Outline

Research to Innovation

Recent Trends in Innovation

Implications for Future Directions in Systems and Control

Conclusions
Research to Innovation

- New knowledge leads to societally useful innovations
- Tremendous acceleration after the industrial revolution
- Rise of science and engineering research ecosystem after the 2nd world war

Science offers a largely unexplored hinterland for the pioneer who has the tools for his task. The rewards of such exploration both for the Nation and the individual are great. Scientific progress is one essential key to our security as a nation, to our better health, to more jobs, to a higher standard of living, and to our cultural progress.
Global R&D Expenditures

Figure 2. R&D Expenditures of Selected Countries, 2000-2015
(in billions of current PPP dollars)


Notes: PPP = Purchasing Power Parity. PPP is used to determine the relative value of different currencies and to adjust data from different countries to a common currency allowing direct comparisons among them.
How does Innovation Show up in Economic Data?

Landmark article on economic growth theory by the Nobel prize winning economist Robert Solow in 1956

**Total Factor Productivity:** Portion of output not explained by inputs into the production process

Known as *Solow residual*

TFP — Attributed to technological innovation

*Literature on endogenous growth theory in economics*
TFP Decreasing Trend
Smoothed TFP Trend

Craft and Mills, 2017
TFP by Decade

Peak Innovation

Total factor productivity measures innovation. It peaked in the 1940s and was strong through 1970. Each bar shows a 10-year average prior to the year shown (2014 bar is for 2001–2014).

Source: MIT Technology Review
TFP Growth Slowdown has Material Impact

“Productivity isn't everything, but, in the long run, it is almost everything. A country’s ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker.”

Paul Krugman

Source: BLS and Hamilton Project Calculations.
Divergence of opinions:

Camp A: Innovations of late 20\textsuperscript{th} - early 21\textsuperscript{st} century period are not as impactful as those in the mid 19\textsuperscript{th} – early 20\textsuperscript{th} century periods

Camp B: Best is yet to come --- it takes time for society to absorb new technologies

Camp C: There is a measurement problem and GDP is a flawed measure of progress
It is Getting Harder to Innovate

Figure 1: Aggregate Data on Growth and Research Effort

- U.S. TFP Growth (left scale)
- Effective number of researchers (right scale)

Factor increase since 1930

Growth Rate

0% 5% 10% 15% 20% 25%

1930s 1940s 1950s 1960s 1970s 1980s 1990s 2000s

Figure 2: Aggregate Evidence on Research Productivity

- Effective number of researchers (right scale)
- Research productivity (left scale)

INDEX (1930=1)

Note: Research productivity is the ratio of idea output, measured as TFP growth, to research effort. See notes to Figure 1 and the online data appendix. Both research productivity and research effort are normalized to the value of 1 in the 1930s.

Source: Are Ideas Getting Harder to Come by, Bloom et al, 2017
Case of Semiconductor Technology

Figure 4: Data on Moore’s Law

Note: The effective number of researchers is measured by deflating the nominal semiconductor R&D expenditures of key firms by the average wage of high-skilled workers. The R&D data includes research by Intel, Fairchild, National Semiconductor, Texas Instruments, Motorola, and more than two dozen other semiconductor firms and equipment manufacturers; see Table 1 for more details.

Source: Are Ideas Getting Harder to Come by, Bloom et al, 2017
EROOM's Law

Need for Innovation has Never Been Greater
NAE Grand Challenges

GRAND CHALLENGES FOR ENGINEERING

- Make solar energy economical
- Provide energy from fusion
- Develop carbon sequestration methods
- Manage the nitrogen cycle
- Provide access to clean water
- Restore and improve urban infrastructure
- Advance health informatics
- Engineer better medicines
- Reverse-engineer the brain
- Prevent nuclear terror
- Secure cyberspace
- Enhance virtual reality
- Advance personalized learning
- Engineer the tools of scientific discovery
UK Industrial Strategy: the Grand Challenges

- Growing the Artificial Intelligence and data driven economy
- Clean growth
- Future of mobility
- Ageing society

EU Horizon 2020 Grand Challenges

- Health, demographic change and wellbeing;
- Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy;
- Secure, clean and efficient energy;
- Smart, green and integrated transport;
- Climate action, environment, resource efficiency and raw materials;
- Europe in a changing world - inclusive, innovative and reflective societies;
- Secure societies - protecting freedom and security of Europe and its citizens.

UN Sustainable Development Goals

Source: UN
## And a Flood of New Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Manufacturing</td>
<td>27%</td>
</tr>
<tr>
<td>Artificial Intelligence</td>
<td>21%</td>
</tr>
<tr>
<td>Big Data</td>
<td>27%</td>
</tr>
<tr>
<td>Bioengineering</td>
<td>21%</td>
</tr>
<tr>
<td>Bionanotechnology</td>
<td>15%</td>
</tr>
<tr>
<td>Cloud Computing</td>
<td>19%</td>
</tr>
<tr>
<td>Embedded Processing</td>
<td>12%</td>
</tr>
<tr>
<td>Information Technologies</td>
<td>37%</td>
</tr>
<tr>
<td>Genomics/Proteomics</td>
<td>13%</td>
</tr>
<tr>
<td>Medical Diagnostics</td>
<td>22%</td>
</tr>
<tr>
<td>Nanotechnology</td>
<td>20%</td>
</tr>
<tr>
<td>Quantum Computing</td>
<td>7%</td>
</tr>
<tr>
<td>Renewable Energy</td>
<td>20%</td>
</tr>
<tr>
<td>Robotics/Automation</td>
<td>26%</td>
</tr>
<tr>
<td>Software</td>
<td>32%</td>
</tr>
<tr>
<td>Space Technologies</td>
<td>7%</td>
</tr>
<tr>
<td>Sustainability</td>
<td>24%</td>
</tr>
</tbody>
</table>

