Envisioning the Microworld Adventures Ahead

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1. Opening

Many thanks Paul for the generous introduction, and thanks to all of you for inviting me to join you today!

It's been a thrill to return to MIT this week, a place where engineering adventurers who've gone before have left such big tracks behind, and to ponder with you tonight where it's all headed next.

And while doing so, to become ever-more aware of the strength of our shared engineering culture as it empowers our imaginations for exploring the greatest of frontiers: the frontier of what it is "possible to do."

It's also wonderful to share war-stories with friends and colleagues from yesteryear. In the end, far more than the tracks we've left behind, it's our memories of teams we joined, and adventures we went on together, that count.

As when on a flight to Silicon Valley last spring, I remembered another flight out there 50 years ago. It was 1965 and I was 27, and on the team architecting a secret new IBM supercomputer.

With me were my lab-notes for the machine's architectural simulator. And just as thousands of other young engineers streaming into what would become Silicon Valley, I felt pulled along by a sense of serious adventures ahead … not just in technology but in life itself … for as we flew along, I studied a spellbinding new book: Steve Roper's "*A Climber's Guide to Yosemite Valley*."

But when I joined Xerox PARC in 1973. I had no idea what a wild ride lay ahead as we jumped onto and straddled two huge incoming waves: the personal-computing revolution and the VLSI microelectronics revolution.

We're now entering an even more dramatic time, as research adventurers explore, map and mine for gold in the micro-bio-nano-world, and as entrepreneurs, system designers and makers innovatively embed engineered microsystems into, and thus functionally enhance, almost everything.

But before visualizing what's ahead, let's reflect on some earlier technology-empowered societal revolutions. As Winston Churchill said:

"The farther backward you can look, the farther forward you can see."

2. Back to the Future: Visualizing past waves of disruptive techno-social exploration

In the Age of Discovery, as a mix of technologies in shipbuilding, navigation, timekeeping and map-making commingled the onset of mass-communication by printing triggered an exponentiation of the explorations.

The Industrial Age was similarly empowered by a commingling of innovations: in coal and iron mining, steam-powered engines, and railroading, all of which was suddenly exponentiated by the innovation of telegraphic communications. The mines and railroads, empowered by coal and steam, yielded more coal and iron for building more steam-powered trains and their railways.

Like an invasive species it spread across the earth, providing rapid transportation and communication infrastructure for adventuring, exploring, finding and mapping things, in a kind of hyper-version of the age of discovery.

At the turn of the 20th century, electrical generators, motors, machine tools and lighting … along with internal combustion engines, autos and aircraft … were suddenly launched by telephone and radio communications into rapid-coordinated-evolution via explorations in machining, manufacturing, agriculture, transportation, urbanization and human empowerment.

Notably, machinery empowered by electric motors was used to manufacture ever-improving motor-driven human-empowerment products, and ALSO ever-improving electric-motor-driven factory-machinery, thereby producing high-evolutionary-gain in the manufacturing ecosystem.

During and after WW-II electronic materials, components & circuits, pulse & digital electronics, servomechanisms and computing underwent rapid evolution in research and engineering "hothouses", such as at MIT's Building 20, all enhanced by increasingly powerful calculating, computing and communication technology.

Stepping back and 'Going Meta', we can visualize such unfolding dramas NOT just as making things and spreading them across seas and landscapes, but INSTEAD as the coalescing of innovative ideas … and launchings of those idea-mixtures into dynamic-motion in the minds of expanding-groups of interconnected-people … especially ideas about how to make and use things to explore terra-incognita and report back on what's out there.

3. An inside-peek at the VLSI Revolution:

During the 1970's, as microelectronic fabrication technology began riding "Moore's Law" of scaling, the stage was set for the VLSI revolution.

What if YOU had seen that huge wave building out there, full of potential energy waiting to be unleashed? And working like crazy, you and your team innovated a cluster of microsystem knowledge that could open that floodgate?

But what if your methods, though basic and elegant, would turn current industry practices inside-out … and thus seem bizarrely "unsound" to stove-piped experts looking at individual pieces without seeing the whole?

There'd be no point in publishing fragments of it across scattered traditional pay-for-access journals, other than boosting your publication count. So, where would you go and what would you do to launch the knowledge into use and trigger something big?

