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Photonic Systems Manufacturing Consortium

Define the difficult challenges.
Create the potential solutions.

Data Center, IoT and Cost Modeling Drivers

PSMC- AIM Photonics Webinar Series
October 27, 2015

http://photonicsmanufacturing.org/

Driving Photonics Manufacturing

The Photonic Systems Manufacturing Roadmap

Leadership
Robert C. Pfahl, Jr, iNEMI, Principal Investigator, PSMC
Lionel C. Kimerling, MIT, Principal Investigator, PSMC
Jim McElroy, iNEMI, Executive Director, PSMC

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NIST AMTech

Technology Working Groups

- **Monolithic Integration**: Lionel C. Kimerling, MIT
- **Data Center Emulator**: Bob Pfahl, iNEMI
- **IoT Emulator**: Richard Grzybowski, MACOM
- **Emulator Cost Modeling**: Elsa Olivetti and Randolph Kirchain, MIT
- **Photonics Packaging**: Bill Bottoms, Third Millennium Test Solutions
- **Boards, Backplanes, Connectors**: John MacWilliams, US Competitors
- **Assembly and Test**: Dick Otte, Promex Industries

Weekly Webinar Series beginning October 20
Roadmap Release on December 7

Agreement to merge this Roadmap into AIM's IPTR
More than 125 companies participated in 2015

Agenda

- Overview of the Roadmapping Process:
  Product Emulators (PEGs) and Technology Working Groups (TWGs)
  Dr. Robert Pfahl
- Data Center Product Emulator
- Internet of Things Product Emulator

  Dr. Richard Grzybowski, Macom
- Cost Modelling Emulator

  Dr. Randolph Kirchain and Prof. Elsa Olivetti

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Product Emulators (PEGs) and Technology Working Groups (TWGs)

Dr. Robert Pfahl

TWGs and PEGS

Technology Working Groups

- Roadmap the necessary enabling technology (materials, processes, equipment) for a segment of the system supply chain
- Identify the required objectives and the roadblocks and potential Show-Stoppers holding back these developments.
- Develop a plan (Technical Plan) to address these roadblocks

Product Emulator Groups

- Roadmap the drivers and enabling technology needs for a market segment.
- The drivers include future cost and performance expectations
- Cost modelling serves as a key tool to evaluate alternative enabling technologies

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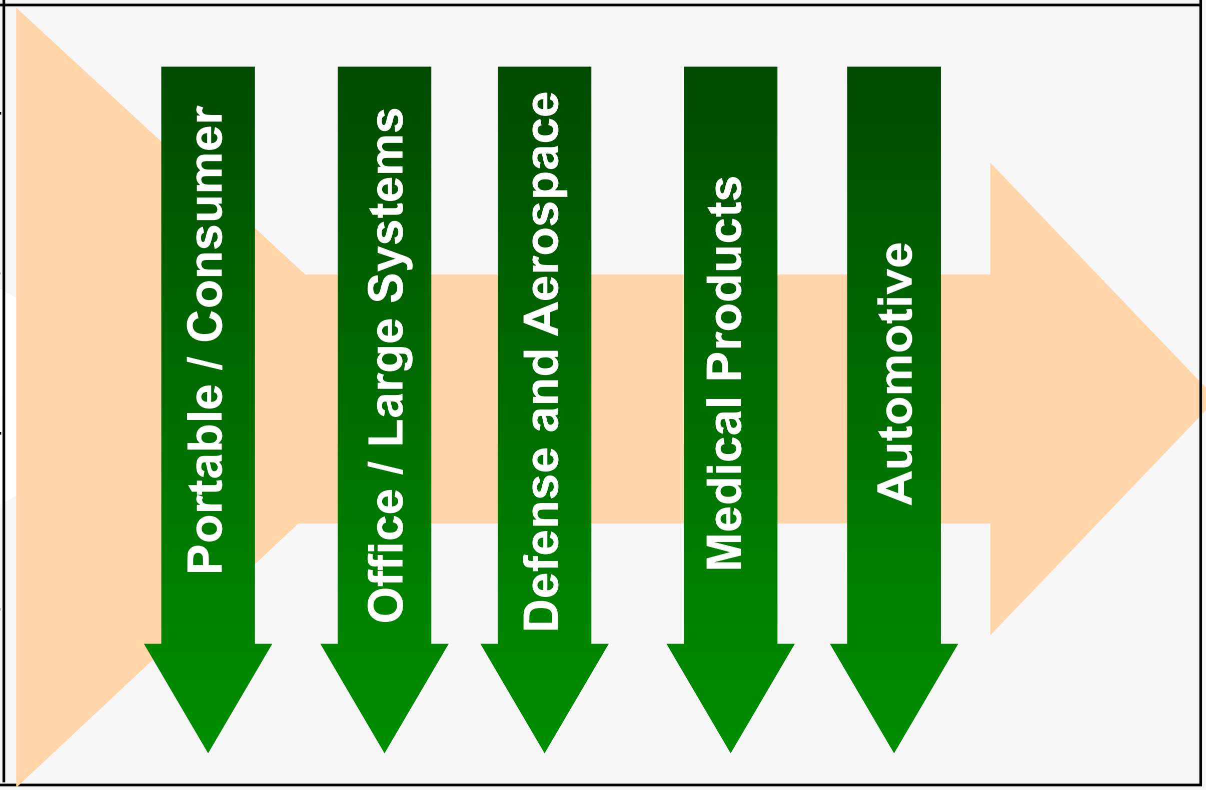
Roadmap Development-The iNEMI/ITRS Methodology

Product Sector Needs Vs. Technology Development

21 TWGs
Semiconductor Technology
Business Processes **Prod Lifecycle Information Mgmt.**
Design Technologies Modeling, Thermal, etc.
Manufacturing Technologies Board Assy, Test, etc.
Comp./Subsyst. Technologies Packaging, Substrates, Displays, etc.

