Process Systems Engineering in the Information Age

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THE UNIVERSITY of WISCONSIN MADISON

June 2, 2017
2040 Visions of Process Systems Engineering
Symposium for the Retirement of George Stephanopoulos
MIT

Outline

George loves to discuss the future

My salad days,
When I was green in judgment, cold in blood

—Anthony and Cleopatra (I.v.607)

George loves to discuss the future

My salad days,
When I was green in judgment, cold in blood

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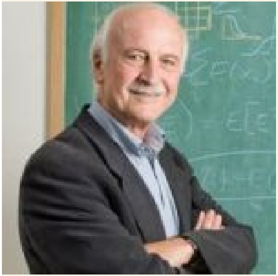
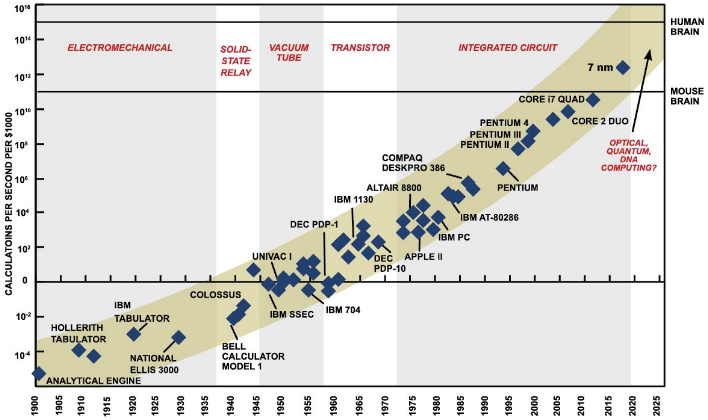
An early experience with George



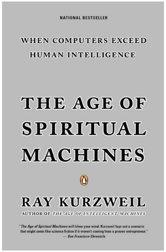
- George visited and gave the Pirkey lecture at UT-Austin, 1991
- We had an entire afternoon to discuss my research agenda
- George gave me invaluable and insightful advice

Everything is exponential. . . until it isn't



SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

The Age of Spiritual Machines, Ray Kurzweil (1999)



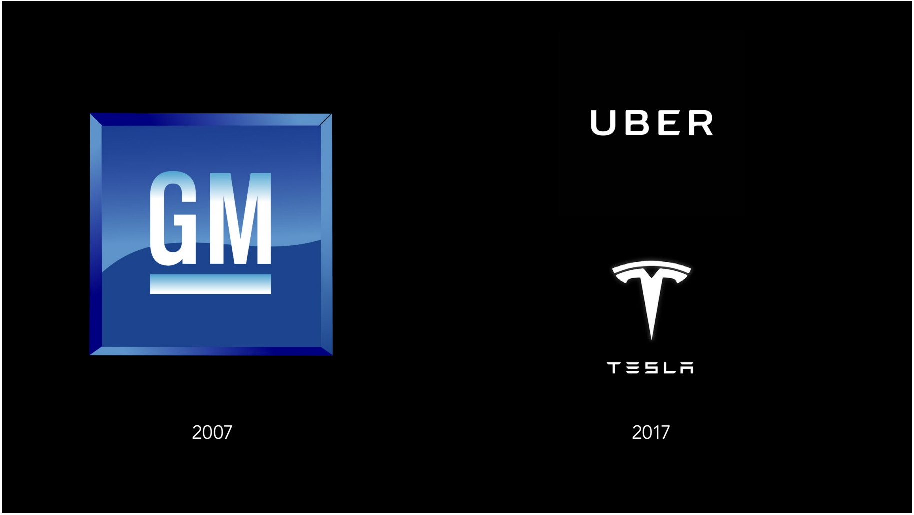
The master of futurologists: Ray Kurzweil