I faced such a challenge in 1977-1980. Bert Sutherland, my lab manager at PARC, was on MIT's EECS Dept visiting committee. Coordinating with Paul Penfield and Jon Allen, Bert arranged for me to teach a course on the radical new "Mead-Conway" VLSI design methods at MIT in the fall of '78.

As Paul has said, it was "a match made in heaven": MIT had retained a combined EECS department in anticipation of the generation of foundational cross-disciplinary electronic and computing knowledge.

As for me, I was not only on a "VLSI mission", but I also knew Institute and student culture, having done most of my undergrad work at Tech in the 1950's.

As for the students, they were intensely motivated to learn "how microprocessor chips were being designed in Silicon Valley", not realizing they were learning new and possibly "unsound methods" … in what amounted to a "giant meta-level MIT hack"!

The course went like magic: The students learned how to design VLSI chips during the 1st half and then did team-design-projects in the 2nd half. The chips were then fabricated in collaboration with HP, using newly innovated QTA prototyping methods, and returned to students by IAP in January.

The 18 projects completed by 25 of the students were amazing and included outstanding exploratory architectures such as an entire Lisp microprocessor by Guy Steele. News quickly reached key folks at Stanford and Berkeley via the Arpanet and also alerted many Silicon-Valley insiders, stunning them all.

Meantime, naysayers in traditional academic and industry circles began sniping at what they saw as the "non-optimal toy chips" designed at MIT.

Grasping for ways to keep up momentum, I suddenly visualized how to scale up chip prototyping by creating what's now call an "e-commerce system" that enabled lots of designers to bid for space and send design-files to an Arpanet server for merging into multi-project mask-sets and then "printing in silicon".

That summer, risking everything, I announced the "MPC79" service over the Arpanet, saying that "we at PARC would implement chip design projects for any universities that ran MIT'78 type courses using the new Mead Conway text" … and 12 major universities took the bait that fall!

"Apocalypse Now" type-rumors also began spreading that somebody named Conway had gone off the reservation, slipped up the river into Cambodia and was spreading unsound methods! If MPC79 didn't work, my name would be Kurtz'd!

But the huge Arpanet-based MPC79 hackathon worked! 82 projects were returned to 124 designers in January, including Jim Clark's "Geometry Engine" prototype for Silicon Graphics. In 1981 DARPA supported the transfer of the MPC79 technology from Xerox PARC to USC-ISI, creating the MOSIS service. By 1982, 112 universities were offering MIT'78 type courses. The VLSI revolution was on!

It wasn't till 2012 that I could come forward to explain what happened back then, in a Special-issue of IEEE SSCM and in the essay "MIT Reminiscences: Student years to VLSI revolution." But better late than never!

Reflecting on it now, we see how the MIT'78 course triggered an open-source coordinated evolution of a multilevel cluster of knowledge systems. The rapid evolution of the system-complex was then driven by quick turnarounds from ideas to media-visible working prototypes amongst a rapidly-expanding collaborative-competitive community of participants.

4. The vast incoming wave of innovation

The rising visibility microsystems is about to trigger a huge tsunami of wonder, imagination, engineering-exploration and entrepreneurism out in the larger world. THIS ONE is the "BIG ONE!

But to glimpse this incoming wave, now just over the social-horizon, we must grasp the techno-social dynamics of its technology-generation-ecosystems.

Folks working in microsystems have seen bits and pieces of this coming for decades, in an ever-widening array of innovations in microelectronics, MEMS, micromachining, microassembly, synthetic biology and nanotechnology.

However, those pieces have been embedded deep inside macroworld things, such as smartphones, autos and drones. Thus the explosion of micro-innovations has remained out-of-sight, underappreciated and underexploited by system-integrators … even as they witness transformative applications such as Z-MAN glass-climbs … and serious out-of-body experiences, such as when flying Parrot Bebops using Oculus Rifts.

However, when looking back at what's happening, one conceptual milestone will stand out: Motorola's "Project Ara" to create modular smartphones as reconfigurable LEGO-like micro-hardware assemblages of visible microworld subsystems, signaling that microsystem-based hardware apps will join software apps in the public imagination.

