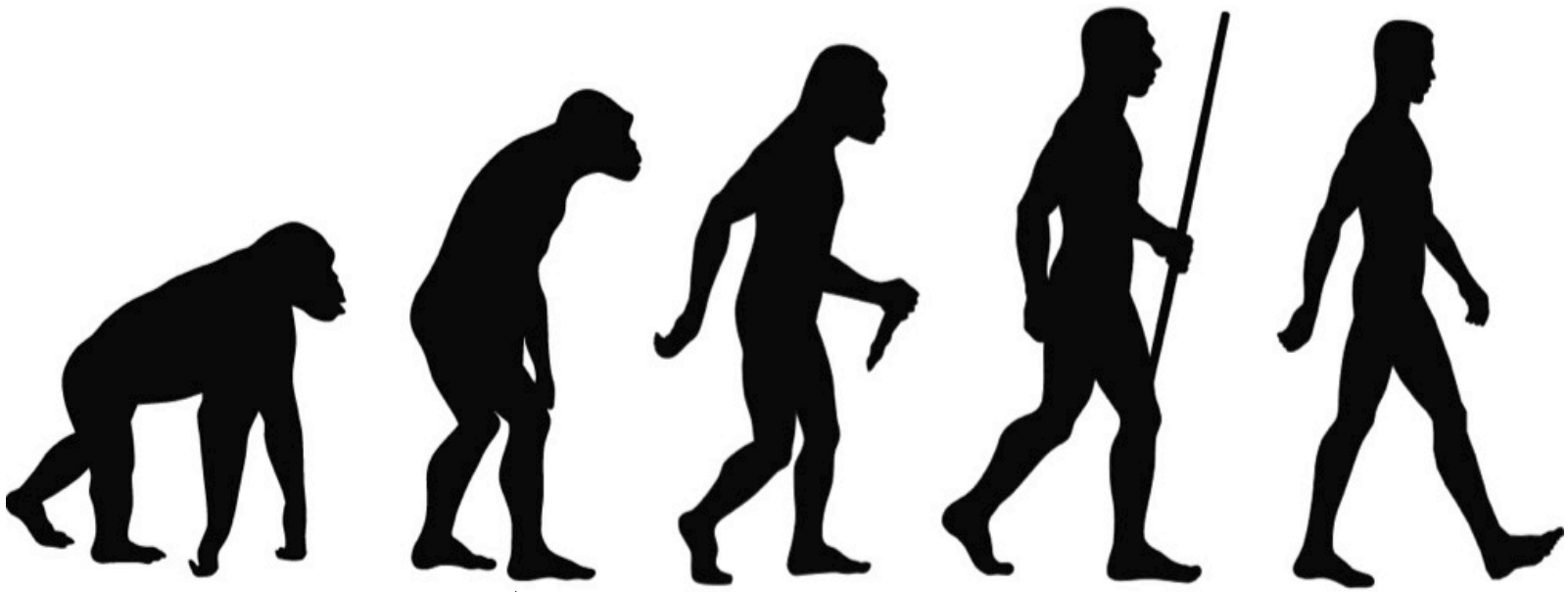


Vijay Kumar

Professor and Nemirovsky Family Dean
Penn Engineering



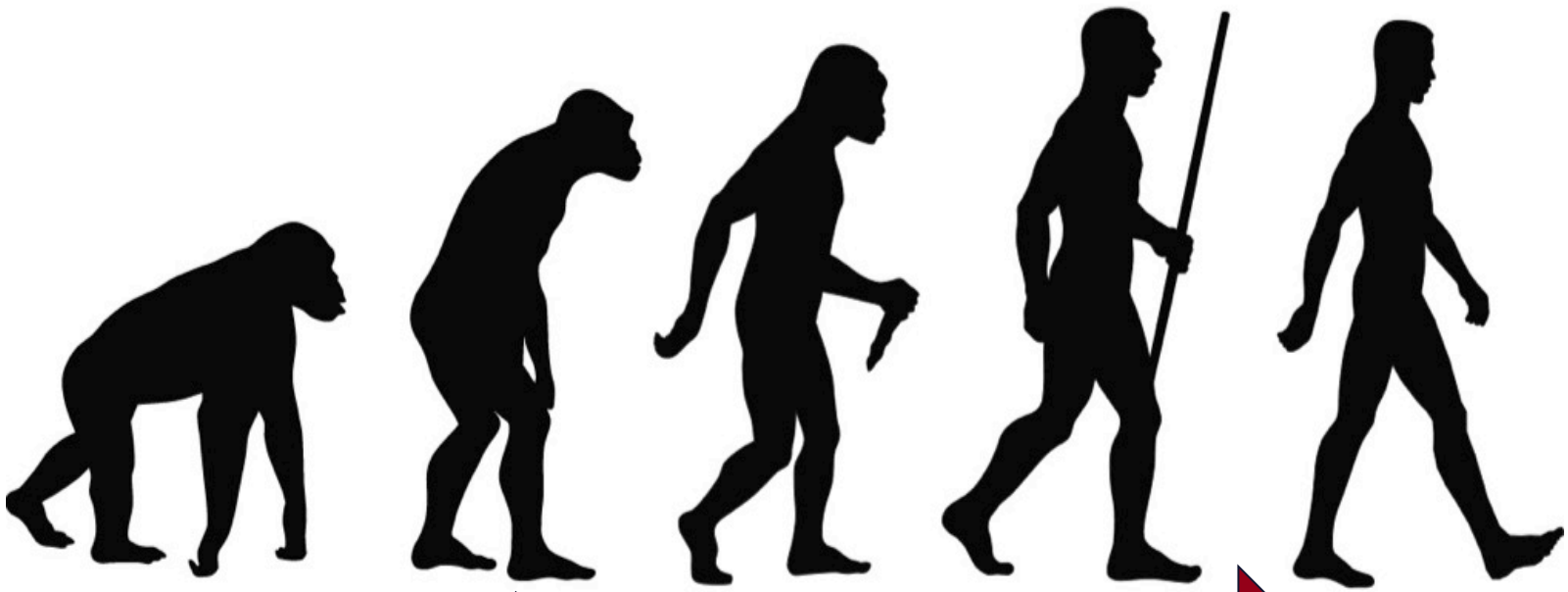
Aerial Robots



We are here!

Aerial Robots

Penn Engineering



Small

Safe

Smart

Speed