2009 • Most books will be read on screens rather than paper. • Most text will be created using speech recognition technology. • Intelligent roads and driverless cars will be in use, mostly on highways. • **People use personal computers the size of rings, pins, credit cards and books.** • Personal worn computers provide monitoring of body functions, automated identity and directions for navigation. • Cables are disappearing. Computer peripheries use wireless communication. • People can talk to their computer to give commands. • **Computer displays built into eyeglasses for augmented reality are used.** • Computers can recognize their owner's face from a picture or video. • Three-dimensional chips are commonly used. • Sound producing speakers are being replaced with very small chip-based devices that can place high resolution sound anywhere in three-dimensional space. • A $1,000 computer can perform a trillion calculations per second. • There is increasing interest in massively parallel neural nets, genetic algorithms and other forms of "chaotic" or complexity theory computing. • Research has been initiated on reverse engineering the brain through both destructive and non-invasive scans. • Autonomous nanoengineered machines have been demonstrated and include their own computational controls. **2019** • The computational capacity of a $4,000 computing device (in 1999 dollars) is approximately equal to the computational capability of the human brain (20 quadrillion calculations per second). • The summed computational powers of all computers is comparable to the total brainpower of the human race. • **Computers are embedded everywhere in the environment (inside of furniture, jewelry, walls, clothing, etc.).** • People experience 3-D virtual reality through glasses and contact lenses that beam images directly to their retinas (retinal display). Coupled with an auditory source (headphones), users can remotely communicate with other people and access the Internet. • These special glasses and contact lenses can deliver "augmented reality" and "virtual reality" in three different ways. First, they can project "heads-up-displays" (HUDs) across the user's field of vision, superimposing images that stay in place in the environment regardless of the user's perspective or orientation. Second, virtual objects or people could be rendered in fixed locations by the glasses, so when the user's eyes look elsewhere, the objects appear to stay in their places. Third, the devices could block out the "real" world entirely and fully immerse the user in a virtual reality environment. • **People communicate with their computers via two-way speech and gestures instead of with keyboards. Furthermore, most of this interaction occurs through computerized assistants with different personalities that the user can select or customize.** Dealing with computers thus becomes more and more like dealing with a human being. • Most business transactions or information inquiries involve dealing with a simulated person. • **Most people own more than one PC, though the concept of what a "computer" is has changed considerably: Computers are no longer limited in design to laptops or CPUs** contained in a large box connected to a monitor. Instead, devices with computer capabilities come in all sorts of unexpected shapes and sizes. • Cables connecting computers and peripherals have almost completely disappeared. • Rotating computer hard drives are no longer used. • Three-dimensional nanotube lattices are the dominant computing substrate. • Massively parallel neural nets and genetic algorithms are in wide use. • Destructive scans of the brain and noninvasive brain scans have allowed scientists to understand the brain much better. The algorithms that allow the relatively small genetic code of the brain to construct a much more complex organ are being transferred into computer neural nets. • Pinhead-sized cameras are everywhere. • Nanotechnology is more capable and is in use for specialized applications, yet it has not yet made it into the mainstream. "Nanoengineered machines" begin to be used in manufacturing. • Thin, lightweight, handheld displays with very high resolutions are the preferred means for viewing documents. The aforementioned computer eyeglasses and contact lenses are also used for this same purpose, and all download the information wirelessly. • Computers have made paper books and documents almost completely obsolete. • Most learning is accomplished through intelligent, adaptive courseware presented by computer-simulated teachers. In the learning process, human adults fill the counselor and mentor roles instead of being academic instructors. These assistants are often not physically present, and help students remotely. • Students still learn together and socialize, though this is often done remotely via computers. • All students have access to computers. • **Most human workers spend the majority of their time acquiring new skills and knowledge.