Suddenly, innovators will begin exploiting micro-modules such as MEMS IMUs, pressure, temp and flow sensors, micro-cameras, tranducers and servos and their micro-controllers and interconnects to craft micro-HW Apps that plug-n-play within macroscale products … increasingly empowering wearable technology, medical systems, mobility technology, smarthomes and environmental technology, way beyond the currently-envisioned "Internet of Things."

Such innovations will also be fed-back into micro-manufacturing via enhanced 3D printing and other additive manufacturing systems, closing the cybernetic loop and thus providing "gain" in the microworld-application exploration-system.

But where will all the innovators come from?

Will 20th century engineering education . . . focused on narrow analysis and stove-piped local optimization of existing systems be the answer? I don't think so!

Fortunately, a wave of change is sweeping our universities as they explore MOOCs, experiential learning, flipped courses and blended learning, emphasizing entrepreneurial, multidisciplinary, user-centered problem-solving … and as exploration rates are enhanced by faculty and students rapidly sharing innovations via open-access journals (see "Open Access Explained"), e-newsletters, wiki's and webinars.

Many incoming students have also been to LEGO Camps, are in the Maker movement, used Arduino, worked in FAB LABS, been in robot competitions, and motivated into user-engaged, team-problem-solving to meet human needs.

But what tools will incoming learners use to explore and shape the future world?

The answer: electronic design automation, along with rapid prototyping facilities will provide increasingly effective "intellectual power-tools" to create digitally-makeable open-access-sharable microsystems.

Along with development of digital design rules (more) and standards for digitally-specified fabrication processes, such tools also enable innovators to quickly exploit advances in micro-manufacturing.

For example, the rush is on to exploit 3D chip-stacking using Through-Silicon-Vias (TSVs) . . . along with an explosion of innovations in interposer and packaging technology, opening the door to ever tinier, increasingly powerful parametrically-form-factorable, microhardware apps.

A revolution is also underway in tools for user-engaged 3-dimensional visualization, design, modeling, simulation and prototyping … as environments such as Dassault Systems "3D Experience Platform" support participatory user/designer/fabricator explorations into how to embed microsystem functionality in a wide range of macro and meso scale products.

As an example let's visualize what's ahead for the auto industry:

The need to embed rapidly-evolving information, communication and entertainment devices . . . along with increasing numbers of sensors and actuators to meet safety, operational and intelligent vehicle-roadway requirements is now straining existing models of in-vehicle connectivity.

The auto industry will thus stimulate and be affected by innovations in signal & power connectivity among modular microsystems distributed within partially-customizable, upgradable products of all kinds.

We also glimpse, over the horizon, an incoming shift in auto architecture to low-drag "Very Light Cars" (VLCs). Exploiting high-tech, parameterized, lightweight Drive-train Axle-assemblies containing electric motors, regenerative brakes and wheel sets -- VLCs can be powered by battery modules and or internal-combustion-engine plus generator modules, depending on regional driving-conditions, energy-markets and roadway infrastructure.

Microsystem-enhanced VLC outer shells and compartments could be modularly fabricated by OEM's, or regional and local manufacturers, or collaborative combinations of the above, enabling targeting of widely varying international submarkets based on local user needs, road designs and driving conditions, and local labor, material and energy costs.

The regionally diverse microsystem-enhancement of auto-products will then further cross-trigger the embedding of modular-interconnected microsystems into clothing, mobility technology, buildings and cities, i.e., almost everything.

As this wave of spreads, microsystem manufacturers won't be limited to selling into narrow-industry, tiered supply chains, and instead connect with diverse makers, multiproduct supply-chains and emerging markets as supply-chains for the electronics, clothing, automotive, medical, home-appliance and building industries begin to cross-couple and commingle.

We'll thus see rapid expansion beyond production of commodity-microparts aimed at mass-markets, into production of a vast range of value-added, higher-margin, specialty-market componentry.

We'll also see reshorings, dispersals and market-democratization of many areas of manufacturing, including the rise of many specialized component-integration/subassembly shops, with user-engagement, creative partial-customizations and order-to-delivery times being key success factors.