5 Product Emulator Groups



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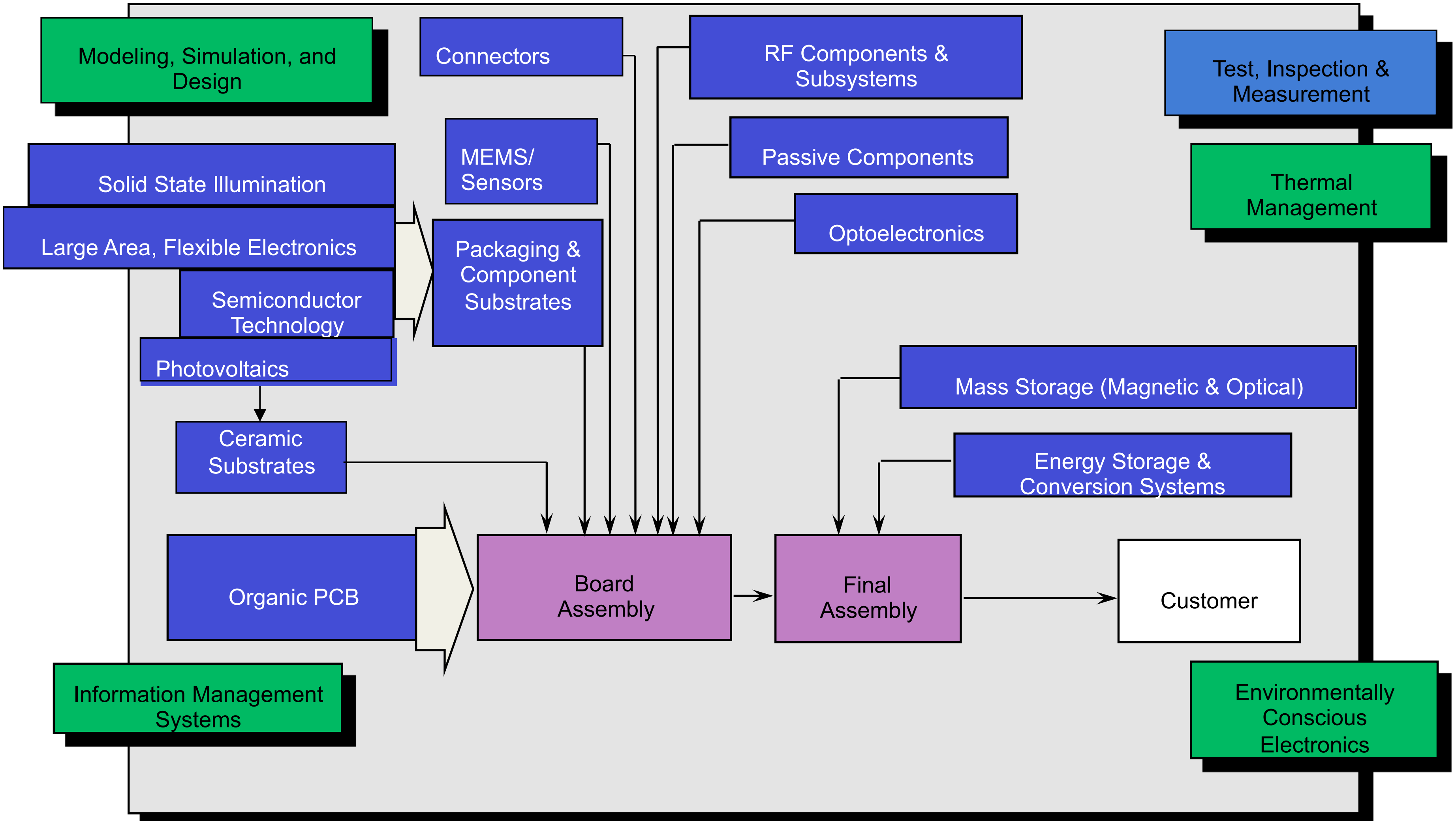
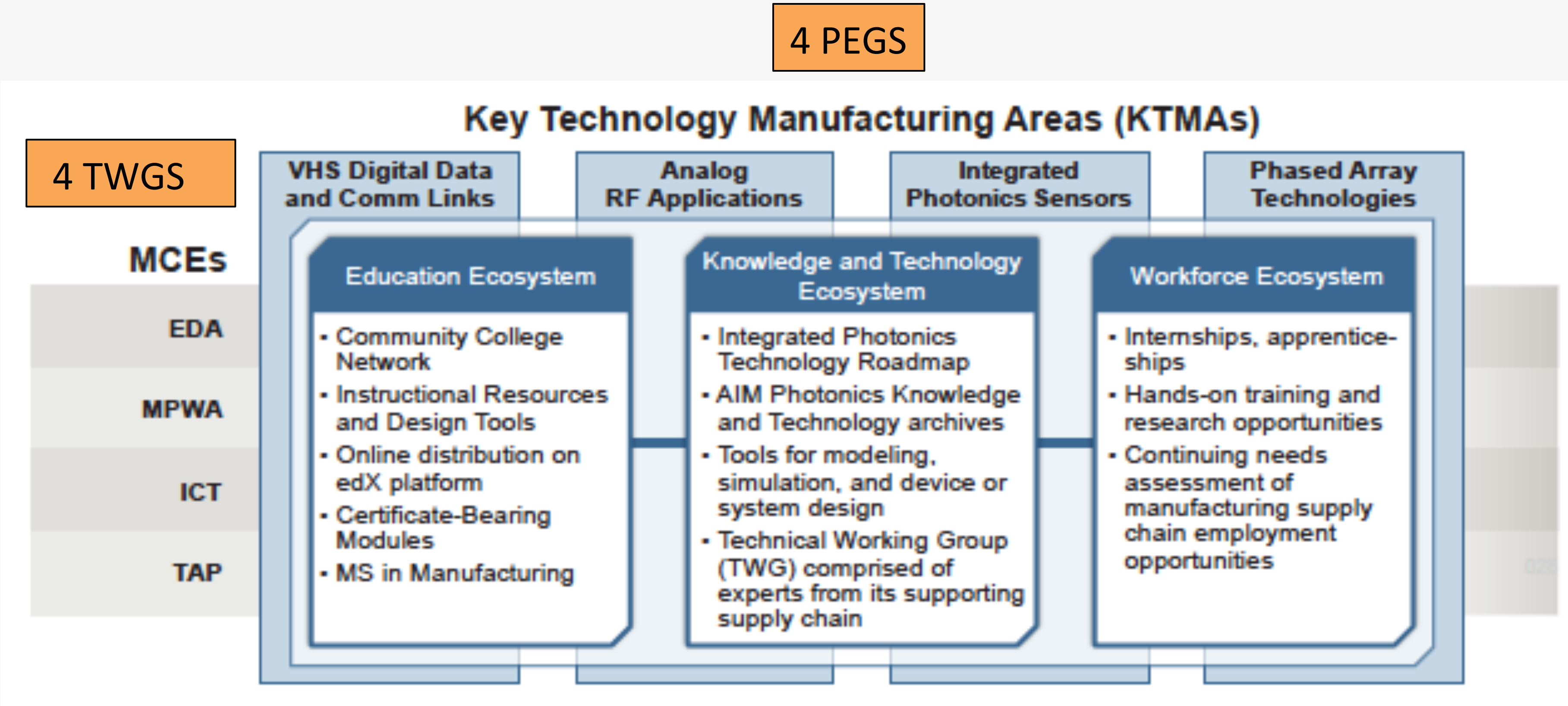
iNEMI Roadmap Biannual Process
21 Technology Working Groups (TWGs)



Green=Engineering Purple=Manufacturing Blue=Component & Subsystem

AIM Photonics Academy

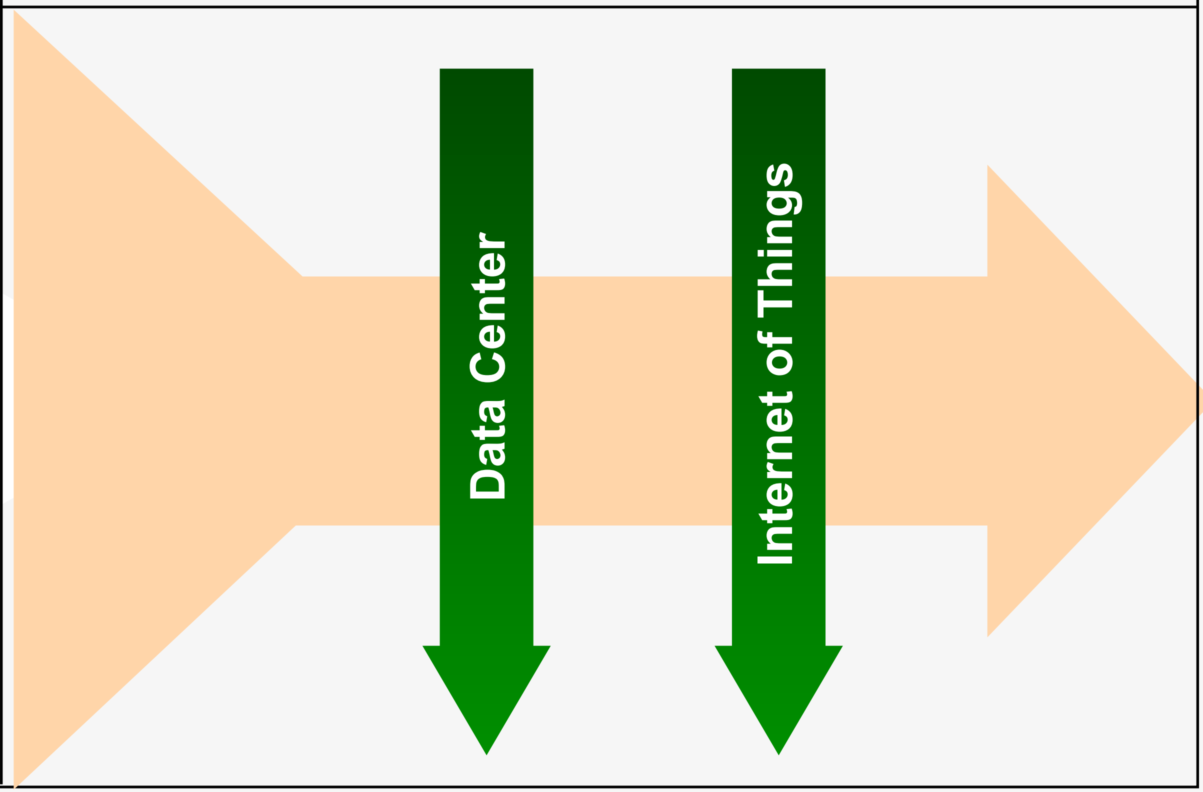


AIM Photonics Academy will provide the unified knowledge, technology, and workforce interface for AIM Photonics.