Swarms

We are here!

The World of Technology

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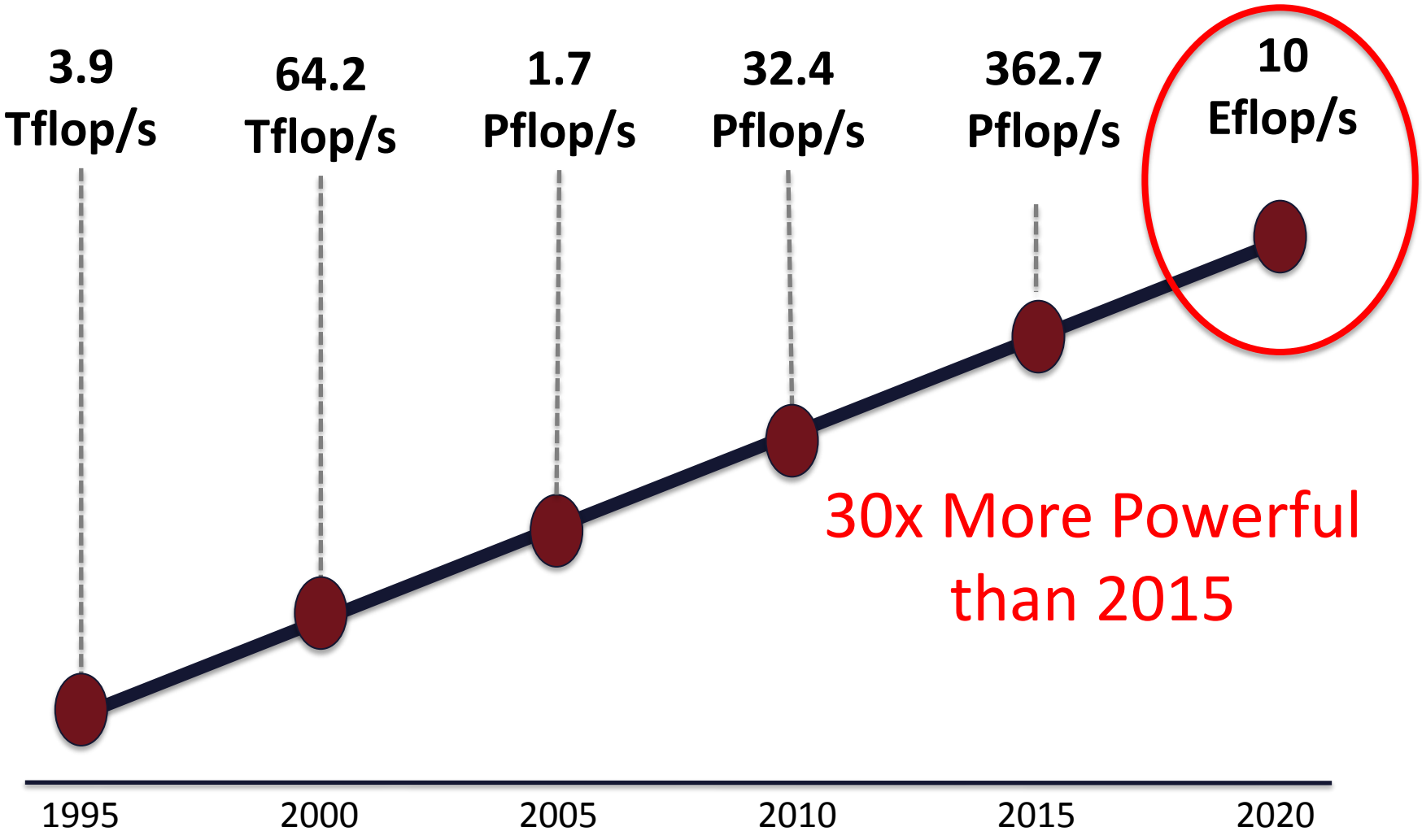
I knew who I was this morning, but I've changed a few times since then. Alice in Wonderland, Lewis Carroll

