What gave the U.S. its prosperity and influence?
World-leading and enduring industries!

A few examples:
- Steel
- Automobiles
- Aerospace
- Nuclear
- Telecommunications
- Petrochemical
- Pharmaceuticals
- Internet

- Semiconductors
- Machine tools
- Solar Cells
- Lithium-ion batteries

Artificial Intelligence?
Detroit

Process innovation: Assembly line
1924 Model T, Dearborn, MI

1920’s – 1950’s Detroit
Wealthiest city in the world
Detroit today – urban decay and world class skills

Detroit from above...

Heart of automation: N-S along I-75,
E-W along I-90 Buffalo to Chicago

Hundreds of interconnected suppliers!!
Ohio example – Honda assembly (Accord, Acura, etc.)

Honda Supplier Map

- About 600 North American Suppliers
- Over $20B/yr spend in N. America
- Over $10B/yr in Ohio alone
- Lasting legacy of Henry Ford...
Old-School Process Innovation (Chinese Porcelain)

**Black Pottery Cauldron** Hemudu Culture Neolithic Period (ca. 5000 - 3000 B.C.). These cooking cauldrons from built-up layers of clay flakes, which were decorated with an overlapping rope pattern. They were placed over open fires.

Collection of Palace Museum, Beijing. Painted pottery pot with dragon and phoenix relief, as well as taotie designs for the lug handles. Western Han Dynasty, 206-8 B.C.

Han dynasty developed Porcelain!! ~1200° C firing >500 years before Europe!

Ming Dynasty: Goldfish Vase, reign of the Jiajing Emperor (1521–67); Porcelain; Paris, Musée Guimet 261101

Porcelain wares, such as those similar to these Yongle-era porcelain flasks, were often presented as trade goods during the 15th-century Chinese maritime expeditions. (British Museum)

Han Dynasty Kiln
Types of “Innovation”

• **Scientific Discovery (ideas)**
  • US leads the world!
  • Provides Nobel Prizes and **ideas**.

• **Product Innovation**
  • Examples: iPhone, Dyson vacuum, IKEA furnishings, Tesla S
  • Can be fast

• **Practice Innovation**
  • Practices that involve new thinking or algorithms
  • Examples: Uber, Lean, AmazonPrime, Crowdsourcing, FedEx.
  • Can be fast

• **(Physical) Process Innovation**
  • Maturation of enabling physical processes; new hardware is involved.
  • Examples making: steel, aluminum, tires, glass, semiconductors, or new ways of mining, such as fracking.
  • Frustratingly slow... But provides sustained advantages
We need science, and to put it into production.
Process and Product Innovation in the iPhone

Idea

Process and Product Innovation in the iPhone

Great discussion on this: Mforesight Manufacturing Prosperity, at http://mforesight.org/download-reports/

M Foresight summit: June 18 @ Hamilton Hotel, Sens. Rubio & Peters Keynote!

Factories & Jobs


LG Display (South Korea) - LG Display is the largest display panel supplier for the iPhone 6.

Japan Display (Japan) and TPK Touch Solutions (Taiwan) - Japan Display is the second largest supplier for the iPhone 6.

Sony (Japan) - Sony produces the iPhone 6’s Touch ID sensor.

TDK (Japan) - TDK supplies the iPhone 6’s ceramic capacitors.

Toshiba (Japan) and SK Hynix (South Korea) - Toshiba supplies the iPhone 6’s NAND flash.

Texas Instruments (TX, US) - Texas Instruments produces the iPhone 6’s RF chips.

Catcher Technology (Taiwan) - Catcher Technology produces the iPhone 6’s metal frame.
Another great event...

