The Role of DARPA in Seeding and Encouraging Technology Trajectories: Microelectronics, Integrated Photonics, and Moore's Law

Erica R.H. Fuchs

Assistant Professor

Department of Engineering and Public Policy

Carnegie Mellon University

erhf@andrew.cmu.edu

Plato's Cave: It's not about the funding.

"Are you familiar with the allegory of the Cave?" (Plato, *The Republic*)

"… It's the same thing with (trying to deduce technology directions from) funding. The technology direction is a separate thing."

(Lead Technologist, Government Lab)

Background: Innovation and the (U.S.) State

- Unlike other countries, whom have open and explicit developmental policies (Chalmers 1982; Wade 1990; Amsden 1989, 1994, 2001, 2003; Breznitz 2007, Block 2007)
- Strong prevalence of free-market thinking in U.S. (Harcourt 1980)
- Despite extensive historical documentation of the importance of federal agencies in technology development
- Developmental state largely "hidden" (Hughes 2005, Block 2007)

Little research unpacking the underlying processes and institutions by which the state's influence on technology development works

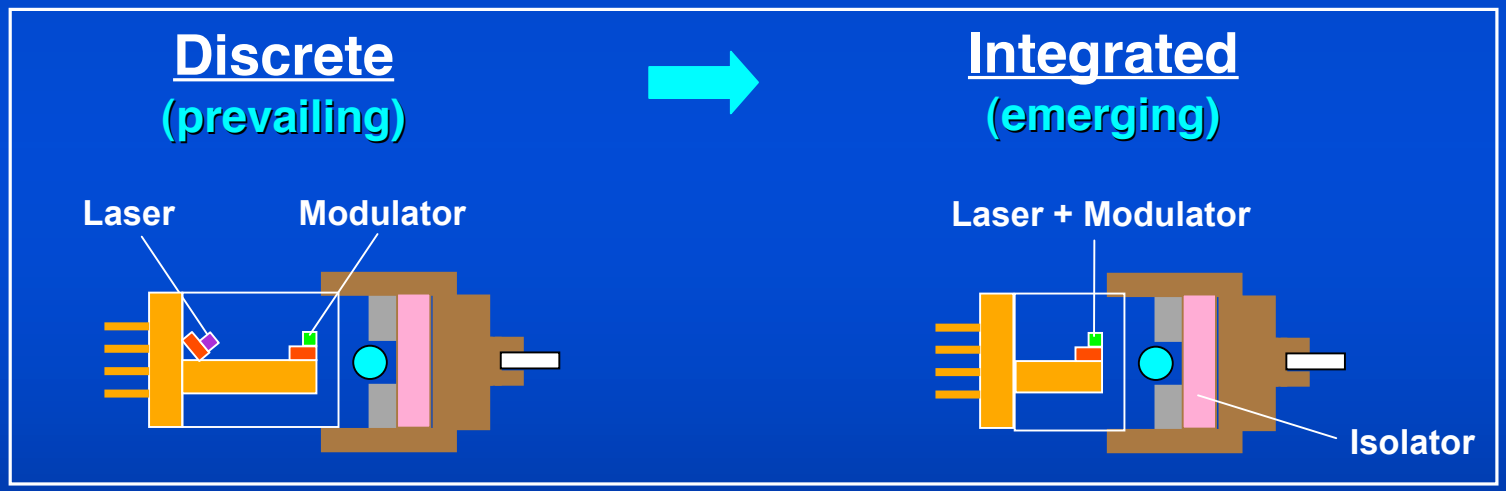
Background: Social Networks and Knowledge Flows

- Type of Tie: strong vs. weak (Granovetter 19737)
- Structure of Network:
  - Structural holes (Burt 2004),small worlds (Milgram 1967, Fleming 2007)
- Type of Node:
  - Social brokers vs. technology boundary spanners (Fleming 2007)
  - Star scientists (within institution, to start-ups) (Zucker 1996)
- Innovation networks: co-authorship patents, publications
  - Despite acknowledged dissemination of knowledge through informal channels both in academia and industry (Marshall 1919, Crane 1972, Allen 1983, Piore 1984, Von Hippel 1987, Saxenian 1994, Almeida 1999)
- Origin and evolution of innovation networks
  - Self-organizing? (Jackson 1996, Carayol 2003)
  - Cooperative Technical Organizations (Rosenkopf 1998)

How does the state act, if at all, within this institutional framework to influence technology development?