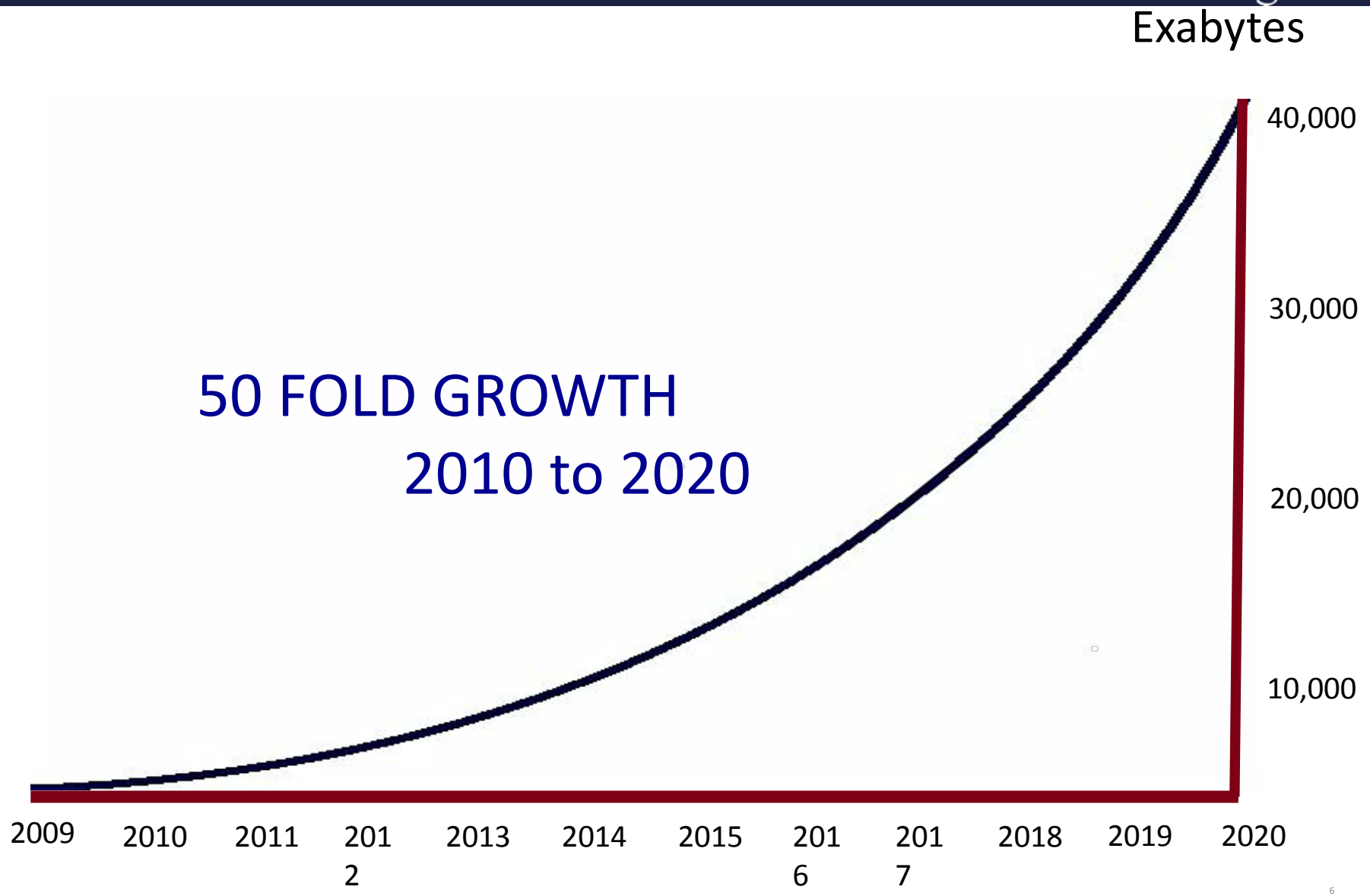
Alice-in-Wonderland.net

Computation



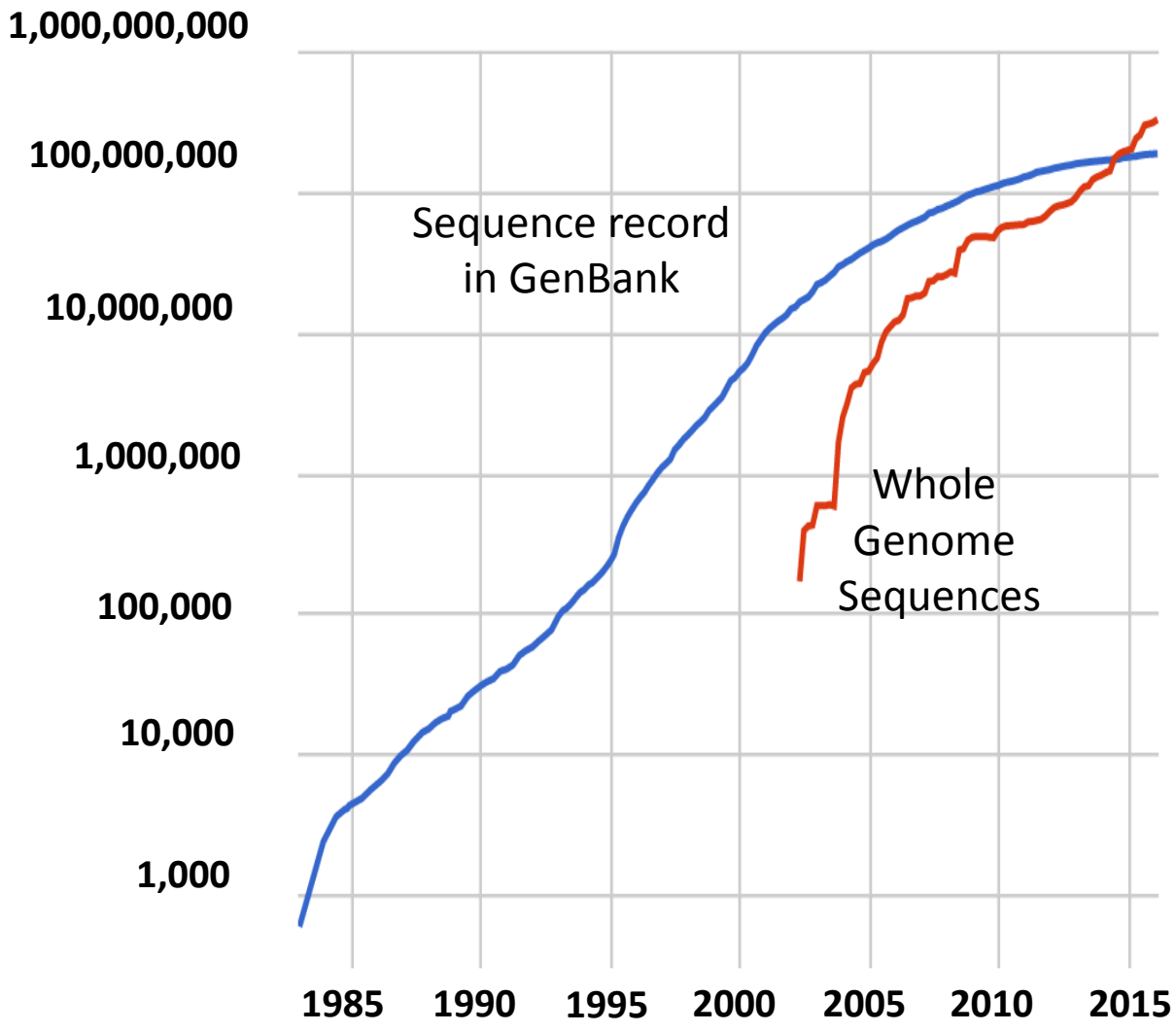
D. Butler, A world where everyone has a robot, Nature, 2016