FEATURED SPEAKERS

- Senator Marco Rubio
- Senator Gary Peters
- Representative Ro Khanna
- Representative Haley Stevens
- David Anderson
  President – SEMI Americas
- Alan Shaffer
  Deputy Undersecretary – Department of Defense
Process innovation is precious and makes clusters

• New processes build persistent cluster economies
  • Detroit → Automotive
  • Akron → Elastomers / polymers
  • Wichita, KS → Airframe components
  • Seattle, WA → Airframes
  • Detroit → Automotive
  • Rochester, NY → Optics
  • Minneapolis → Medical Implants
  • Warsaw, IN → Orthopedic implants
  • Fort Wayne, IN → Electromagnets and wires
  • Corning, NY → Ceramics
  • Toledo, OH → Glass
  • Shenzhen, China → Electronic systems

• New processes teach new skills, and a culture of doing

• “Innovate here, build there” does not work!
Incentives (become different in each country)

• **Government** – Employment, infrastructure, development.

• **Universities** – Happy & successful students, faculty and donors.

• **Companies** – Lucrative markets, low cost production, sources of innovation.

• **Legislators** – Happy constituents (including companies).

• *Made in China 2025* is very different than an American course of action. Innovation and entrepreneurship are areas of focus.
A new way to make structural parts

Stuff does matter – materials and processing is a big part of our economy and accounts for about 1/3 of the greenhouse gas we produce.
Metamorphic Manufacturing

• An opportunity to do something establish new processes in the US.

• Treats needs for components (aerospace, heavy industry, medical, etc.) with completely new and simpler production paths.

• Has similar potential to *additive manufacturing*.

• Allows sustainable production of components where they are needed.
Short Tutorial: How do we make things now...

1. Take something from nature (tree, rock, etc.)
2. Cut or machine something to size
3. Solidify or cure a liquid in a mold
4. Build something from small parts (add)
5. Form to shape with dies (sheet, forge, etc.)

Example cold-forged parts

Open and closed die hot forgings
Cast metal products

• Easy way to complex shape
• Very little waste
• Surprising levels of innovation
• Often poor properties vs. wrought
Closed Die Forging

- Awesome properties
- Can be expensive
- Long time and big $ to first part
Digital Manufacturing

• Part description is stored on a computer
• Equipment makes the part without dies or molds
• Flexible, rapid product changes, short lots.
• Potentially sustainable
• Manufacturing can be at point of need.
CNC Machining
1st Wave Digital Manufacturing

Subtractive/Removal
MIT - starting in ~1949
Additive Manufacturing (a.k.a. 3-D printing)  
2nd Wave of Digital Manufacturing

NSF, etc., start early 1980’s

Federal spending of hundreds of $M spent on Additive since the 1990’s
3rd Wave -- Metamorphic Manufacturing (Manual)

- Change shape
- Change Properties

A – actuator
C – computation
S – sensors
R – robotics
T – thermal
Metamorphic Manufacturing Study

- **Overarching Goal of Study:** *jump start the development, emergence, and growth of this potentially disruptive technology*

- Identifies MM value proposition, foundational underlying technologies, fundamental science and engineering challenges/needs

- Develops recommendations and detailed action plans

- All intended to help community achieve above goal, and *make quantifiable progress within next 3 years*
The Study Team

• Glenn Daehn (Team Chair) – Ohio State University
• John Allison – University of Michigan
• Elizabeth Bilitz - Finkl Steel
• David Bourne - Carnegie Mellon University
• Jian Cao - Northwestern University
• Kester Clarke - Colorado School of Mines
• Johnnie J. DeLoach Jr. – Office of Naval Research
• Ed Herderick – OSU Center for Design & Man. Excellence
• John Lewandowski - Case Western Reserve University
• Tony Schmitz – University of North Carolina
• Howard Sizek – Air Force Research Laboratory
• A. Erman Tekkaya – Tech. Univ. of Dortmund

*Expertise in varied areas: metals, forging, manufacturing (including additive), welding, deformation, robotics, machines...
Key study question:

What would be the benefits and challenges in developing a robust and general capability for the digital reshaping of metal?