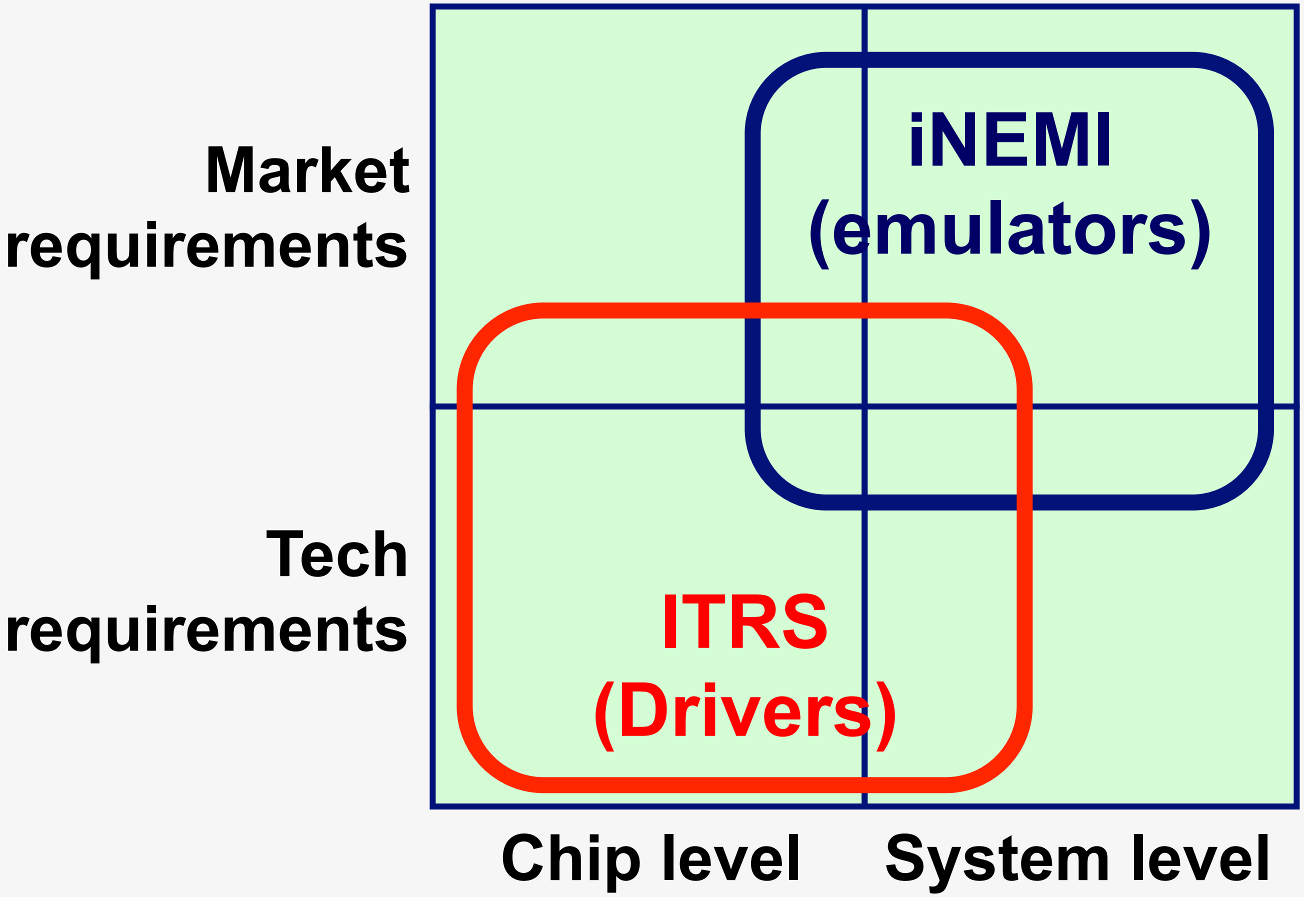
Current PSMC Roadmap Structure

Product Sector Drivers Vs. Technology Development

4 TWGs	2 Product Emulator Groups
Monolithic Integration	
Photonic Systems Packaging	
Interconnect Connectors, Cable Assemblies & Printed Circuits.	
Assembly & Test	



ITRS Design TWG/iNEMI ITRS-iNEMI Domain Space



Format for Product Emulator Chapters

- Introduction
- Situation Analysis
  - Benchmark state of Industry and Technology
  - Key Drivers: cost, performance, size, market
- Roadmap of Quantified Key Attribute Needs (2015 – 2025)
- Critical (Infrastructure) Issues –
  - Identify Potential Paradigm Shifts
  - Provide Vision of Final Assembly Process
  - Discuss System Test
  - Discuss Environmental Issues
- Prioritized Technology Requirements and Trends: Research, Development, Implementation
- Contributors

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Data Center Product Emulator

Dr. Robert Pfahl

Driving Photonics Manufacturing

Data Center PEG Charter

- The goal of the Data Center PEG is to define the application needs and system performance targets, based upon an understanding of the consequences of parallelism, virtualization, and software defined networks. The "grand challenges" for data center hardware are 1) photonic integration for bandwidth density and 2) high-volume manufacturing to meet system demands and cost objects.

Data Center PEG Membership

- Robert Pfahl, PSMC/iNEMI-Chair
- Dale Becker, IBM,
- Chuck Richardson, iNEMI,
- Amit Agrawal, Cisco
- Keith Newman, Hewlett-Packard
- Russell H. Lewis, HP
- Sherwin Kahn, Alcatel-Lucent
- Debendra Malik, Intel
- Lionel Kimerling, MIT
- Bill Bottoms, 3MTS
- Richard Grzybowski, MACOM
- Richard Otte, Promex

Situation Analysis

- Traditional discrete server, storage and datacom applications have begun to merge in the data center
- End users desire more integrated, ‘open-source’ data center systems.
- End users have emerged as a powerful factor in hardware selection.
- An emerging topic in data center networks is disaggregation
- Integrated photonics is an enabling technology for disaggregation.

The Enabling Technology User

iNEMI

cisco
intel
Alcatel·Lucent
DELL
IBM
JUNIPER NETWORKS
hp invent

PSMC

Microsoft
f
amazon Prime
Google

Data Centers:
Key Drivers: cost, performance, size, market

- End user is establishing cost goals
- High bandwidth (single mode/wave division multiplex)
- Low latency
- Low power consumption
- Continuous duty at full speed
- Thermal stability for photonic components
- Heterogeneous integration
- Variable frequency for power reduction
- Redundancy or other means to insure no failures
- Optical to electronic (O to E) and electronic to optical (E to O) located in PWB mounted SiP (system in package)
- Low cost with path to continuous cost improvement
- Continuous Size Reduction to Increase Capacity

Performance scaling of 1000x/10yr at constant cost

Key Drivers: cost, performance, size, market

OEM Revenues ($M)

	2013	2015	2017	2019	2025	CAGR
Total Data Center	**162,280**	**176,972**	**192,202**	**211,776**	**273,436**	**4.4%**
HPC and Mainframes	24,036	24,207	28,146	33,340	42,874	
Data Centers	7,269	9,235	11,417	14,009	21,913	
Enterprise Communications	42,055	48,786	53,056	57,377	78,801	
Service Provider Equipment	88,920	94,745	99,582	107,050	129,848	

The data for Market Forecasts and Situational Analysis has been provided by IHS Technology.

Roadmap of Quantified Key Attribute Needs Data Center Interconnections (2015 – 2025)

An example of cost Information

Parameter	Metric	2013	2015	2017	2019	2025
PCB Costs						
2 layer flexible	$ per cm2	0.03	0.025	0.025	0.02	0.019
4 layer flexible	$ per cm2	0.065	0.06	0.055	0.04	0.02
4 layer conventional	$ per cm2	0.012	0.011	0.01	0.008	0.006
6 layer conventional	$ per cm2	0.016	0.015	0.013	0.01	0.009
4 layer w/ microvia	$ per cm2	0.019	0.018	0.0165	0.013	0.01
6 layer, blind/buried	$ per cm2	0.032	0.033	0.026	0.02	0.01
8 layer	$ per cm2	0.03	0.0275	0.025	0.02	0.015
10 layer conventional	$ per cm2	0.048	0.045	0.042	0.035	0.02
10 layer w/ blind / buried	$ per cm2	0.095	0.09	0.08	0.06	0.03
14 layer, no blind/buried	$ per cm2	0.11	0.1	0.09	0.075	0.05
28 layer, blind & buried vias	$ per cm2	0.33	0.31	0.29	0.26	0.2
48 layer, blind & buried vias	$ per cm2	1.00	0.95	0.9	0.75	0.5
48 layer, (low loss material)	$ per cm2	1.30	1.56	1.79	1.97	NA
Assembly Costs						
Average Board Assembly Cost	¢ per I/O	0.75	0.7	0.65	0.55	0.35
Average Final Product Assembly Cost	$/unit	1300.00	1100	900	500	300
Package Costs						
IC Package Cost	¢ per I/O	0.18	0.16	0.15	0.15	0.12
Package Cost (High Density Ceramic/w/ Area Connector)	¢ per I/O	5	4	3	2	1
Package Cost (High Density µvia Laminate w/ Area Connecto	¢ per I/O	4	3	2	2	1
Connector Cost	¢ per I/O	1.90	1.6	1.3	1	0.5
Energy Cost	$/Wh	0.40	0.30	0.25	0.20	0.10
Memory Cost (Flash)	$/MB	0.18	0.15	0.13	0.10	0.05
Memory Cost (SRAM)	$/MB	0.18	0.15	0.13	0.10	0.05
Cost of Test as a ratio to assembly	ratio	0.40	0.50	0.60	0.60	0.80

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Roadmap of Quantified Key Attribute Needs Data Center Monolithic Integration (2015 – 2025)