Data



D. Butler, A world where everyone has a robot, Nature, 2016

DNA Sequencing



www.ncbi.nlm.nih.gov/genbank/statistics/

Cost of X is Decreasing

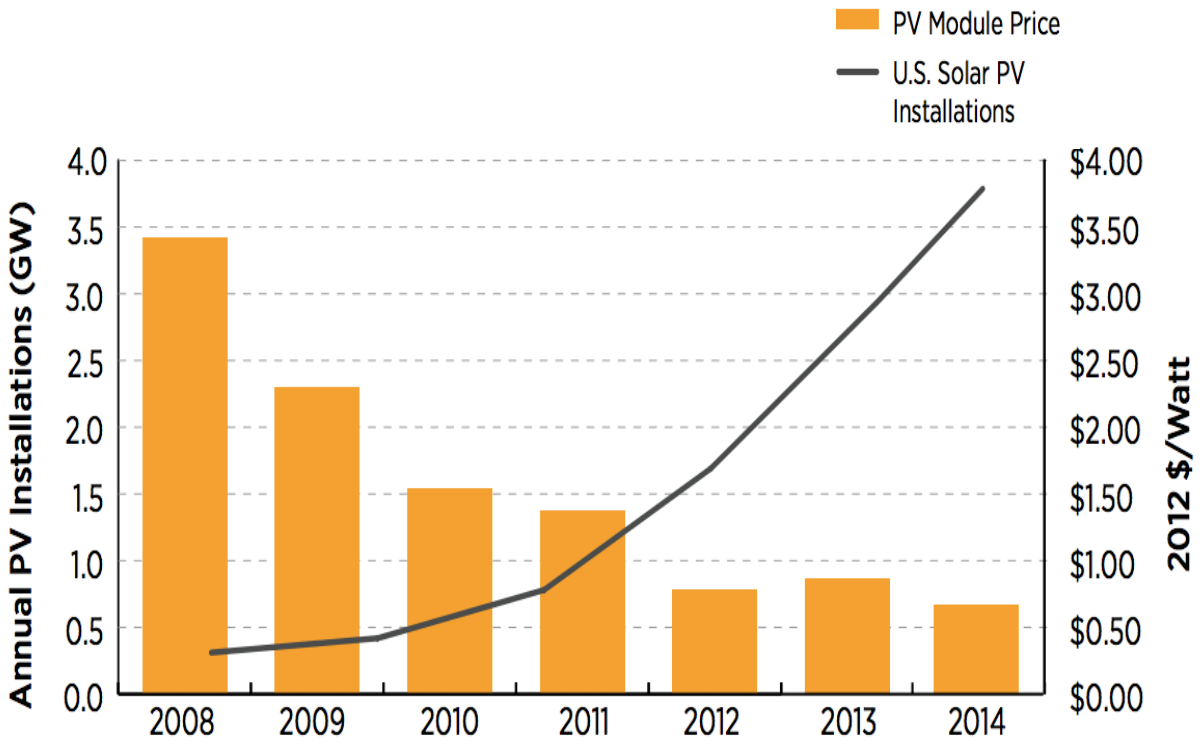
X={computation, communication, sensing, energy, manufacturing, …}

Cost of X is Decreasing

- Computing: $/M transistors - 33%/year
- Storage: $/GB – 38%/year
- Bandwidth: $/Gb/s – 27%/year