Integration in Optoelectronic Transmitters

- Produce multiple functions on a single chip
- Originally, driven by telecom market
  - Improve network performance; reduce size, cost



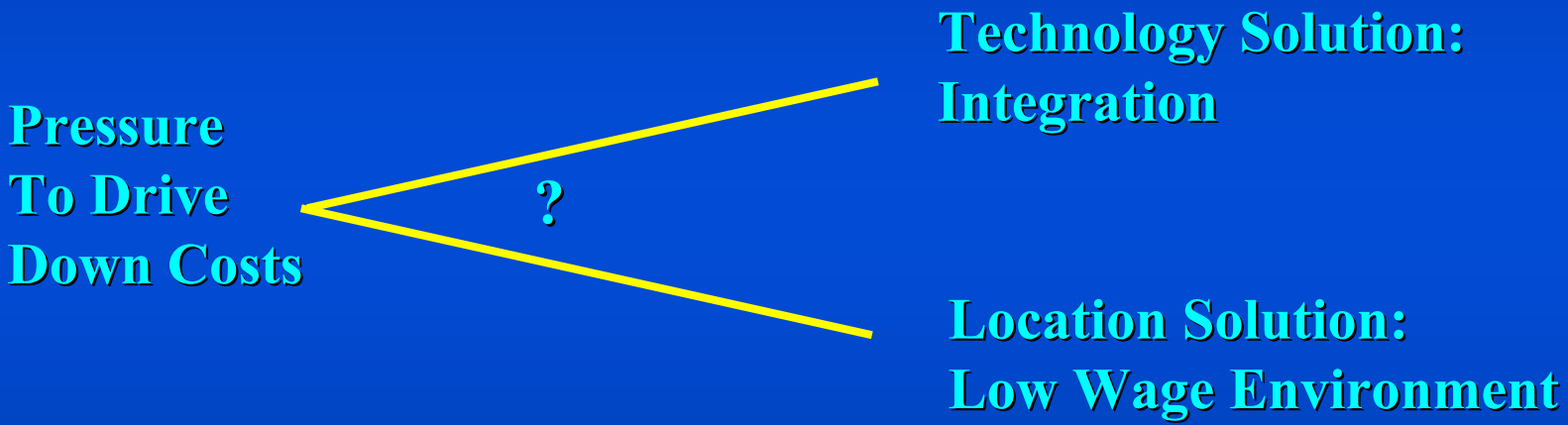
- Long term, address interconnect bottleneck
  - Computer optical bus: integration seven functions

Fuchs and Kirchain (2008) Design for Location: The Impact of Manufacturing Offshore on Technology Competitiveness. R&R with *Management Science.*

Dramatic Shift in Telecom Market

- In 2000, burst of telecom bubble

- Two options to reduce cost:



- 15 of 16 firms moved offshore (15 → 8)
- Cut R&D departments, ceased to push forward efforts in integration
- DARPA to the rescue? (UNIC Solicitation, 2006)

Fuchs and Kirchain (2008) Design for Location: The Impact of Manufacturing Offshore on Technology Competitiveness. R&R with *Management Science.*

Methods: Grounded theory-building (Glasner and Strauss 1967, Eisenhardt 1989)

- Fieldwork:
  - 50 semi-structured interviews
  - –
  - –
  - –
- Arc
  - –
  - C
  - DARPA Annual Reports, Annual Meetings (online)
  - News releases: DARPA, Companies, Industry journals

Case Study (Yin 1994, Eisenhardt 1989)

Focus: Optical interconnect technology (UNIC)
- Computer & Communications Industry

Technologies Relevant to Moore's Law
- Past: Strained SiGe, VCSELs, Lithography
- Current: Integrated photonics, atomic clocks, clockless logic

DARPA: Microsystems Technology Office

IDA
n the

Methods: Grounded theory-building (Glasner and Strauss 1967, Eisenhardt 1989)

- Fieldwork:
  - 50 semi-structured interviews
    - DARPA program managers
    - Intel, IBM, HP, Start-ups (Luxtera, Kotura)
    - University professors
    - Government labs (Lincoln Labs, Lawrence Livermore)
  - Participant observation of DARPA UNIC team
  - Attendance of industry conferences
    - Microphotonics Consortium 2007, Photonics North 2007, OIDA Annual Forum 2008, OIDA Manufacturing and Innovation in the 21st Century 2008
  - Attendance of IEEE computing industry workshop
    - Technology fellows from Intel, IBM, HP, Start-ups
- Archival Data:
  - Online biographies, CVs of key technologists
  - Congressional testimonies
  - DARPA Annual Reports, Annual Meetings (online)
  - News releases: DARPA, Companies, Industry journals

What made the old DARPA unique as an institution?