Ah, but what about the complexity of the interactivity among multi-industry markets, investors, innovators, designers, entrepreneurs, intellectual property brokers, tool builders, fabricators, supply chains, system integrators, logistics systems and engaged users?

How on earth will companies connect and thrive within such a massive, rapidly-evolving, collaborative-competitive industrial-ecosystem?

The enabler: The commingling and hybridization of design and simulation tools, QTA digital prototyping and manufacturing, and social-media will provide multi-technology "exploration infrastructure" for widespread user-engaged market development and rapid open-source technology evolution.

By exploiting collaborative learning, crowdsourcing, crowdfunding, IP brokering, agile methods, rapid-digital-prototyping and more, everyone . . . from users to makers to researchers … will be able to dramatically scale up their connectivity, participation and impact. Especially see the recent Washington Post report: "Crowdfunding propels scientific research."

The key idea: Applying insights into social physics and techno-social dynamics to rapidly involve escalating numbers of participants in collaborative-competitive feedback to provide gain in, and thus empower, our expanding exploration-ecosystems.

As the incoming wave of innovators, investors, social infrastructure, design tools, manufacturers, products and markets crests it will trigger disruptive change . . . the micro-bio-nano world will suddenly be seen for what it is: an immense frontier for exploration, charting, surveying, mining and application!

5. Framing our Microworld Explorations

With each passing week we learn of further exemplar innovations in micro-bio-nano materials, processes, components and systems. While seeming mere lab curiosities to some, many are landmarks for modern explorers of the vast micro-bio-nano world. Consider a couple of such "signposts":

When a while back Wyss Institute researchers announced the first controlled flight of robotic insects, it seemed like 'lab magic' to those who seldom wonder how things are made. However, to research engineers it contained a deep message: Although the team dreamt for years of creating "robotic bees", it was their innovation of a laser-cut, laminated-micro-material, origami pop-up-book-like mass-production-method that enabled them to conceive, prototype and evolve a successful design.

When a team at NC State formed 3-D micro-scale flexible, bendable structures and wires using liquid metals, they revealed how surface-tension scaling-effects can provide needed micro-scale structural integrity. In each case, the impactful innovation wasn't "the thing" itself. It was methods to multi-physically characterize, parametrically scale and make whole classes of analogous things.

As more and more such micro-landmarks are discovered and shared, ever more researchers will begin connecting the dots, peering further into the micro-bio-nano world – searching for routes, for passageways, for breakthroughs, as they prospect for gold in this new frontier. And each new landmark compounds the possibilities for further connections, increasing the pace of discovery.

Some keys to all this are evolution of instruments that enable more and more researchers to "together look more deeply into the microworld" will be development of ever-more comprehensive multi-physics simulation tools to make scaling-effects interactively visible and innovatively exploitable … the use of 3D techno-socio exploration infrastructure such as that in now in use for macro-world application-explorations … along with open-standards for metrological, cartographic and infographic exchanges, so as to make widely visible, measurable and sharable the mappings, findings and "makings" of microworld expeditions as they venture into the unknown.

Disruptive changes in scale also provoke questions about old-time macro-industry ways of doing things. For example: Does a major manufacturing facility have to be 'large'? Not if it makes micro-scale things!

Some micro/nano part-production factories might fit in a suitcase, some meso/micro assembly plants might fit in a garage … with 2D micro-nano-bio sheet-laminators and weaving-machines feeding composed-meta-materials into 3D printers, self-assemblers and additive-manufacturing machines.

The challenge is analogous to building a 'ship in a bottle.' While the desired final product is clear, there are questions on how to remotely construct it within volumetric constraints. We'll need to learn lots more about microscopy, micro-metrology, micro-tooling and micro-self-assembly, before we can generate and embed vast numbers of micro things.

Such micro-production and micro-embedding facilities promise to be among the most multidisciplinarily-innovative systems ever created, thus the incoming revolution presents many challenges to traditional 20th century stovepiped scientific and engineering culture:

What's the new game? Who gets to play, how do we team-up, and what rules do we play by?

In a 2013 *Science* editorial, Keith Yamamoto asked:

"What if baseball were organized like science? Aspiring catchers or shortstops, like students of physics or molecular biology, would be trained by professional counterparts, and top prospects with dazzling skills would turn pro without learning that by combining specialized talents, they could create an entirely different game.