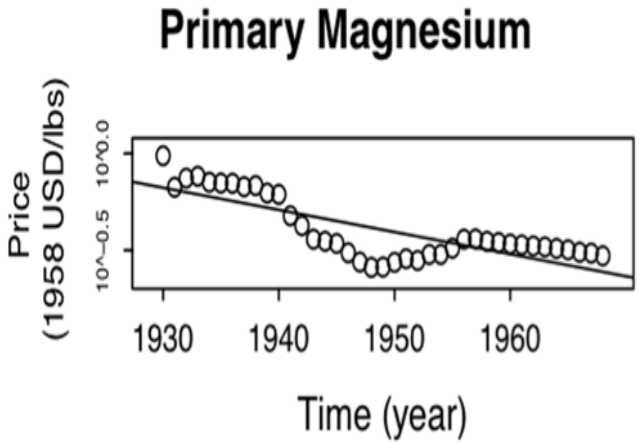
Cost of Solar Power

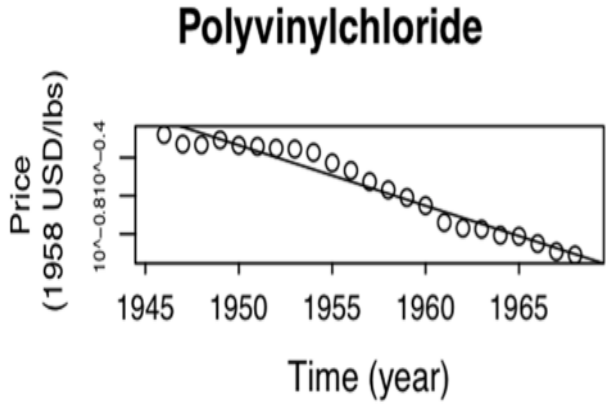
75% over last 5 years

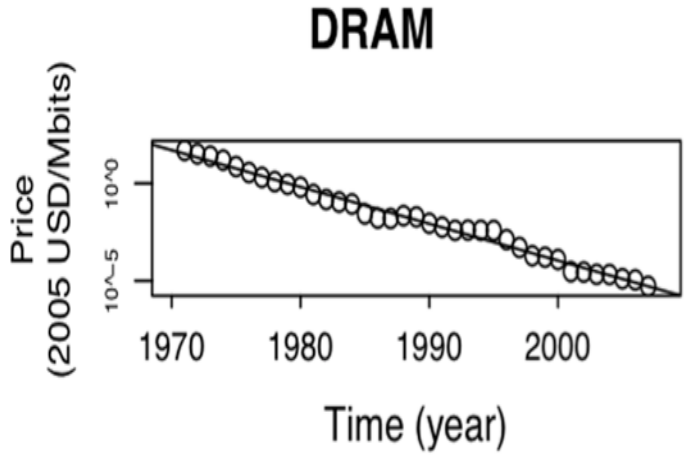


SunShot, U.S. Department of Energy

X ={materials, components, products}



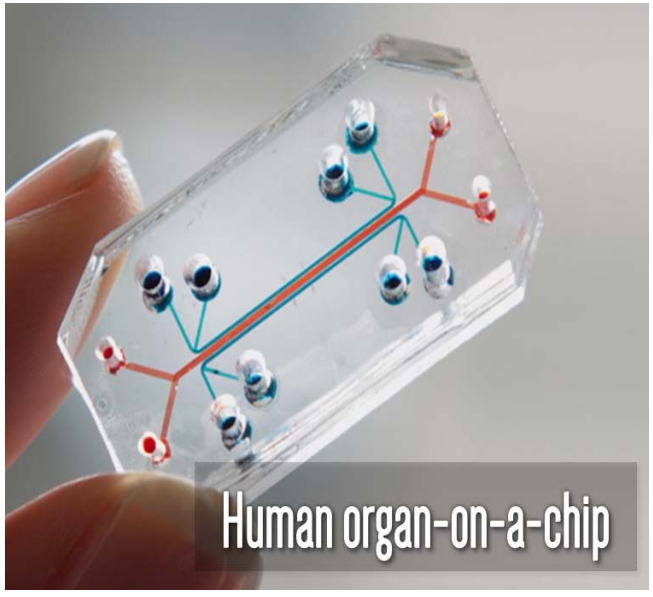




Nagy, Doyne Farmer, Bui, Trancik, Statistical Basis for Predicting Technological Progress, *Plos One*, 2013

Cost/Speed of 3D Printing

MakerBot



Dan Huh, Bioengineering

Printing Speed