- Cost ($/Gb/s)
- Energy (pJ/bit)
- Bandwidth density (Gb/cm^2)
- Reach (cm)
- Critical Dimension for each device (nm)
- Interface/Sidewall rms and p-p roughness (nm)
- Thermo-optic spectral stability for each device (pm/K)
- Integration level (devices/cm^2)
- Production capacity (wafer starts per week)
- Impedance matching (FP oscillation amplitude in S/N)
- Latency (ns)
- Coupled Photodetector responsivity (A/W)
- Coupled Photodetector saturation level (mW)
- Coupled Photodetector response time (pS)
- Coupled Modulator extinction/insertion-loss (dB/dB)
- Coupled Modulator efficiency (dB/V)
- Coupled Laser threshold current (mA)
- Coupled Laser threshold current temperature stability (mA/K)
- Coupled Laser slope efficiency (W/A)
- Waveguide transmission loss (dB/cm)
- I/O coupling loss (dB/interface, dB/chip)
- Matrix switch capacity (ports-in x ports-out)
- I/O port count (ports, channels/port, Gb/s/channel)
- I/O capacity (Gb/s for packaged chip)
- Yield (die and line)
- Reliability (MTTF, FIT)
- Time-to-Market (design to production: months)
- Design (simulation, automation)
- Layout (automation to tapeout)
- Inspection (in-situ, in-line, throughput)
- Package (thermal, BW density)
- Test (throughput, BIST)

Technology Requirements to Meet Data Center Needs

- Advanced silicon integration using stacked silicon with through silicon vias,
- advanced packaging integration built on the System in Package and Package on Package technologies (already in production use in mobile computing),
- optical interconnection for increased reach of bandwidth into the data center,
- silicon photonics to enable integration of optics,
- high-bandwidth connectors,
- low-loss materials and design features to maximize the reach of electrical interconnect
- power regulation integration to improve efficiency.

The increased performance that these enabling technologies will provide must be provided below the cost of existing technology for their adoption by the industry

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Internet of Things (IOT) Product Emulator

Dr. Richard Grzybowski
MACOM

Internet of Things PEG Charter

- The goal of the Internet of Things PEG is to define the application needs and system performance targets for integrated photonic systems, based upon an understanding of the consequences of vast networks of sensors, actuators, and smart objects whose purpose is to interconnect "all" things in such a way as to make them intelligent, programmable, and more capable of interacting with humans and each other. The "grand challenges" for IoT include: 1) Low Bandwidth, "High" Latency, Low Power – Primarily E to O, and 2) the Plethora of consumer, industrial, medical and military applications.

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IoT PEG Membership

- Richard Grzybowski, MACOM
- Robert Pfahl, PSMC/iNEMI-Chair
- John MacWilliams, US Competitors LLC

Situation Analysis

- Technological advances are fueling the growth of IoT. Improved communications and photonics enabled network technologies, new photonic sensors of various kinds, improved—cheaper, denser, more reliable and power efficient—storage both in the cloud and locally are converging to enable new types of products that were not possible a few years ago.
- IoT ecosystem is hard to define, complex, and difficult to capture due to the vastness of possibility and the rapidity with which it is expanding.
- There is no common definition of IoT, but it is shaping the evolution of the Internet, creating numerous challenges and opportunities for engineering and science and the success of IoT depends strongly on standardization, which provides interoperability, compatibility, reliability, and effective operations on a global scale.

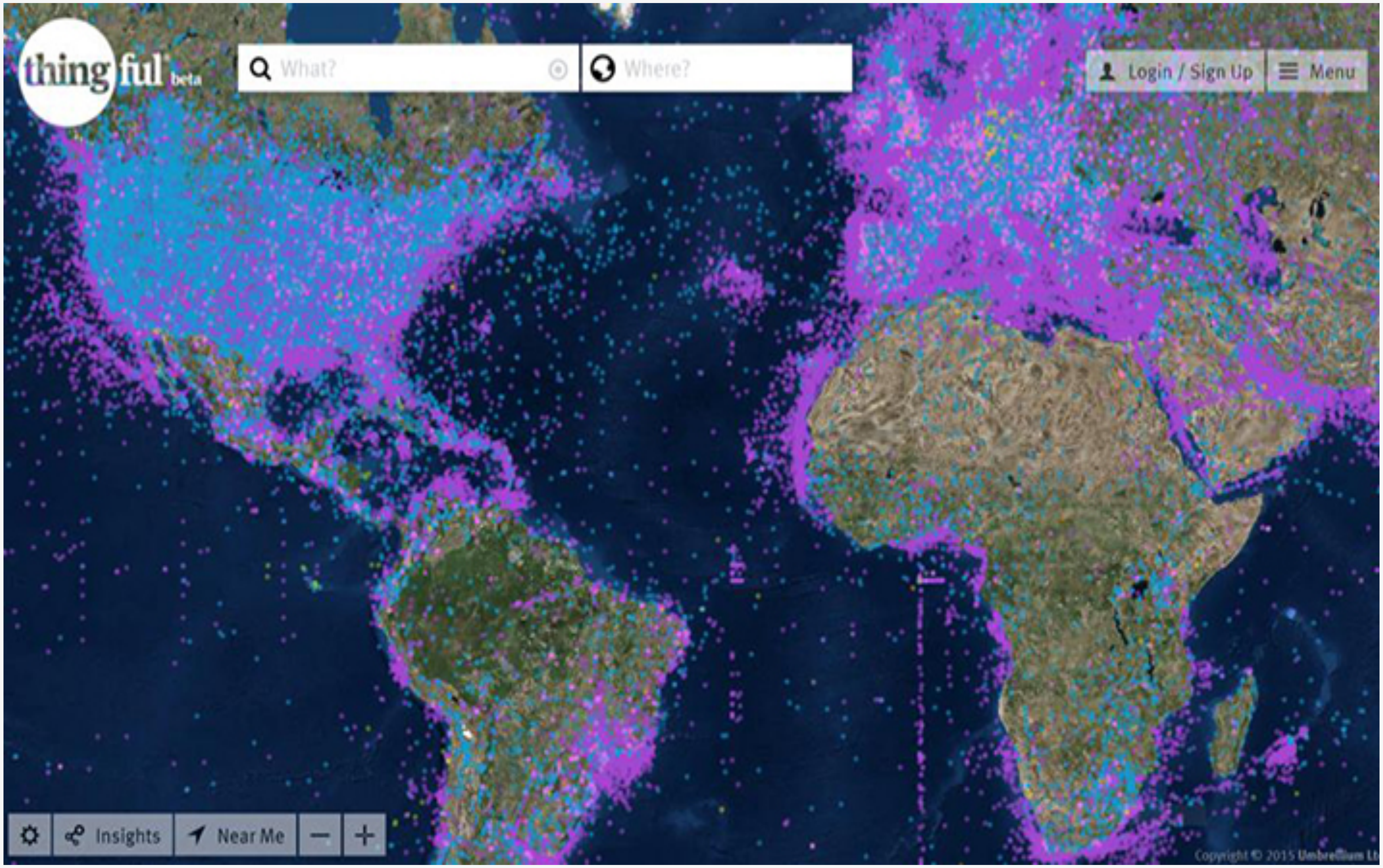
Well…like what?

- The **internet** evolved from a communication platform that provides access to information "anytime" and "anywhere"…**IoT** is evolving into a network that integrates "anything" by gathering and disseminating data from the physical world - enabling a better understanding of our environment.
- Wearables - It took years for smartphones to develop their various use cases. We're now seeing the same thing with wearables – collecting biometrics photonically.
- Medical - Using tools such as photonic integrated sensors, lasers, fiber and integrated labs-on-chip without drawing blood. It may not be long before needles will be a thing of the past – for some tests.
- Automotive - Advanced Driver Assistance Systems (ADAS): Imaging and Sensing, car surroundings; intelligent headlights; optical car-to-X communication; head-up displays…
- The IoT allows us to make inferences about phenomena and take mitigation measures against unwanted environmental effects.