A Culture Which Supports Risk Taking.

(At DARPA you can) "…place bets with enormous risk, and very few penalties of failing. It's probably better to have spectacular failures than just lots of failures"

(DARPA Program Manager)

"NSF is much more peer-review, and so, you don't see these revolutionary things go on in NSF. DARPA is much more, 'This is a revolutionary idea.' When you have a huge peer review and so on, if something is too radical, it gets killed. So you kind of get the lowest common denominator funded. But with DARPA, they'll take flyers. They'll say this is really radical. A huge chance of success or a huge chance of failure, but a big upside."

(University Professor)

Low Threshold for Action

"I pretty much enjoyed my years as a program manager more than anything. I was absolutely unlimited. People could just go do things. **The threshold for action was fairly low.** You had to be smart about what you did, you couldn't make foolish calls, but there wasn't a lot of baggage. **The administrative minutia was gone.** And it was absolutely slack because we just made it that way."

"I mean, you could just turn on a dime. **We could basically call people up, and have a discussion. With the idea that if we see something here, we could fund a seedling, and get something started, and see if there's a next step.**"

(DARPA Program Manager)

What processes does DARPA use to influence technology development?

The Program Manager

"It really comes down to the program manager. A program manager that has a passion for an idea, that understands the technical elements of an idea, and has some vision for where it might go."

- Taken from existing research network (government labs, universities, industry)
- Not always have Ph.D.s
- 3-5 year position
- A step-ladder in one's career

Pull on their existing social networks

"… I knew there was a chance they wouldn't make it. But at the time, I was betting on the person. Usually, I'd bet on a few people."

(DARPA Program Manager)

"And then he touched on people like <professor> and others who he knew well, and said, hey, help me, give me the ideas. So, he touched on <professor>, he touched on other key leaders in the field that he knew and he trusted."

(University Professor)

"Good venture capitalists do very good due diligence. …. They're tough on making you show what you really have. DARPA doesn't do any of that. Relationships are important in the VC community, but DARPA is more about relationships."

(Start-up Company)

Bringing Leaders together to Brainstorm Mission Goals

"We were talking with Paul Robinson about the notion of building very very high volume carbon nanotubes that were functionally matched… And I said, gee, Rick's always been working in that area, let's just call him in. Rick's a nobel prize chemist. So we called him. He was there in two days. And so Lieber came over from Harvard. We sat around. And it was a great discussion."

(DARPA Program Manager)

- Paul Robinson, Director Sandia National Labs
- Richard Smalley, Professor Chemistry, Physics, Astronomy, Rice U. 1996 Nobel Prize for discovery of "buckeyballs"
- Charles Lieber, Professor of Chemistry, Harvard University, Elected member NAS, 290 papers, more than 30 patents, None with Robinson, Smalley, P.M.

Seeding Disparate Researchers to Gain Momentum around Common Themes

"So I'll tell you the SiGe story…. So, the first guy to show me this, actually two guys, …was the guy who founded Amberwave. He showed me this is possible. And then Jason Woo and UCLA, … he showed me a plot of bandgap as a function of percent Ge. And he had two plots. He came to DARPA. And he said, look, there is a dependency, here it is, it follows band gap theory. … And I said, 'Jason, two dots don't make a program…. I need a third dot.' And he faxed me a chart the next day. …So I sent him a small seedling.

At the same time, I called Bernie (a fellow at IBM), and I said, 'Bernie, have you even seen this bandgap dependency in SiGe? You know, do you think it's something we can exploit?' He said, 'Funny you should ask.' We've been looking at the same thing, and we've got some ideas as well.' So I funded him $2M or whatever it was."