** • Blind people wear special glasses that interpret the real world for them through speech. Sighted people also use these glasses to amplify their own abilities. • Retinal and neural implants also exist, but are in limited use because they are less useful. • Deaf people use special glasses that convert speech into text or signs, and music into images or tactile sensations. Cochlear and other implants are also widely used. • People with spinal cord injuries can walk and climb steps using computer-controlled nerve stimulation and exoskeletal robotic walkers. • Computers are also found inside of some humans in the form of cybernetic implants. These are most commonly used by disabled people to regain normal physical faculties (e.g. Retinal implants allow the blind to see and spinal implants coupled with mechanical legs allow the paralyzed to walk). • Language translating machines are of much higher quality, and are routinely used in conversations. • Effective language technologies (natural language processing, speech recognition, speech synthesis) exist • Access to the Internet is completely wireless and provided by wearable or implanted computers. • **People are able to wirelessly access the Internet at all times from almost anywhere** • Devices that deliver sensations to the skin surface of their users (e.g. tight body suits and gloves) are also sometimes used in virtual reality to complete the experience. "Virtual sex"—in which two people are able to have sex with each other through virtual reality, or in which a human can have sex with a "simulated" partner that only exists on a computer—becomes a reality. • Just as visual- and auditory virtual reality have come of age, haptic technology has fully matured and is completely convincing, yet requires the user to enter a V.R. booth. It is commonly used for computer sex and remote medical examinations. It is the preferred sexual medium since it is safe and enhances the experience. • Worldwide economic growth has continued. There has not been a global economic collapse. • The vast majority of business interactions occur between humans and simulated retailers, or between a human's virtual personal assistant and a simulated retailer. • Household robots are ubiquitous and reliable. • Computers do most of the vehicle driving—-humans are in fact prohibited from driving on highways unassisted. Furthermore, when humans do take over the wheel, the onboard computer system constantly monitors their actions and takes control whenever the human drives recklessly. As a result, there are very few transportation accidents. • Most roads now have automated driving systems—networks of monitoring and communication devices that allow computer-controlled automobiles to safely navigate. • Prototype personal flying vehicles using microflaps exist. They are also primarily computer-controlled. • Humans are beginning to have deep relationships with automated personalities, which hold some advantages over human partners. The depth of some computer personalities convinces some people that they should be accorded more rights. • **While a growing number of humans believe that their computers and the simulated personalities they interact with are intelligent to the point of human-level consciousness, experts dismiss the possibility that any could pass the Turing Test.** • Human-robot relationships begin as simulated personalities become more convincing. • Interaction with virtual personalities becomes a primary interface • Public places and workplaces are ubiquitously monitored to prevent violence and all actions are recorded permanently. Personal privacy is a major political issue, and some people protect themselves with unbreakable computer codes. • The basic needs of the underclass are met. (Not specified if this pertains only to the developed world or to all countries) • Virtual artists—creative computers capable of making their own art and music—emerge in all fields of the arts. **2029** • A $1,000 personal computer is 1,000 times more powerful than the human brain. • The vast majority of computation is done by computers and not by human brains. • Further progress has been made in understanding the secrets of the human brain. Hundreds of distinct sub-regions with specialized functions have been identified. Some of the algorithms that code for development of these regions have been deciphered and incorporated into neural net computers. • Massively parallel neural nets, which are constructed through reverse-engineering the human brain, are in common use. • **The eyeglasses and headphones that used to deliver virtual reality are now obsolete thanks to computer implants that go into the eyes and ears. The implants are either permanent or removable.** They allow direct interface with computers, communications and Internet-based applications. The implants are also capable of recording what the user sees and hears. • Computer implants designed for direct connection to the brain are also available. They are capable of augmenting natural senses and of enhancing higher brain functions like memory, learning speed and overall intelligence. • Computers are now capable of learning and creating new knowledge entirely on their own and with no human help. **By scanning the enormous content of the Internet, some computers "know" literally every single piece of public information (every scientific discovery, every book and movie, every public statement, etc.) generated by human beings.** • Direct brain implants allow users to enter full-immersion virtual reality—with complete sensory stimulation—without any external equipment. People can have their minds in a totally different place at any moment. This