2023 — 80 cm^3 hr^{-1}

2018 — 40 cm^3 hr^{-1}

2013 — 10 cm^3 hr^{-1}

Moore's Law Like Trends

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1 Cost of creating hardware and software is decreasing

2 Time to ideate, create, test and redesign is decreasing

The Game of Technology

More players…

More shots on goal…

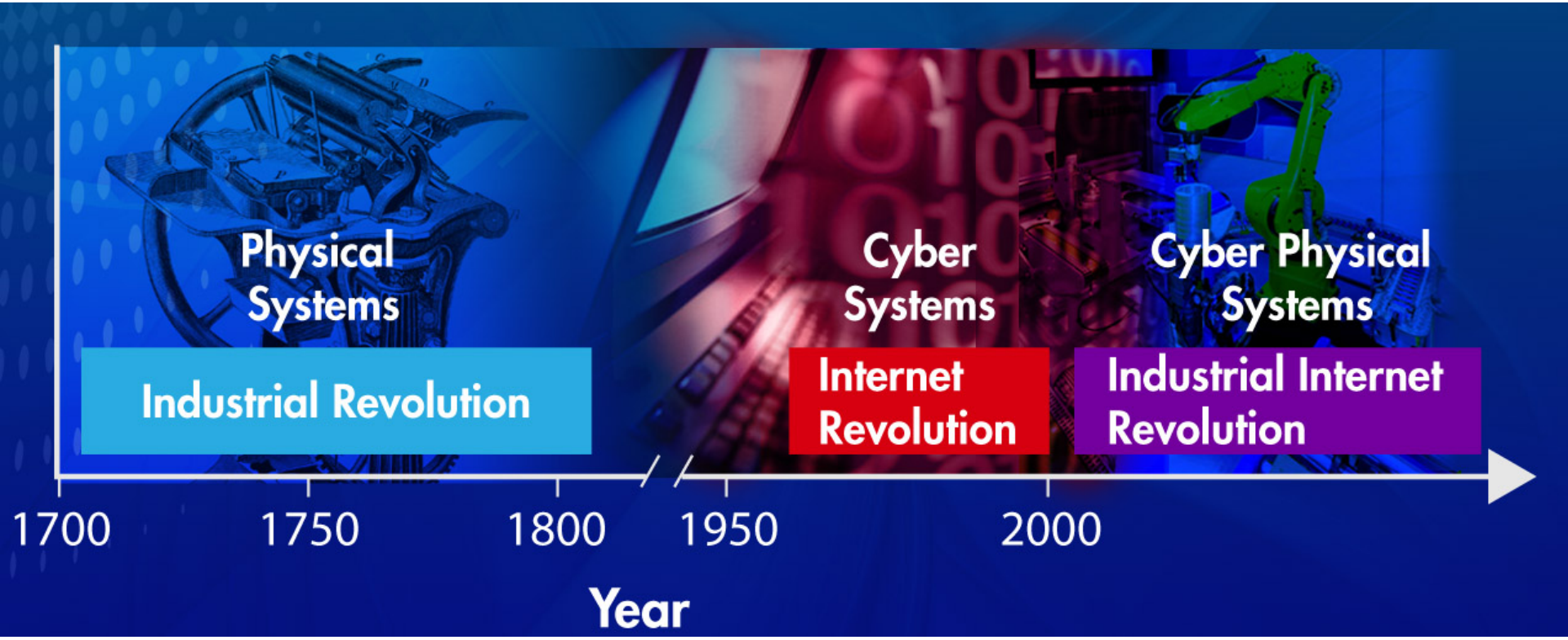
More scores…

Higher scoring game …

Attract better talent …

The rate of technology innovation is accelerating!