Managers, owners, and marketers would seek and reward individual stars at each position but would not facilitate or nurture a team culture or even a team game. In science, traditions, policies, and bureaucracies isolate scientific disciplines and their discoveries and technologies, squandering exciting opportunities that could be empowered by merged ideas and efforts—in short, by teamwork."

Bottom line: It's "Time to Play Ball"!

6. Reflecting on our Travels through Social Time

We've clearly entered a period of historic techno-social change. Vision, teamwork and technology are enabling ever more of us to find our voices, communities and rightful places in the world. In return, our accumulating collective impacts are fueling ever-more-rapid techno-social change.

Although this is very exciting, researchers working in deep stovepipes on the sidelines find the prospects very scary. They don't want to be left behind as trains leave the station. But which trains to take, and when to jump on them? After all, the early ones could run off their rails! How to plan? How to position for careers, and more? Especially: how to keep up?

It's not going to be hard, if you're "open to it" and want to be a "player", for the emerging cross-linked innovation-communities will welcome you in.

All you need do is be curious, peek out of your stovepipes of comforting expertise, be excited about learning new things, be unafraid to be a beginner at new things, and be eager to join new teams, learn the ropes, and contribute however you can.

After all, we're all natural born explorers. While many rein it in due to social pressure as they grow up, some of us, like many here, never grow out of it!

The secret is to retain the fun and excitement of being partly childlike, always ready to crawl, then walk, then jog, before running-relays in some new game … at the same time paying close attention to skill development, gearing-up, peer-collaboration-and-competition, team-building and social learning and leadership, especially when exploring unknown territory.

As the Social Age unfolds and top-down 20th century institutions fade, *ever more of us* can focus our attention on building social reputations as learners, sharers, helpers, contributors, innovators, leaders and explorers … *rather than merely* seeking money, material things, formal positions, the appearances of individual expertise and the trappings of power.

By doing so, we'll steadily increase our techno-social agility and our opportunities for teaming up with cool people, gaining new skills, going exploring, enjoying exciting adventures, and leaving tracks behind!

7. Envisioning the Adventures Ahead

Connecting the dots … it's clear this is the "Big One." The microworld 'Gold-Rush' has begun, and is exponentiating due to the gain in the exploration-ecosystems emerging in the 'Cambridges', 'Silicon Valleys', 'Maker Valleys' and 'Artists Valleys' all around the world … as they innovate, exploit, share and expand the humanistic techno-social infrastructure of the emerging Social Age.

Furthermore, this revolution in human enterprise is technologically, economically, politically and socially inevitable, because the long term success of humanity depends upon *sustainably providing ever-more* infrastructural functionality and life empowerment per person, while *consuming ever-less* energy and material resources per person.

It can also move societies towards more diverse, inclusive and thriving futures, as ever more people *migrate from being* isolated consumers of mass-produced goods and entertainment *towards being* socially interconnected, participatory customizers of their habitats and life experiences.

The microworld has thus become the great frontier for modern-day explorers seeking the keys to sustainable human-life-empowerment.

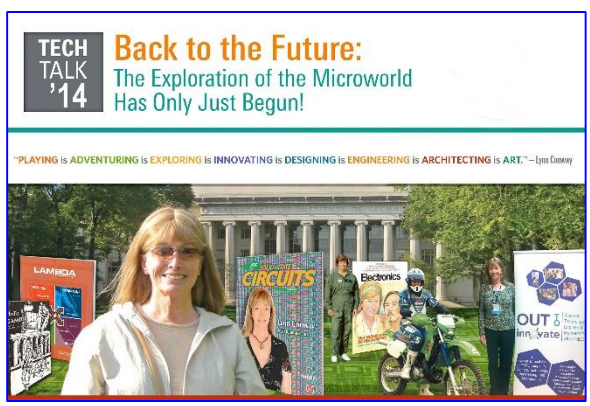
* * *

Words to recall while traveling through time:

If you want to change the future, start living as if you're already there!

And have no fear: Embrace and enjoy the escalating rate of techno-social change for it has a truly wonderful side effect: it's enabling us to live far further into the unfolding future than we could ever have imagined!"

We're heading into quite an adventure!



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