Some trends outside of science and technology. Do we see a straight line from this . . .

. . . to this ?

GM on the verge of extinction



And the empire strikes back . . .

Chevy changes the game. Again.

THE GROUNDBREAKING CHEVROLET BOLT EV IS THE CAR OF TOMORROW. TODAY.

That sound? It's almost imperceptible, but it's there. The soft rustle of air over steel and glass, the muted hum of rubber on tarmac, the faint whirr of spinning metals. It's the sound of electrons at work, the sound of electrical energy being converted into motion, the sound of the automotive world shifting on its axis. It's the sound of the 2017 *Motor Trend* Car of the Year, the Chevrolet Bolt EV.

Difficulty of long-range prediction

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Culture Speeds Up Human Evolution

Analysis of common patterns of genetic variation reveals that humans have been evolving faster in recent history

By David Biello | December 10, 2007

Homo sapiens sapiens has spread across the globe and increased vastly in numbers over the past 50,000 years or so—from an estimated five million in 9000 B.C. to roughly 6.5 billion today. More people means more opportunity for mutations to creep into the basic human genome and new research confirms that in the past 10,000 years a host of changes to everything from digestion to bones has been taking place.

"We found very many human genes undergoing selection," says anthropologist Gregory Cochran of the University of Utah, a member of the team that analyzed the 3.9 million DNA sequences* showing the most variation. "Most are very recent, so much so that the rate of human evolution over the past few thousand years is far greater than it has been over the past few million years."

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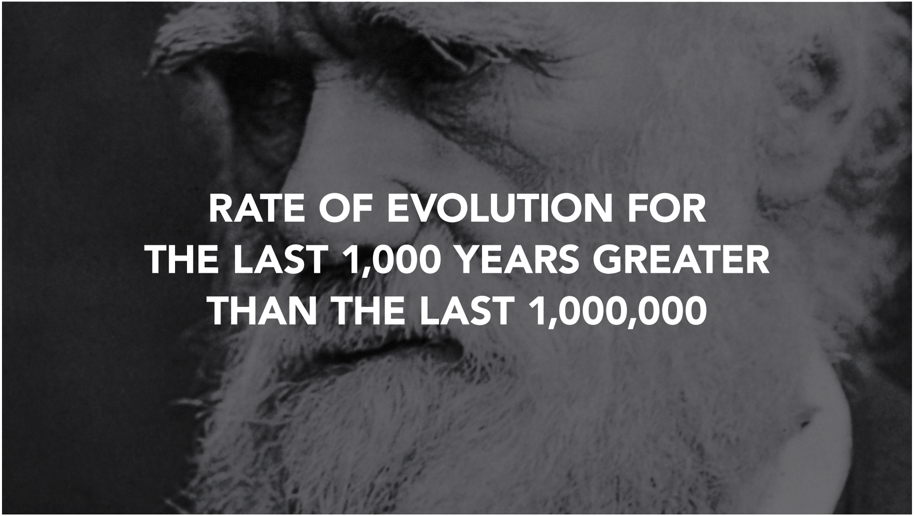
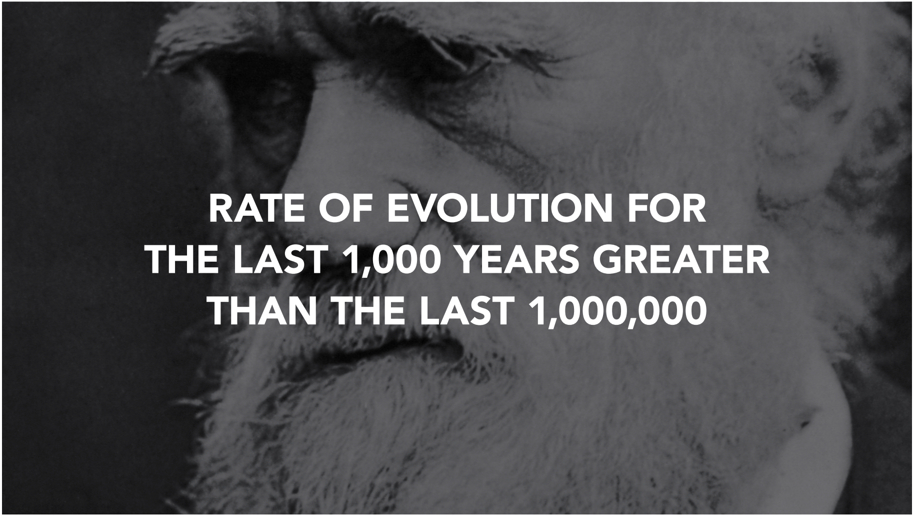
Dynamic time warping



Dynamic time warping



Let's refer to this effect as dynamic time warping (statisticians, forgive us)

George doesn't mind being wrong if we learn something

George doesn't mind being wrong if we learn something

A vision from 1969

A vision from 1969

Instead the mobile office turned out to be something slightly less bizarre:

George doesn't mind being wrong if we learn something

A vision from 1969

Instead the mobile office turned out to be something slightly less bizarre: Starbucks and a laptop

Complete this analogy

2017 is to 2040

—as—

Process Systems Engineering in 2040

Complete this analogy

2017 is to 2040

—as—

1994 is to 2017

Process Systems Engineering in 2040

Complete this analogy

2017 is to 2040

—as—

1994 is to 2017 (neglecting the dynamic time warping)

Process Systems Engineering in 2040

Complete this analogy

2017 is to 2040

—as—

1994 is to 2017 (neglecting the dynamic time warping)

Q: How difficult would it have been to predict the PSE of today in 1994?