What steps are needed to actualize such a vision?
Foundational ideas

Open die forging

Robotic metal forming
**Proof of Concept: The LIFT Prize**

**LIFT Prize** – $25k offered for a single programmable system that can shape 2 of 3 target parts.

Team Honey Badger, of Ohio State University. Alex Koenig, Bhuvi Nirud hoddi and Brian Thurston
See: RoboticBlacksmithing.com for details.
Fundamental Elements

- **S** - sensors
- **A** - actuator
- **C** - computation
- **R** - robotics
- **T** - thermal

METAMORPHIC MANUFACTURING

Shaping the Future of On-Demand Components

A New Frontier for Digital Manufacturing

CONGRESSIONAL BRIEFING

June 6, 2019
Robotic Blacksmith

Sensors
Thermal
Actuators
Robotics
Computation
Report outcome: Value Proposition

Table 1. MM Value Proposition and Key Benefits

<table>
<thead>
<tr>
<th>Value Proposition Categories</th>
<th>Key Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economical and Environmentally Friendly</td>
<td>Lower material waste</td>
</tr>
<tr>
<td></td>
<td>Little (or no) need for die fabrication and storage</td>
</tr>
<tr>
<td></td>
<td>Reduced energy consumption and carbon footprint</td>
</tr>
<tr>
<td>Shape and Property Control</td>
<td>Superior local property control</td>
</tr>
<tr>
<td></td>
<td>Unique, highly complex shapes/geometries</td>
</tr>
<tr>
<td></td>
<td>Larger build envelope</td>
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<tr>
<td></td>
<td>Optimization of process routes and properties via iteration (possibly aided by machine learning)</td>
</tr>
<tr>
<td>Superior Manufacturing Flexibility and Accessibility</td>
<td>Expanded suite of materials options</td>
</tr>
<tr>
<td></td>
<td>Attractive product lines for many small and medium sized businesses</td>
</tr>
<tr>
<td></td>
<td>Small batch production and part design variability capabilities</td>
</tr>
<tr>
<td></td>
<td>Short lead time from concept to production</td>
</tr>
</tbody>
</table>

3 value categories
Actions recommended

1. Launch Computational-MM benchmarking & modeling efforts
2. Build prototype MM process suites & exemplar parts
4. Develop MM internship program
5. Foster small organization-led industry-based MM projects
6. Formulate & address some grand challenge problems
7. Create desktop prototype machine
Example closed-die forged parts

Example forging images from Consolidated Industries: http://www.consolindustries.com/products-military-forgings.php
## The 3 waves of digital manufacturing

<table>
<thead>
<tr>
<th>Technology</th>
<th>1 - Subtractive</th>
<th>2 - Additive</th>
<th>3 - Metamorphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Tool Path</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Material State Control</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Forming Strategy</td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Sense, Compute, Control</td>
<td></td>
<td></td>
<td>●</td>
</tr>
</tbody>
</table>
Comparing Additive and Metamorphic Manufacturing

**Additive**

- Wider range of materials
- Less energy consumed
- Scales to larger sizes
- Better materials properties

**Metamorphic**

- Wider range of materials
- Less energy consumed
- Scales to larger sizes
- Better materials properties
- Integrates with other processes
- Challenges: awareness, training, tools, algorithms.
Practical Problem

Bigger problem than usually handled in University environment.

Pre commercial.

Needs many disciplines: Materials, Robotics, Computation, Metrology, Artificial Intelligence, Equipment hosting, etc., etc.

Needs an unusual structure and support.

Useful to find a way to do it here.
Technical case

Subtract → Add → Morph. (shape and properties)

Based on fast advancing disciplines
  Robotics
  Integrated Computational Materials Engineering
  Artificial Intelligence
  Sensors
  Control

Can scale naturally to large sizes

Provides exceptional materials properties; extendable to graded chemistry

Naturally provides a path for qualification and certification

Is an opportunity for the USA. Helps balance of trade. Cement this here by:
  Fast innovation
  Skilled workforce (motivated by creative opportunity)
  Unique and accessible equipment
Concluding Remarks...

- D-Day reminds to be self reliant to make what we need in a crisis...
- This process innovation provides infrastructure and skills; hard to move.
- Metamorphic Manufacturing (robotic blacksmithing) offers an opportunity to invest on the ground floor for a new technology. This can provide:
  - Skills
  - Capabilities
  - Jobs
  - Competitive advantages
- Do support manufacturing technology. We need to keep parity with rival countries.