(DARPA Program Manager)

Seeding Disparate Researchers to Gain Momentum around Common Themes

"So I'll tell you the SiGe story…. So, the first guy to show me this, actually two guys, …was the guy who founded Amberwave. He showed me this is possible. And then Jason Woo and UCLA, … he showed me a plot of bandgap as a function of percent Ge. And he had two plots. He came to DARPA. And he said, look, there is a dependency, here it is, it follows band gap theory. … And I said, 'Jason, two dots don't make a program…. I need a third dot.' And he faxe
seedl

said,
depe
some
ask.'
some
was."

-Eugene Fitzgerald, Professor Materials Science and Engineering, M.I.T., Founder Amberwave, over 186 papers, more than 15 patents, 1st paper 1986

-Bernard Meyerson, IBM Fellow, Vice President and Chief Technologist, Systems & Technology Group, over 180 papers, more than 40 patents, 1st paper 1986

*** Have never co-authored or co-patented

(DARPA Program Manager)

Validating Directions: Other Funding Agencies

"See, once you've gotten funding from DARPA, you have an issue resolved, and so on, then you go right ahead and submit an NSF proposal. By which time your ideas are known out there, people know you, you've published a paper or two. And then the guys at NSF say, yeah, yeah, this is a good thing. … So NSF funding usually comes in a second wave. DARPA provides initial funding. … So DARPA plays a huge role in selecting key ideas.

(University Professor)

…that can't be accomplished with peer review?

Validating Directions: Industry

"So the DARPA piece, while large, was the validation for IBM to spend their own money. The same way for the Intel piece. You know, Intel certainly looked at that project, and then Intel ended up funding it internally, but the fact that DARPA went back to them 3 and 4 times and said, this is an important thing, this is an important thing, you know, it got to the board of directors, and it got high enough that they set up a division to do this."

(DARPA Program Manager)

"So in many cases money doesn't matter. I mean, it's important, but. It becomes a sort of announcement. And companies say, well, of course we should do it, because these guys think it's important. We better get on the ball."

(DARPA Program Manager)

But not sustaining the technology

"So we ran all of these design-of-experiment concepts, and you know, … we were doing great stuff, really good science. **But the tipping point, … is the fact that IBM saw the value in this to the point that they started investing in it.**"

(DARPA Program Manager)

The State Seeding and Encouraging New Technology Trajectories?

Although there were inevitably failures, historical evidence these processes worked really well…

-Bromberg (1991) The Laser in America
-NAS (1992) The Government Role in Civillian Technology
-Sternberg (1992) Photonic Technology & Industrial Policy
-Malone (1995) The Microprocessor: A Biography
-NAS (1999) Funding a Revolution
-Fong (2000) "Breaking New Ground…"
-Fong (2001) "ARPA Does Windows"
-Allan (2001) A History of the Personal Computer
-Newman (2002) Net Loss
-Roland (2002) Strategic Computing
-Hecht (2005) Beam: The Race to Make the Laser

Change in Innovation Ecosystem

Before	Now
Corporate R&D Labs (Macher 2000, Mowery 2000, NAS 2006)	Increased reliance on external sources of R&D (Mowery 2000)
Firm-based innovation trajectories	Complex networks of firms, universities, government labs Interdependency of innovation trajectories across products (NRC 1998, Mowery 1999:7, Powel and Grodal 2005)

Change in Computing Industry Structure

Few, pioneering firms supplied computers	Hundreds loosely linked suppliers (Breshnan 2000)
Primary demand government contractors	Primary demand (high volumes) commercial applications
Government contractors order customized products	Government contractors customizes commercial products

Change at DARPA (past 7 years)

Before	Now
Broad Area Announcements	Phases: 12-16 mo intervals Funds tied to go/no-go reviews linked to specific deliverables [1, 2, 3]
Funding primarily of universities	Funding shifted from universities to established vendors Many preclude universities, small start-ups as prime contractors; require formation of teams [4]

- Met severe criticism from computer science community[1, 2, 3]

[1] Joint Statement of the Computing Research Community. House Science Committee Hearing on The Future of Computer Science Research in the U.S. May 12, 2005.

[2] Lazowska, E. and Patterson, D. Editorial: An Endless Frontier Postponed. *Science Magazine*. Vol. 308. May 6, 2005.