Process Systems Engineering in 2040

Complete this analogy

2017 is to 2040

—as—

1994 is to 2017 (neglecting the dynamic time warping)

Q: How difficult would it have been to predict the PSE of today in 1994?
A: Easy!

One researcher's agenda in 1994

[148] Eaton, J. W. and J. B. Rawlings. Octave—a high level interactive language for numerical computations. *CACHE News*, 40:11–18, Spring 1995.

[149] Meadows, E. S. and J. B. Rawlings. Topics in model predictive control. In Berber, R., editor, *Methods of Model Based Process Control*, pages 331–347. Kluwer, 1995.

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PUBLICATIONS

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[2] Allan, D. A., C. N. Bates, M. J. Risbeck, and J. B. Rawlings. On the inherent robustness of optimal and suboptimal MPC. Accepted for publication in Systems and Control Letters, 2017.

[3] Risbeck, M. J., C. T. Maravelias, J. B. Rawlings, and R. D. Turney. A mixed-integer linear programming model for real-time cost optimization of building heating, ventilation, and air conditioning equipment. Accepted for publication in Energy and Buildings, 2017.

[4] Rawlings, J. B. and M. J. Risbeck. Model predictive control with discrete actuators: Theory and application. *Automatica*, 78:258–265, 2017.

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[6] Wu, F., T. Tian, J. B. Rawlings, and G. Yin. Approximate method for stochastic chemical kinetics with two-time scales by chemical Langevin equations. *J. Chem. Phys.*, 144:174112, 2016.

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That researcher's agenda in 2017

PUBLICATIONS

Free Source [1] Andersson, J. A. E., J. Gillis, G. Horn, J. B. Rawlings, and M. Diehl. CasADi—a software framework for nonlinear optimization and optimal control. Submitted for publication in Mathematical Programming, 2017.

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Neural networks have not (yet) reappeared

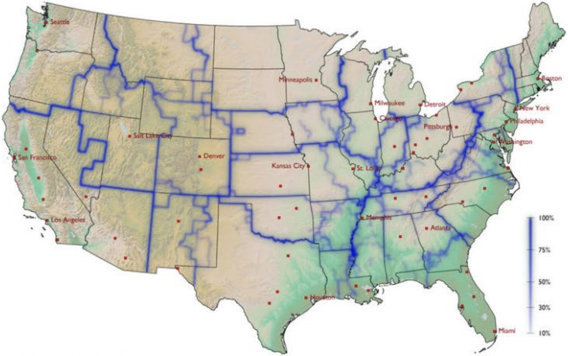
Whither process systems engineering?