3rd Industrial Revolution



Light weight sensing

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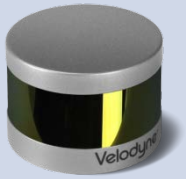
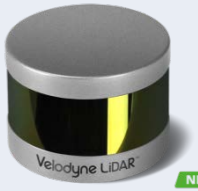
Model	Range	Resolution	Weight*	Power	Cost
 **HDL-64E**	120 m. 26.8º vertical FOV	< 2 cm. 0.08º (azimuth) 0.4º (elevation)	13.2 kg.	60 W	$75K
 **HDL-32E**	100 m. 41º vertical FOV	±2 cm. 0.1º - 0.4º (azimuth) 1.33º (elevation)	1 kg.	12W	$30K
 **VLP-16 (Puck)**	100 m. 30º vertical FOV	±3 cm. 0.1º - 0.4º (azimuth) 2º (elevation)	830 g.	8 W	$7999
 **VLP-16 Lite** NEW	100 m. 30º vertical FOV	±3 cm. 0.1º - 0.4º (azimuth) 2º (elevation)	590 g.	8 W	$9399

Light weight computing

Penn Engineering

Computer	Intel NUC (i3-5010U)	Intel NUC (i5-5250U)	Intel NUC (i7-5557U)	Odroid XU3 (Exynos 5422)	Qualcomm Eagle (Snapdragon 801)
Cores	2	2	2	4	4
Clock Speed (GHz)	1.7	2.1	3.1	2	2.5
MFLOPS (Single-Core)	1900	2730	3440	1030	1200
MFLOPS (Multi-Core)	4250	5400	7480	4270	4350
Mass (g)	210	210	210	38	27
MFlops / g (Single-Core)	9.05	13	16.38	27.11	44.44
MFlops / g Multi-Core)	20.24	25.71	35.62	112.37	161.11

Robots for Everyone

"Your smart phone is your robot!"

Matt Grob, CTO Qualcomm

Two big enablers for AI

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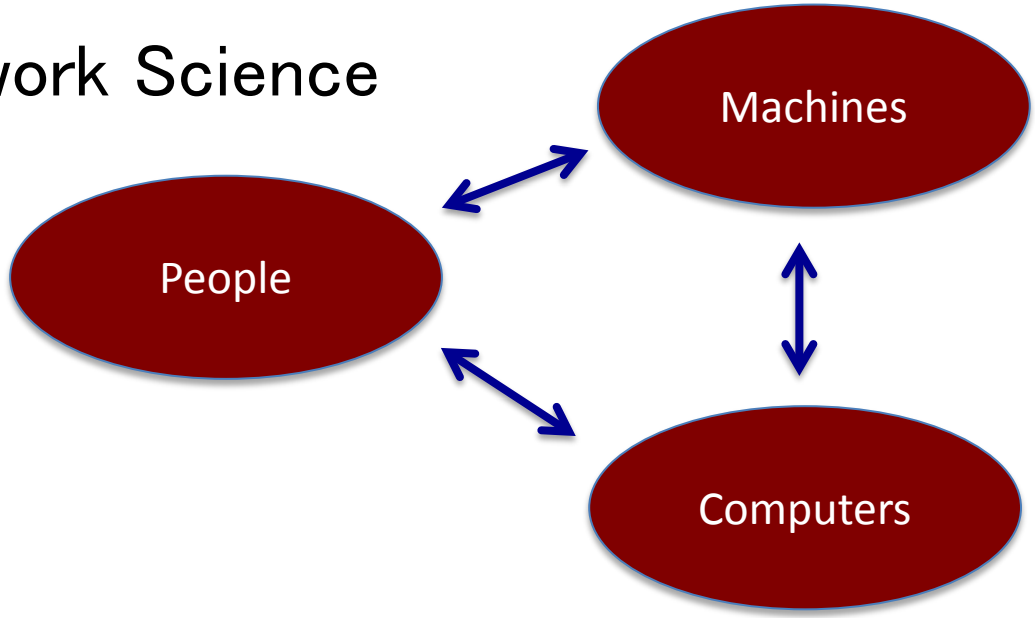
Data Science

Network Science



Most disruptive application: Autonomy

- Most challenging domain: cyber physical systems

Six myths about AI and autonomy

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- The ability to crunch through large amounts of data (which we mistakenly call learning) does not translate to knowledge
- The ability to make complex calculations rapidly does not translate to autonomy
- 99.99% correct is exponentially harder to achieve than 90% correct
- Perception + action is exponentially harder than just perception
- Tasks with physical contact is exponentially harder than tasks like driving or flying
- Human machine collaboration is impossible unless they share representations. We only know how to do this at some very simple levels

Data, Information, Networks and Society

Social Challenges

Democratization of S&T (opportunity and threat)

