Process Systems Engineering in the Information Age

James B. Rawlings

Department of Chemical and Biological Engineering

June 2, 2017
2040 Visions of Process Systems Engineering
Symposium for the Retirement of George Stephanopoulos
MIT
1. Introduction: the nature of prediction
   - Is change exponential
   - Time warping

2. Where are we and how did we get here

3. Whither process systems engineering?
   - How we create
     - *Who* knows

4. Conclusion
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

—Anthony and Cleopatra (I.v.607)

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

The Age of Spiritual Machines, Ray Kurzweil (1999)
Most books will be read on screens rather than paper. Most text will be created using speech recognition technology. 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.

● Computers display 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 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 eye looks 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 packed 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 coursework 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 will 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.

2009 ● Most books will be read on screens rather than paper. Most text will be created using speech recognition technology. 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. Computers display 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 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 eye looks 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 packed 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 coursework 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 will 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.

2009 ● Most books will be read on screens rather than paper. Most text will be created using speech recognition technology. 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. Computers display 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 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 eye looks 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 packed 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 coursework 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 will 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.
Some trends outside of science and technology. Do we see a straight line from this . . .
... to this?
GM on the verge of extinction

2007 2017

GM

2007

UBER

2017

TESLA
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.
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."
Dynamic time warping

Rate of evolution for the last 1,000 years greater than the last 1,000,000
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

ARCHITECT
HANS HOLLEIN
DESIGNS A
MOBILE OFFICE

IT’S INFLATABLE
George doesn’t mind being wrong if we learn something

A vision from 1969

ARCHITECT
HANS HOLLEIN
DESIGNS A
MOBILE OFFICE

IT’S INFLATABLE

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

ARCHITECT
HANS HOLLEIN
DESIGNS A
MOBILE OFFICE

IT’S INFLATABLE

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

2017 is to 2040
—as—

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

2017 is to 2040
—as—
1994 is to 2017
Complete this analogy

2017 is to 2040
—as—
1994 is to 2017 (neglecting the dynamic time warping)
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?
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


### One researcher’s agenda in 1994

|---|---|
PUBLICATIONS


That researcher’s agenda in 2017

PUBLICATIONS


## PUBLICATIONS


<table>
<thead>
<tr>
<th>Free Source</th>
<th>PUBLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
A 'Whom Do You Hang With?' Map Of America

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.

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
<table>
<thead>
<tr>
<th>The two basic issues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>With whom do we hang?</strong></td>
</tr>
<tr>
<td>Chemical Engineering</td>
</tr>
<tr>
<td>Mathematics</td>
</tr>
<tr>
<td>Computer Science</td>
</tr>
<tr>
<td>Electrical and Computer Engineering</td>
</tr>
<tr>
<td>Industrial and Systems Engineering</td>
</tr>
<tr>
<td>Physics</td>
</tr>
<tr>
<td>Chemistry</td>
</tr>
<tr>
<td>Biology</td>
</tr>
<tr>
<td>Process industries</td>
</tr>
<tr>
<td><strong>What are our new dots?</strong></td>
</tr>
<tr>
<td>Machine learning</td>
</tr>
<tr>
<td>Deep neural networks</td>
</tr>
<tr>
<td>Big data</td>
</tr>
<tr>
<td>Complexity</td>
</tr>
<tr>
<td>Scale</td>
</tr>
<tr>
<td>Optimization?!</td>
</tr>
<tr>
<td>Grand societal challenges</td>
</tr>
</tbody>
</table>
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.
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.

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.
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
A more recent experience with George

- Aspentech bought many smaller PSE companies and hired many of our PhD graduates
- Then they nearly imploded
A more recent experience with George

- Aspentech bought many smaller PSE companies and hired many of our PhD graduates
- Then they nearly imploded
- George renewed Aspentech’s focus on research and innovation through his founding of the Aspentech Academy
- A big benefit to the PSE community
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.
- George renewed Aspentech’s focus on research and innovation through his founding of the Aspentech Academy.
- A big benefit to the PSE community.
As an undergraduate, while our class was struggling with the interpretation of some complex 500-page novel, the professor told us,
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:*
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!”
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!
Testing the idea

If we apply the “one book, one idea” principle to Kurzweil’s book(s), the summary is:

It’s exponential, baby!
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!*
Let’s take it one step further.
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

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

Some PSE examples; think of these people at age 35

- Ignacio Grossmann:
An extension

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

Some PSE examples; think of these people at age 35

- Ignacio Grossmann: We *can* solve a mixed-integer nonlinear program.
Let’s take it one step further. One career, one idea

Some PSE examples; think of these people at age 35

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

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

Some PSE examples; think of these people at age 35

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

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

Some PSE examples; think of these people at age 35

- Ignacio Grossmann: We can solve a mixed-integer nonlinear program. And MINLP best captures the process design problem.
- Jim Rawlings: We can solve an optimal control problem in real time.
Let’s take it one step further. One *career*, one idea

Some PSE examples; think of these people at age 35

- Ignacio Grossmann: *We can* solve a mixed-integer nonlinear program. And MINLP best captures the process design problem.
- Jim Rawlings: *We can* solve an optimal control problem in real time. And that enables feedback control.
Let’s take it one step further. One career, one idea

Some PSE examples; think of these people at age 35

- Ignacio Grossmann: We *can* solve a mixed-integer nonlinear program. And MINLP best captures the process design problem.
- Jim Rawlings: We *can* solve an optimal control problem in real time. And that enables feedback control.
- Larry Biegler:
An extension

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

Some PSE examples; think of these people at age 35

- Ignacio Grossmann: We can solve a mixed-integer nonlinear program. And MINLP best captures the process design problem.
- Jim Rawlings: We can solve an optimal control problem in real time. And that enables feedback control.
- Larry Biegler: Damn right!
Let’s take it one step further. One career, one idea

Some PSE examples; think of these people at age 35

- **Ignacio Grossmann:** We *can* solve a mixed-integer nonlinear program. And MINLP best captures the process design problem.
- **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.
I cannot answer George’s question of what PSE will look like in 2040, but I know who can.
I cannot answer George’s question of what PSE will look like in 2040, but I know who can.

If you poll ten top senior investigators what their field will be like in twenty years, you will likely get zero correct answers.
I cannot answer George’s question of what PSE will look like in 2040, but I know who can.

If you poll ten top senior investigators what their field will be like in twenty years, you will likely get zero correct answers.

If you poll ten top junior investigators what their field will be like in twenty years, you will likely get two correct answers.
I cannot answer George’s question of what PSE will look like in 2040, but I know who can.

If you poll ten top senior investigators what their field will be like in twenty years, you will likely get zero correct answers.

If you poll ten top junior investigators what their field will be like in twenty years, you will likely get two correct answers. Because they will create the change!
I cannot answer George’s question of what PSE will look like in 2040, but I know who can.

If you poll ten top senior investigators what their field will be like in twenty years, you will likely get zero correct answers.

If you poll ten top junior investigators what their field will be like in twenty years, you will likely get two correct answers. Because they will create the change!

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