A 'Whom Do You Hang With?' Map Of America

APRIL 17, 2013 11:55 AM ET

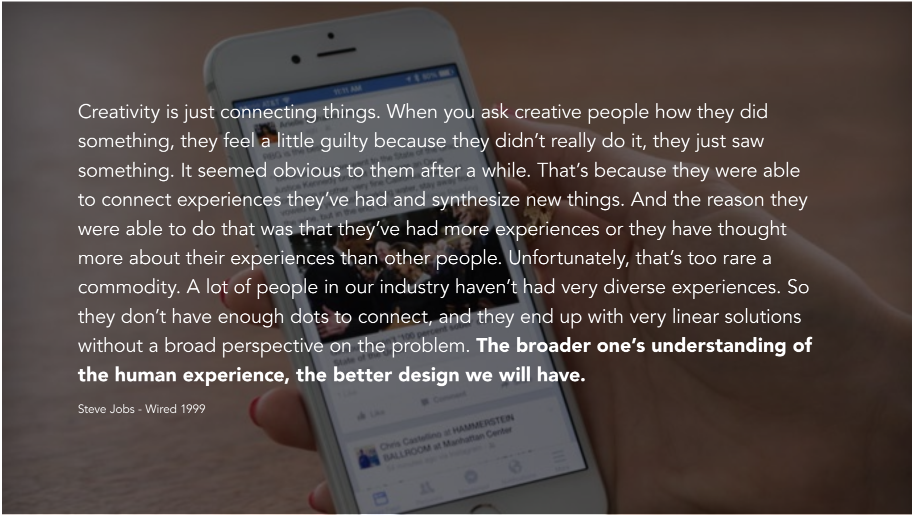
ROBERT KRULWICH

Look at the center of this map, at the little red dot that marks Kansas City. Technically, Kansas City is at the edge of Missouri, but here on this map it's in the upper middle section of a bigger space with strong blue borders. We don't have a name for this bigger space yet, but soon we will.



Dirk Brockmann/Northwestern University

http://www.npr.org/sections/krulwich/2013/04/16/177512687/a-whom-do-you-hang-with-map-of-america



Creativity is just connecting things. When you ask creative people how they did something, they feel a little guilty because they didn't really do it, they just saw something. It seemed obvious to them after a while. That's because they were able to connect experiences they've had and synthesize new things. And the reason they were able to do that was that they've had more experiences or they have thought more about their experiences than other people. Unfortunately, that's too rare a commodity. A lot of people in our industry haven't had very diverse experiences. So they don't have enough dots to connect, and they end up with very linear solutions without a broad perspective on the problem. **The broader one's understanding of the human experience, the better design we will have.**

Steve Jobs - Wired 1999

Whither PSE?

The two basic issues

With whom do we hang?

- Chemical Engineering
- Mathematics
- Computer Science
- Electrical and Computer Engineering
- Industrial and Systems Engineering
- Physics
- Chemistry
- Biology
- Process industries

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What are our new dots?

- Machine learning
- Deep neural networks
- Big data
- Complexity
- Scale
- Optimization?!
- Grand societal challenges

Education

Undergraduate education

- The change will likely not be revolutionary.
- An 18 year-old person will remain an 18 year-old person.
- This audience requires a lot of structure and human interaction to be able to integrate an entire adult education in only four years.
- We can certainly be more efficient and effective, but I doubt we can transform how we educate at this level.

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Graduate education

- There is a lot more room to innovate at this level.
- I would anticipate PhD learning on demand.
- This audience is more mature, highly motivated, and knows what and why they want to learn.
- Fewer semester-long courses, and many short 2-3 week bursts on subjects of interest.

Why does connecting the dots work?

If you have an apple and I have an apple and we exchange these apples then you and I will still each have one apple.

Why does connecting the dots work?

> *If you have an apple and I have an apple and we exchange these apples then you and I will still each have one apple. But if you have an idea and I have an idea and we exchange these ideas, then each of us will have two ideas.*

George Bernard Shaw

George loves to discuss the future

A more recent experience with George

- Aspentech bought many smaller PSE companies and hired many of our PhD graduates
- Then they nearly imploded

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A lesson from the humanities

As an undergraduate, while our class was struggling with the interpretation of some complex 500-page novel, the professor told us,

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As an undergraduate, while our class was struggling with the interpretation of some complex 500-page novel, the professor told us,

> *You're thinking about it all wrong. Think about it this way instead:*
> *One book, one idea!*

Testing the idea

If we apply the "one book, one idea" principle to Kurzweil's book(s), the summary is:

Testing the idea

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> *It's exponential, baby!*

Testing the idea

If we apply the "one book, one idea" principle to Kurzweil's book(s), the summary is:

> *It's exponential, baby!*
> *You can't stop it!*

An extension

Let's take it one step further.

An extension

Let's take it one step further. One *career*, one idea

An extension

Let's take it one step further. One *career*, one idea

Some PSE examples; think of these people at age 35

An extension

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An extension

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- Ignacio Grossmann: We *can* solve a mixed-integer nonlinear program. And MINLP best captures the process design problem.

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- Jim Rawlings: We *can* solve an optimal control problem in real time. And that enables feedback control.
- Larry Biegler: *Damn right!* And I can produce an algorithm that will do it.

Conclusion: I cannot answer George's question

I cannot answer George's question of what PSE will look like in 2040, but I know who can.

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The only remaining issue is to determine which two are correct.