Photonics Enables IoT

- IoT fulfills all the technological requirements to be successful in developing countries:
- Low power technology (e.g. places w/unreliable power supply)
- No fast internet connection needed (nodes send small amounts of data & servers can be local), it is low-cost (or getting there) and it has an immediate impact on people’s lives.
- IoT applications can greatly benefit populations in developing countries:
  - weather can be monitored
  - food safety can be checked
  - water quality can be analyzed
  - air quality can be measured
  - landslides can be detected
  - mosquitoes can be counted in cities in real time

Sensor nodes that publish their data openly



https://www.thingful.net/

Aggregate contribution to the sea of IoT data

- ***While individual photonic sensors may require minimal bandwidth, their aggregate contribution to the sea of IoT data may become quite large.***
- ***As the problems tackled by IoT practitioners, not just in developing countries, but around the world fall into categories (air quality, water quality, smart agriculture, healthcare, etc.), it is crucial that photonic networks connecting IoT scientists & practitioners working in their domain be developed.***
- ***The network will provide a way to harvest, store and communicate data for analysis and for researchers to share solutions and to collaborate on finding the best solution to their problem.***

HPC: Where "Big Data" joins "Big Compute"

Global IP Traffic, 2014-2019 (Source Cisco)							
	2014	2015	2016	2017	2018	2019	CAGR 2014–2019
By Type (PB per Month)							
Fixed Internet	39,909	47,803	58,304	72,251	90,085	111,899	23%
Managed IP	17,424	20,460	23,371	26,087	29,274	31,858	13%
Mobile data	2,514	4,163	6,751	10,650	16,124	24,221	57%
Total IP traffic	59,848	72,426	88,427	108,988	135,484	167,978	23%

A typical HPC interconnect has TWICE the capacity of the Global Internet, being used by >2.1 Billion users

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Exascale (10^{18}) - a Perspective

1,000,000,000,000,000,000 flops/sec

1,000 × U.S. national debt…in pennies

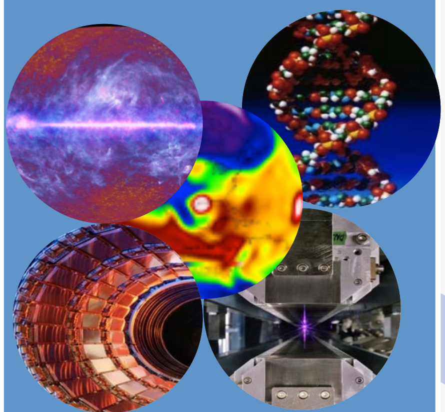
100 × number of atoms…in a human cell

1 × number of insects on Earth…EEEEP!

The "Modern" Supercomputing Center

Big Data

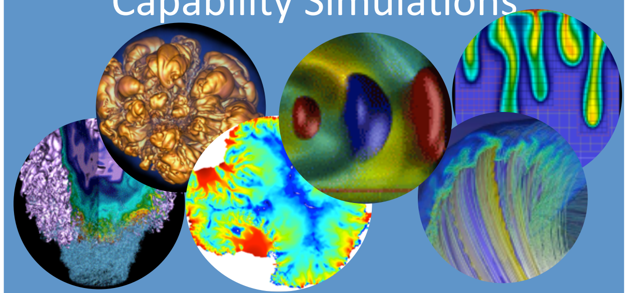
From Experiments
and Simulations



NERSC ingests, stores and analyzes data from IoT Sensors, Telescopes, Sequencers, Light sources, Particle Accelerators (LHC), climate, and environment

Large Scale

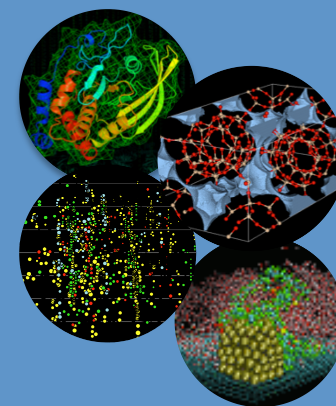
Capability Simulations



Petascale systems run simulations in Physics, Chemistry, Biology, Materials, Environment and Energy at NERSC

High Volume

Job Throughput



NERSC computer, storage and web systems support complex workflows that run thousands of simulations to screen materials, proteins, structures and more; the results are shared with academics and industry through a web interface

NERSC

Petascale Computing,
Petabyte Storage, and Expert
Scientific Consulting

Big data and the IoT → shift away from datacenters to growing adoption of hybrid cloud infrastructure?

- IoT sensors will increase burden on communication networks, increasing need for photonic interconnects.
- Colocation providers like VXchnge are betting that more enterprises will look to virtualization or colocation rather than investing in costly new datacenters.
- Increasing number of applications, workloads and IT infrastructure running on top of open-source technologies can be run reliably and at lower cost in the cloud.
- Big data and the IoT will drive many changes in hardware, software, datacenters and more in the future and <u>photonic integration is a key enabler!</u>
- To improve performance, companies will rely more heavily on pushing data to the edge.

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Cost Modelling Emulator

Drs. Randolph Kirchain & Elsa Olivetti
MIT

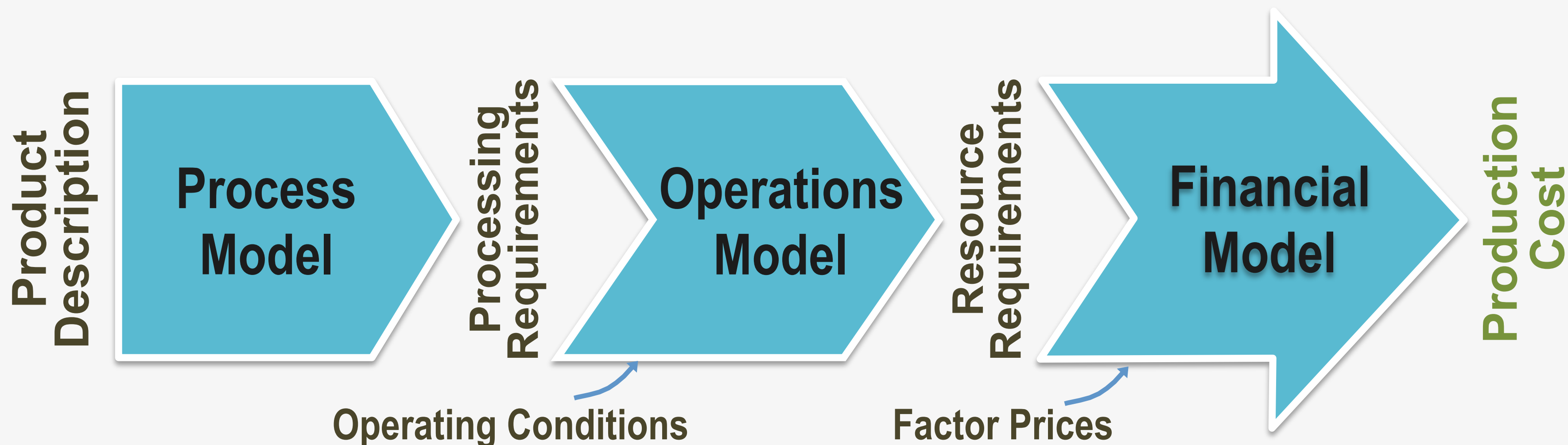
Driving Photonics Manufacturing

Cost Modeling Team Goal & Status

- Create a flexible platform to drive a common understanding of expected solution cost
  - How might new solutions impact cost?
  - What are the key cost obstacles?
- Status
  - MIT has developed a flexible tool to model cost of proposed design and process solution
  - Data is currently limited to ONLY packaging and integration

Process-based Cost Modeling (PBCM)

- PBCM forecasts …
  cost from resources required → →
  resources from processing → →
  processing from device details
- PBCMs provide insight into
  - Relative cost position
  - Implication of technology changes



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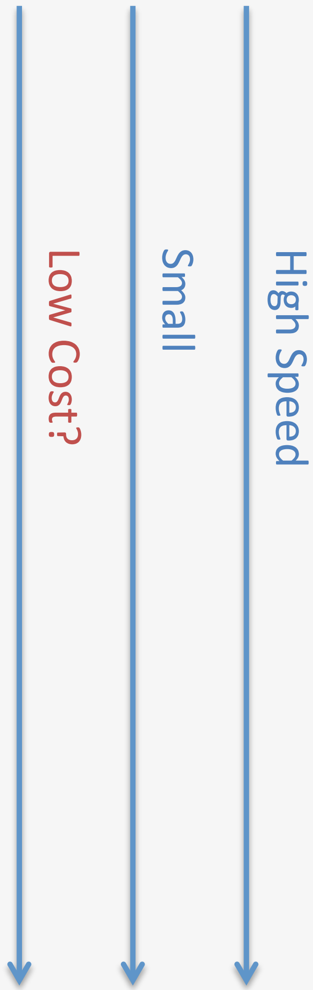
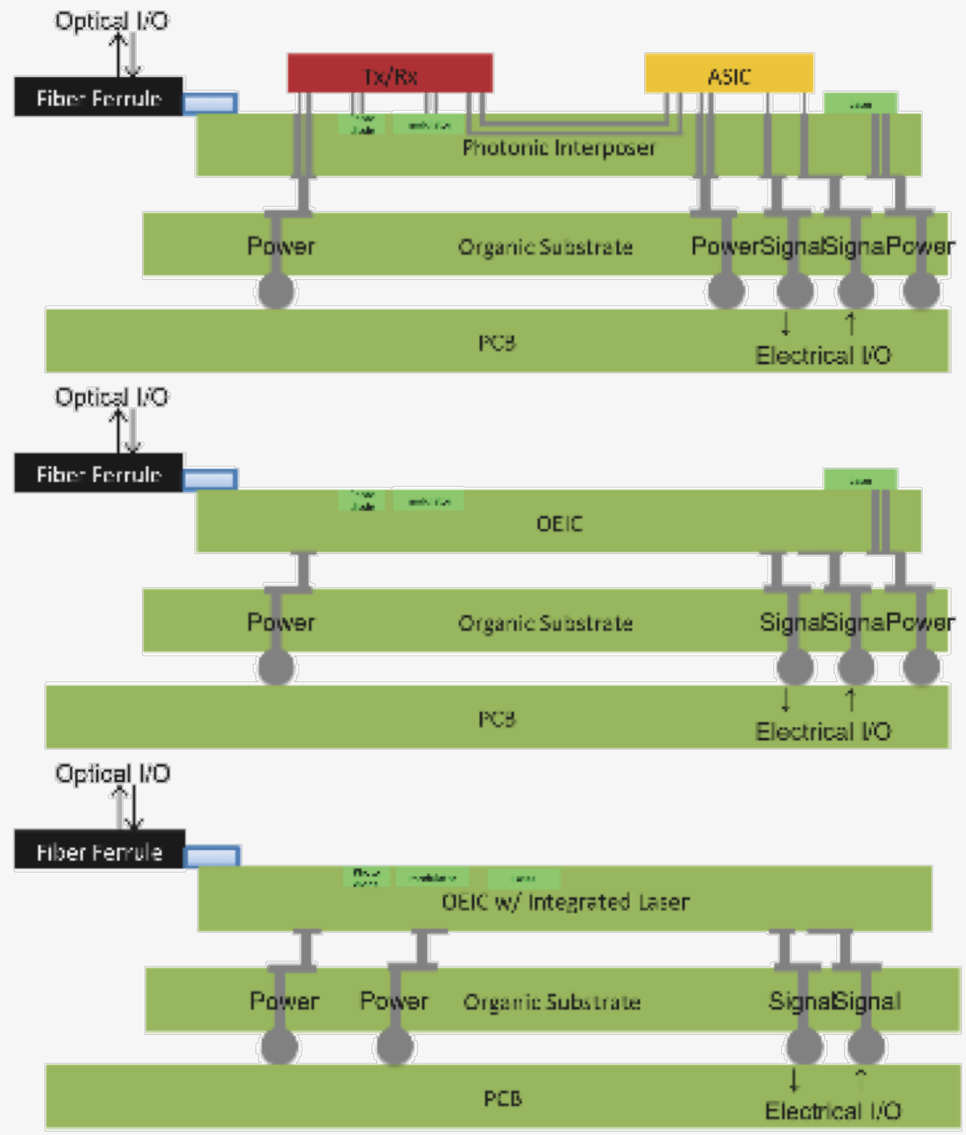
Initial Emulator Case: Integration in Transceiver