Source: R&D Magazine Survey 2017
Recent Trends in Research to Innovation
Linear Model of Research to Innovation is Wrong

Linear model: discovery made – private sector productizes and commercializes

Reality: numerous, interconnected feedback loops and iterations between basic research, prototypes, development and commercialization

Misunderstanding of this interconnection causes major losses in efficiency and productivity

Historical examples go back to the industrial revolution era where the inventions preceded science, e.g., thermodynamics came after steam engines
Technology Innovations Increasingly have a Combinatorial Nature

Examples of Recent Successes

Magnetic Resonance Imaging (MRI)

Internet technologies

Solar Photovoltaics

Laser surgery
Research: Pasteur’s Quadrant

- Pure Basic Research (Bohr)
- Use Inspired Basic Research (Pasteur)
- Applied Research (Edison)

Source: D. Stokes, 1997
GUIRR WORKSHOP
Highly Integrative Basic and Responsive Research (HIBAR): Partnerships for Discovery and Innovation
June 27, 1:30-5:10 pm
Washington, DC
Can we systematically accelerate the process of research driven innovation?
NSF Innovation Corps Program

Research advances

+ Lean startup principles

+ Experiential education for faculty and students

Heart of the program: 100 customer interviews
NSF Innovation Corps Program
Value Creation Best Practices: C. Carlson

Less than 10% of company and national R&D has substantial value for stakeholders

Value creation playbook by C. Carlson

NABC Framework – Need, Approach, Benefit/Costs, Competition

Technologies + market/societal need + key insight + multidisciplinary collaboration

Value creations forums – team feedback in an NABC framework

An iterative process to create an important innovation as against solving an interesting problem
Design Thinking

Major trend in improving product/service design

Human centered innovation

Stanford D-School, IDEO

Potential for application to the research process
Implications for Future of Systems and Controls Research
Review article

Systems & Control for the future of humanity, research agenda: Current and future roles, impact and grand challenges

Francoise Lamnabhi-Lagarrigue\textsuperscript{a,*}, Anuradha Annaswamy\textsuperscript{b}, Sebastian Engell\textsuperscript{c}, Alf Isaksson\textsuperscript{d}, Pramod Khargonekar\textsuperscript{e}, Richard M. Murray\textsuperscript{f}, Henk Nijmeijer\textsuperscript{g}, Tariq Samad\textsuperscript{h}, Dawn Tilbury\textsuperscript{i}, Paul Van den Hof\textsuperscript{j}
Emerging and Aspirational Visions

Smart-X

Smart manufacturing, Industry 4.0
Smart grid, renewable energy, carbon capture and sequestration
Smart and connected vehicles, future of urban transportation
Smart cities
Smart and connected health

Healthy aging and wellness

Food-energy-water nexus

High quality personalized education
Grand Challenges are often Wicked Problems

Wicked problems … there is no clear stopping rule … working on it more … better solution … no single right answer … every attempt can matter because it affects the things people depend upon.

Rittel and Weber, 1973
Characteristics of Wicked Problems

- No definite formulation of a wicked problem.
- No stopping rules.
- Solutions are not true-or-false, but better or worse.
- No immediate and no ultimate test of a solution to a wicked problem.
- Do not have an enumerable (or an exhaustively describable) set of potential solutions.
- Every wicked problem is essentially unique.
- Causes can be explained in numerous ways.
Controls will need to be integrated with complementary disciplines and technologies

- Information and communications technologies
- Electronic, materials, and nanotechnologies
- Biotechnologies: genetic, ohmic, synthetic, …
- Social sciences, humanities, creative arts, …
Dimensions of Team Science

- Diversity of team members
- Disciplinary integration
- Team size
- Goal alignment
- Permeable boundaries
- Geographic proximity
- Task interdependence

*a new interdisciplinary field . . . aims to better understand ... team-based research and practice and to identify the unique outcomes of these approaches ... (Stokols et al.)*

Source: Enhancing Effectiveness of Team Science, NRC, 2015
Influences on Convergent Science Beyond the Team and its Immediate and Institutional Environments

Institutional Multi-Team System in which the Team (T1) is Embedded

Team’s Immediate Environment

Individual Team Members

Physical-Spatial, Social, Organizational-Institutional, Technological Features

Stokols, 2018
Improving Team Effectiveness

- Team processes
- Team composition
- Team professional development
- Leadership for team science
- Support for virtual collaboration
- Organizational support for team research

Source: Enhancing Effectiveness of Team Science, NRC, 2015
We will need to support and encourage a healthy and diverse ecosystem of systems and controls research

Balance internally driven deep disciplinary research against use-inspired transdisciplinary collaborative research

Create opportunities for robust cross-fertilization

Balance the values and culture of the field to be better positioned for collaboration with other disciplines and people

Take steps to reduce wasted efforts in research
References


Comments

Ideas

Questions?

pramod.Khargonekar@uci.edu
http://faculty.sites.uci.edu/khargonekar/