Democratization of Technology

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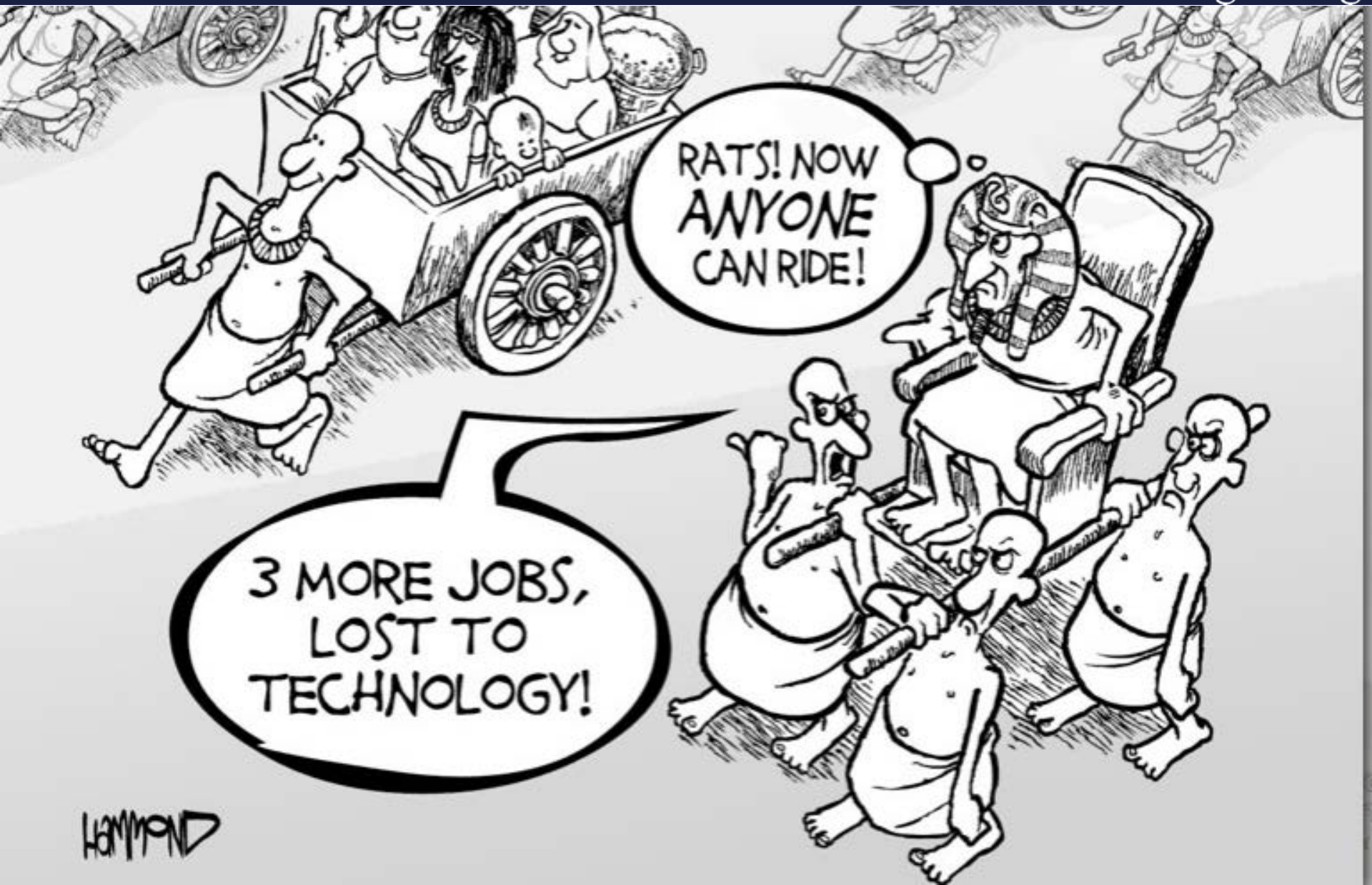

Social Challenges

Democratization of S&T (opportunity and threat)

Jobs

Asymmetric threats (easy to write “bad” programs)

Safety

Cyber security

Privacy

Social Disruption

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2016

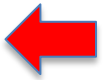
Type of Job	Qualification	Wages
Highly skilled, analytical, making decisions	Advanced degree, tech skills balanced with emotional judgment	$$$$
Analytical, drawing inferences	College degree	$$$
Modest skills, some labor	High school education	$$
Unskilled labor	reading/writing	$

Social Disruption

Penn Engineering

2020

Type of Job	Qualification	Wages
Highly skilled, analytical, making decisions	Advanced degree, tech skills balanced with emotional judgment	$$$$
Analytical, drawing inferences	College degree	$$$
Modest skills, some labor	High school education	$$
Unskilled labor	reading/writing	$



Social Challenges

Democratization of S&T (opportunity and threat)

Jobs

Asymmetric threats (easy to write “bad” programs)

Safety

Cyber security

Privacy

Grand Challenges

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Water Food Health Energy Infrastructure

Technology is central to addressing all these challenges!

Summary

Innovation is global

Autonomy in Cyber Physical systems will be difficult to achieve

Time scale of technology change (years) is much shorter than time scale of a human (decades)

Social challenges: safety, security, privacy, and jobs