1) Hybrid Packaging

2) Monolithic w/ hybrid laser packaging

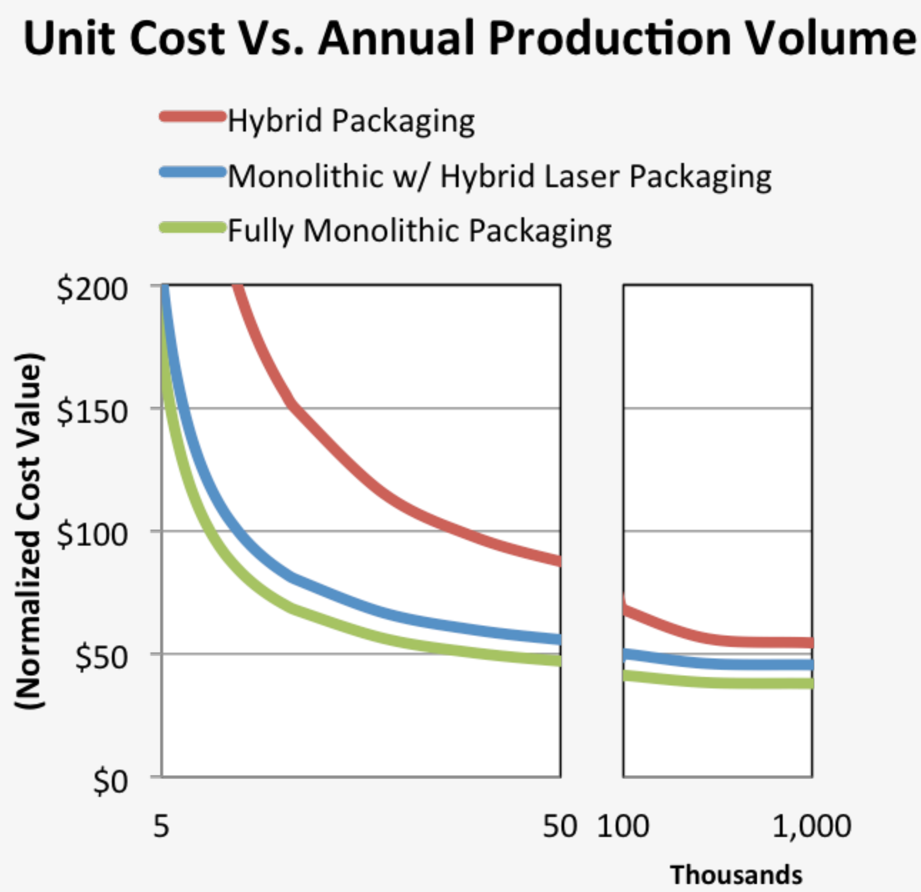
3) Fully monolithic packaging

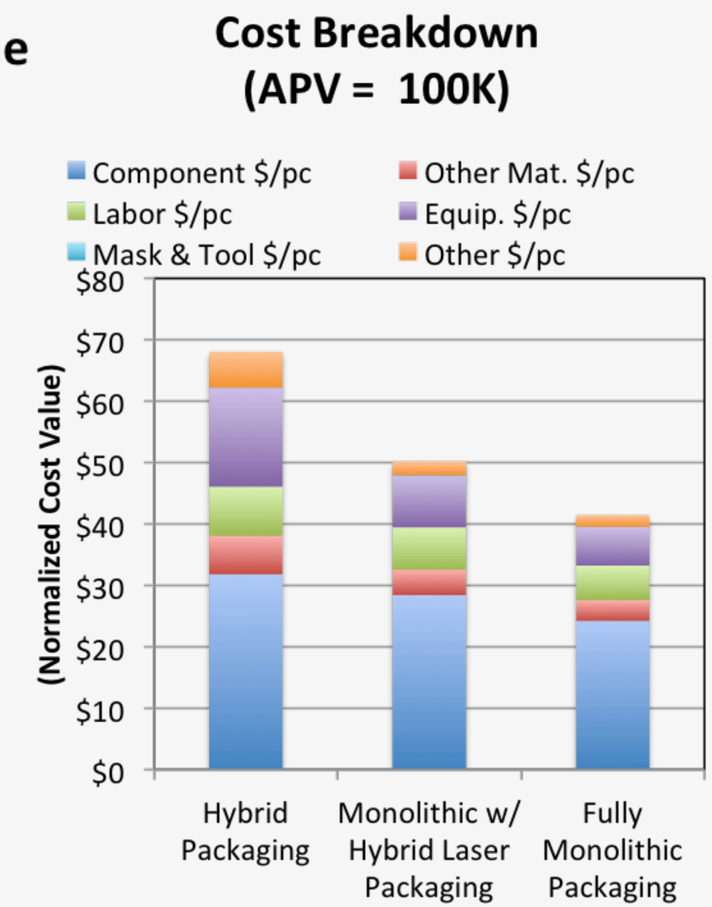


Analysis Caveat: Preliminary and Incomplete

- The subsequent analysis is
  - VERY preliminary
    - Data is collected from publically available sources and ONE consortium member
    - More data is needed
  - Incomplete in scope
    - Analysis only directly models packaging and assembly
    - No explicit modeling of chip production
- Key assumptions
  - Chip cost is proportional to the area
  - Yields are similar for all chips (sensitivity later)

Cost of Packaging for Increasing Integration: Model Exposes Drivers of Difference