[3] Markoff, John. Pentagon Redirects is Research Dollars. *New York Times*. April 2, 2005

[4] Defense Science Board Task Force. High Performance Microchip Supply. Feb. 2005

DARPA: HPC, EPIC, and UNIC Programs

Vision: "Moore's Law for Photonics and Beyond"

- **Phase I (February 2006)**
  - **Super-seedling, validity demonstration, 9 months**
  - **Five Teams: HP, IBM (with Luxtera), Sun Microsystems (with Luxtera), MIT I (with BAE), MIT II (with Analog Devices?)**
- **Phase II (November 2006)**
  - **2 years funding**
  - **Four Teams: HP (with Intel), IBM (with Luxtera), Sun Microsystems (with Luxtera), MIT I (with BAE)**
- **Phase III (March 2008)**
  - **5 1/2 year, $44M Funding of Sun Microsystems (with Luxtera and Kotura, Stanford, UCLA)**

Gathering momentum around an idea.

"So DARPA has program managers, and we were talking to them, and they got excited about this project, and they said, let's try to get a program out. So we worked with … the DARPA program manager, and they got interested in the field, and they got a program out of this. They got a bunch of other people involved in the program."

(Start-up Company)

… CTO and V.P. Engineering out of leading university research labs in integrated optics

Validating Directions: Bringing Credibility to New Ideas

"Investors are highly motivated to see the company succeed. As a consequence, they will lie through their teeth about what the company can do. DARPA funding and ATP funding have the added benefit of communicating to a third party a validation of the technology"

(Start-up Company)

… despite having a focus on relationships rather than having the due-diligence of the VCs

Coordinating technology directions across companies?

- Similar processes:
  - Gaining momentum
  - 3rd Party Validation

- Coordination now across firms within industry

  "I can tell you what you'll find. I was there (at the DARPA UNIC meeting) in Jackson Hole, and they're all presenting to each other what they're going to do. They're all talking to each other. And they're all doing the same thing."

  (University Professor)

A Critical Role for DARPA?

"You need someone with a longer term horizon. Ten years from now, we want a teraflop of computing. But we don't have more than a six month time horizon."

(Company "A" Senior Technical Staff Member)

"Here, the technology is being driven by the systems companies. Very few companies have the resources to do system-level exploration without DARPA funding. DARPA funding is enabling system players to determine the direction of this technology. If you don't get the system guys involved, you end up getting widgets that don't work in the bigger picture."

(Company "B" Senior Technology Fellow)

Avoiding DARPA Closer to the Market?

"So, <Company "C"> as a whole has just shied away from government funding. …<Our company> labs, or whatever, they'll get a little DARPA funding, but most of that is, has never produced anything of value, from a… commercial perspective. That wasn't saying it wasn't of value within industry, but just trying to delineate."

(Company "C" Technology Strategist)

"Sometimes I'm very nervous about getting too much focus on defense money. I don't want to lose track of the fact that I'm developing *products*, not technology. DARPA is funding the industry so far ahead. If you're developing for 10 years from now, DARPA is great. But how do you manage not to lose revenue, unless the market is starting in now.… Some of the technology developed for the next generation (computers) – I don't know if it is applicable that well to this thing (100G Ethernet). I'm not sure DARPA's direction is the direction to go. **I think… <his company's name> is ideally placed for 100G Ethernet technology. But, admittedly, not necessarily for the long term."**

(Start up Company)

-Allen 1978, Sirbu 1978, Zysman 1983
-NAS 2007 SBIR Assessment

Discussion

- The *process* matters.
- The old DARPA model: High-risk, high-reward, open-ended funding of universities
  - Seed and encourage new technology trajectories
  - Facilitating conversations, seeding disparate researchers, developing community, providing external validation
- The new DARPA model: Bridging the Gap.
  - Likely necessary given the dependency of the military on commercial products
  - Essential role in coordinating commercialization of research across universities, start-ups, and system contractors…?

Discussion

But with the decline of corporate R&D labs, and shift in DARPA funding away from universities, who is supporting early stages of the pipeline?

"We never state it publicly, but … I want to fund those companies that will put Intel out of business. I'm not interested in driving Moore's Law. The ITRS roadmap exists, and everyone knows what it is. DARPA is not in the business of maintaining that roadmap. We're in the business of cutting a path across it."

(Former DARPA Program Manager, mid-90s)