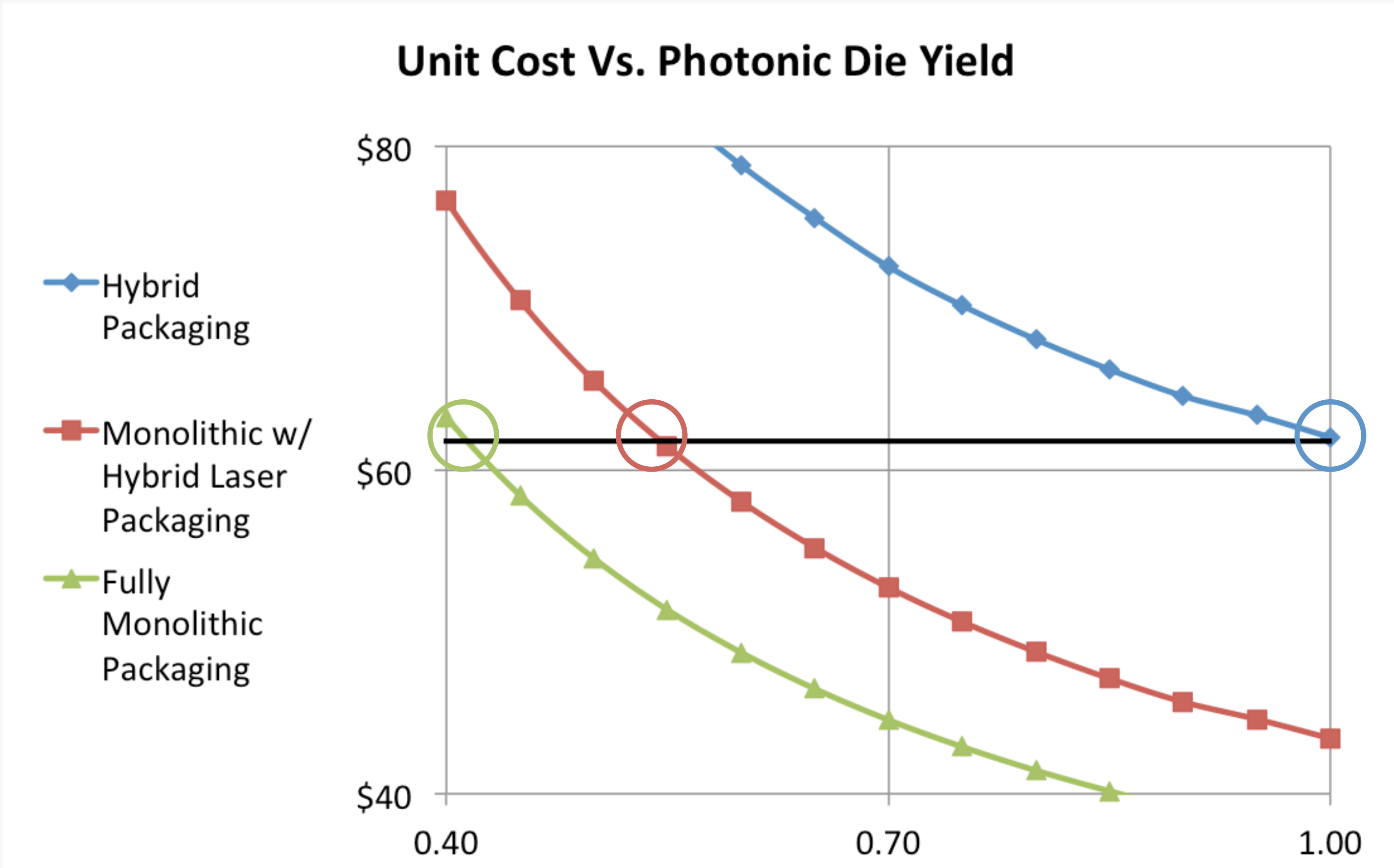




NOTE: Preliminary Results
Packaging Cost Only

Models Allow Roadmap to Identify Critical Targets: Example breakeven Incoming Die Yield

At APV=100K, hybrid device packaging & components cost = $62
Required Photonic Die Yield for cost parity:



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NOTE: Preliminary Results
Chip fab differences not considered

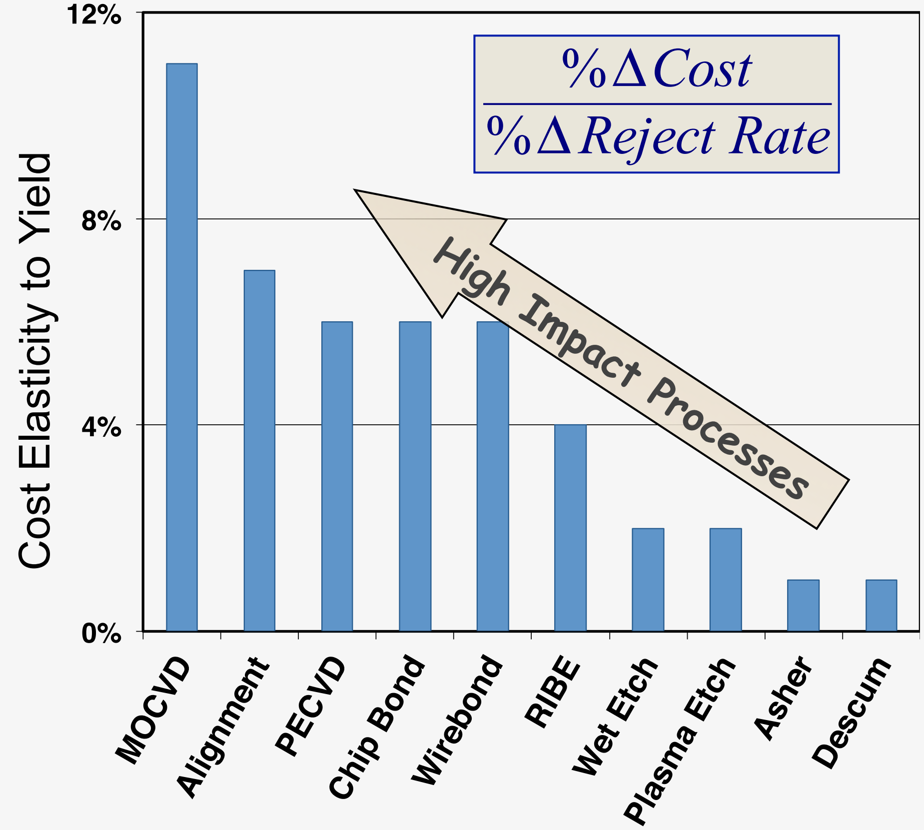
Chip Cost In the Current Model

All the photonic and electronic dies are cut from a 8" wafer whose cost is $1600 each.			
Hybrid Packaging	electronic die	2500 dies / wafer	100% good die
	photonic interposer die	100 dies / wafer	80% good die (base case)
Monolithic Packaging with Hybrid Laser	OEIC die w/o laser	100 dies / wafer	80% good die (base case)
Fully Monolithic Packaging	OEIC die w/ laser	100 dies / wafer	80% good die (base case)

Modeling Vision: Provide Deep Insights into the Impact of Technological Change

Previous work on long-range transceivers shows potential for the method

- Insights at the technical level into
  - Cost drivers
  - Impact of technology change



Fuchs, Kirchain, and Liu; "The Future of Silicon Photonics…", JLT, 29(15), August 2011

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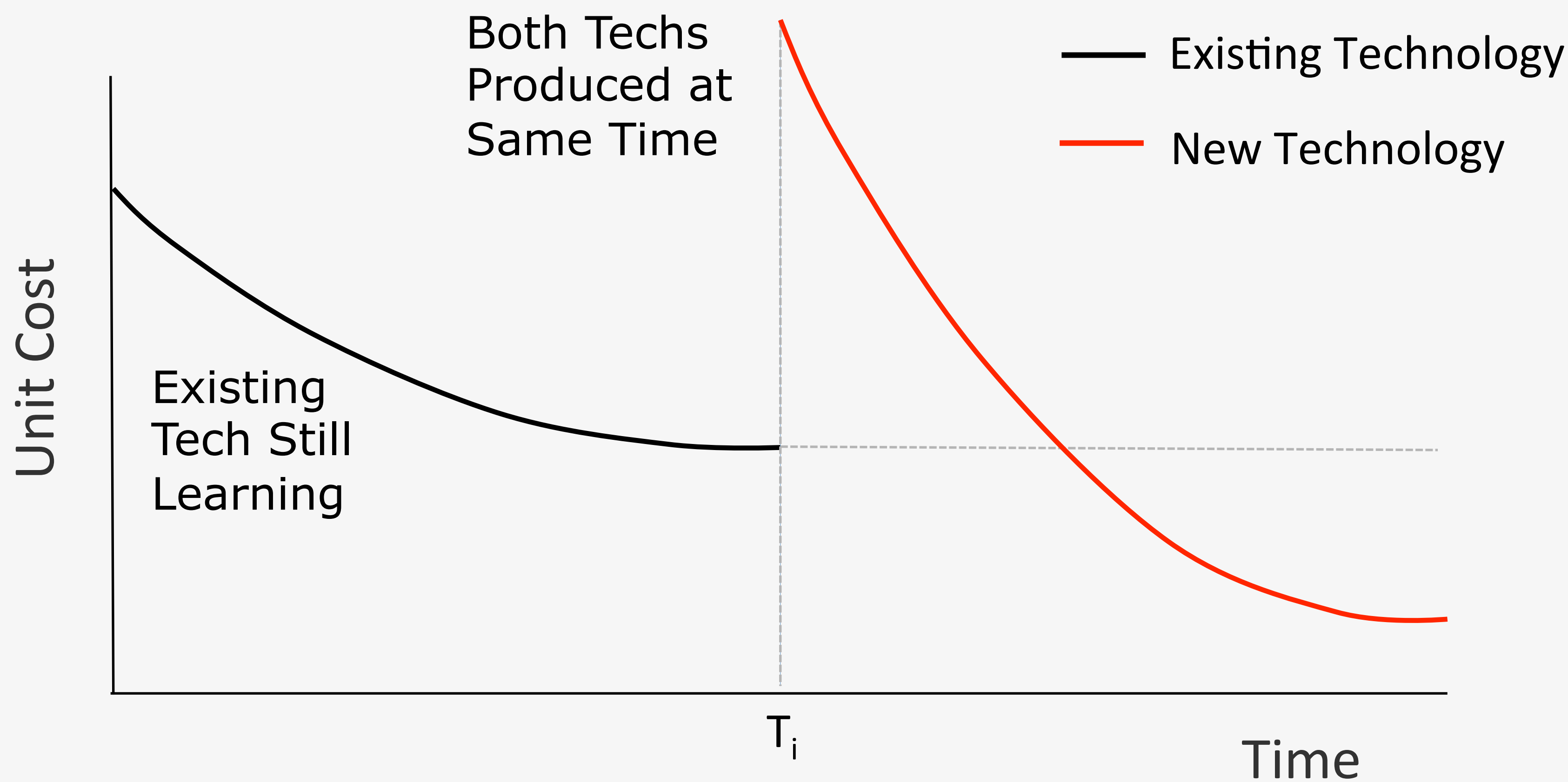
Modeling Vision: Understand cost impact of technology transition & learning for photonics

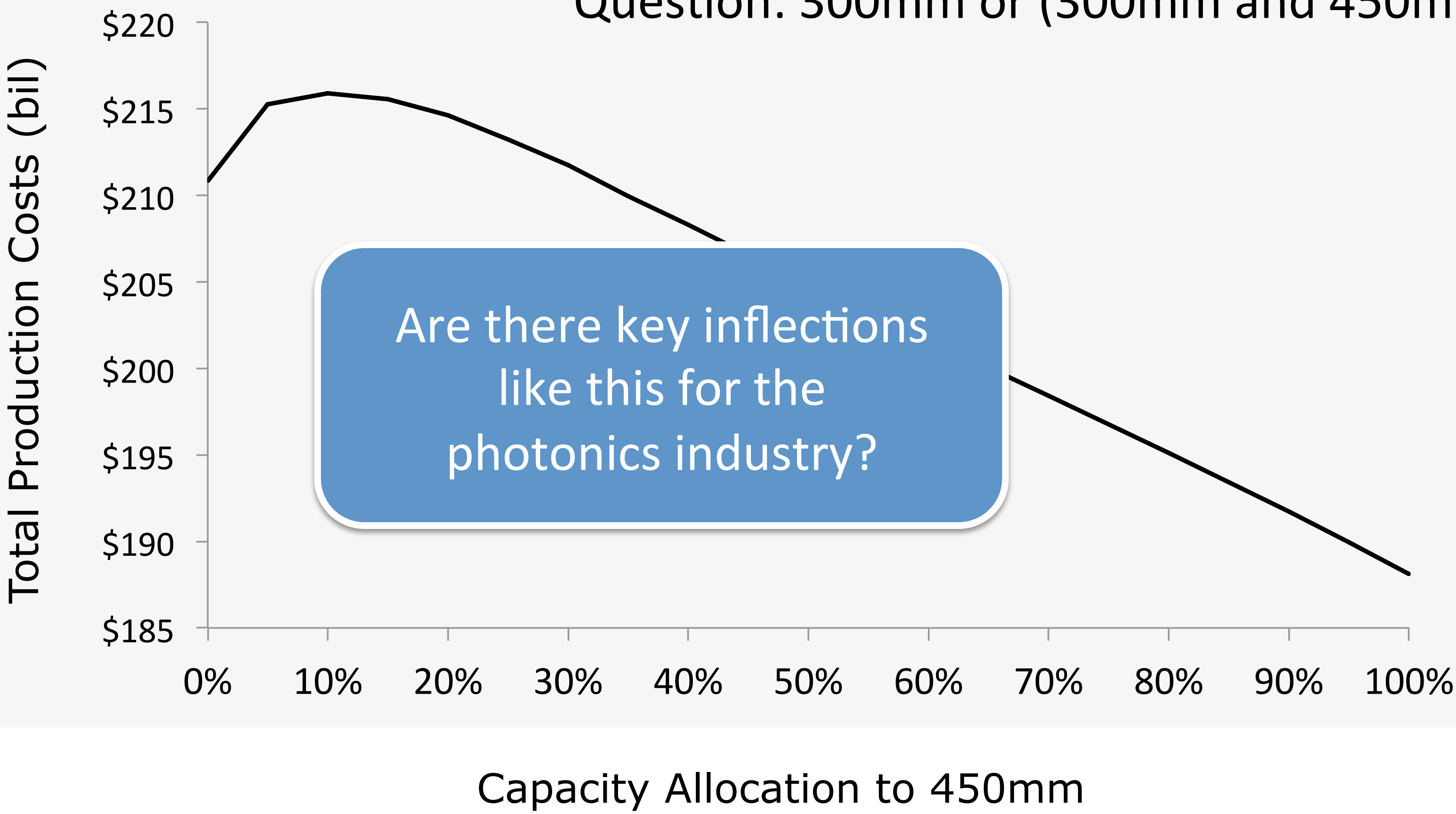


Learning-By-Doing Case Study: 300mm vs. 450mm Wafer Processing, Results

(Rand-Nash, Roth 2012)

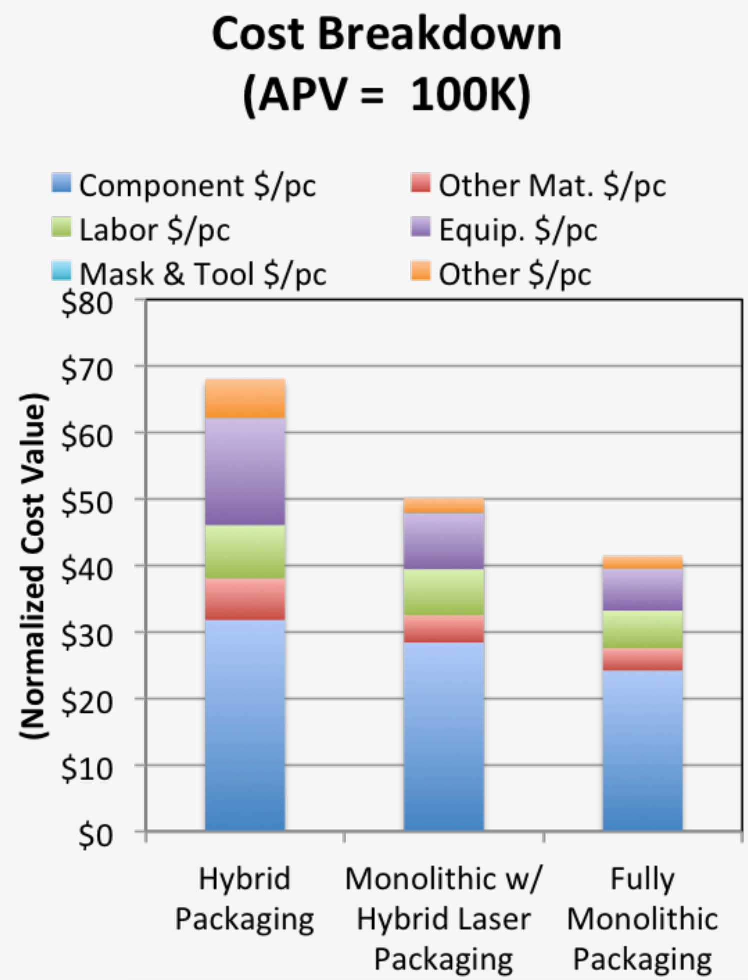
Fully switching is not always possible

Question: 300mm or (300mm and 450mm)?



Current Progress | Prelim Insights

- Model provides insight into:
  - Relative cost position
  - Technical drivers of cost
- (If costs are accurate and complete) Packaging costs
  - $1- $3 per electronic component
  - $2.5 - $5 per photonic component



NOTE: Preliminary Results
Packaging Cost Only

How to Get Involved

- The value of the cost modeling toolkit is limited by your involvement
- Please contact the cost modeling team to
  - Suggest case studies of interest
  - Provide input on
    - Process flows
    - Production data
  - Develop a working group on other costs
    - Life cycle environmental burden
    - Critical materials and resources in the supply chain
- Contact: Randolph Kirchain (kirchain@mit.edu)

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Next PSMC Webinar in Series

Abstract: The next webinar will discuss the Photonic System Packaging TWG. This TWG roadmaps the critical showstoppers for achieving low-cost high-volume photonic systems manufacturing.

- 11/3 Photonic System Packaging TWG
  - Wilmer (Bill) Bottoms

Following PSMC Webinar in Series

Abstract: The next two webinars continue the roadmapping of manufacturing technology and design needs to achieve low-cost, high-volume manufacturing of integrated photonic systems that have been identified and quantified to date.

- 11/10 Interconnection TWG
  - – John L. MacWilliams
- 11/17 Assembly and Test TWG
  - – Richard Otte

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For Additional Information Contact:

bob.pfahl@inemi.org
http://photonicsmanufacturing.org/

Driving Photonics Manufacturing