Closing the Sustainability Gap in Nano- and Microelectronics Research and Education

Carol Handwerker
Purdue University

Korea – US Forum – Seoul
3-4 April 2023

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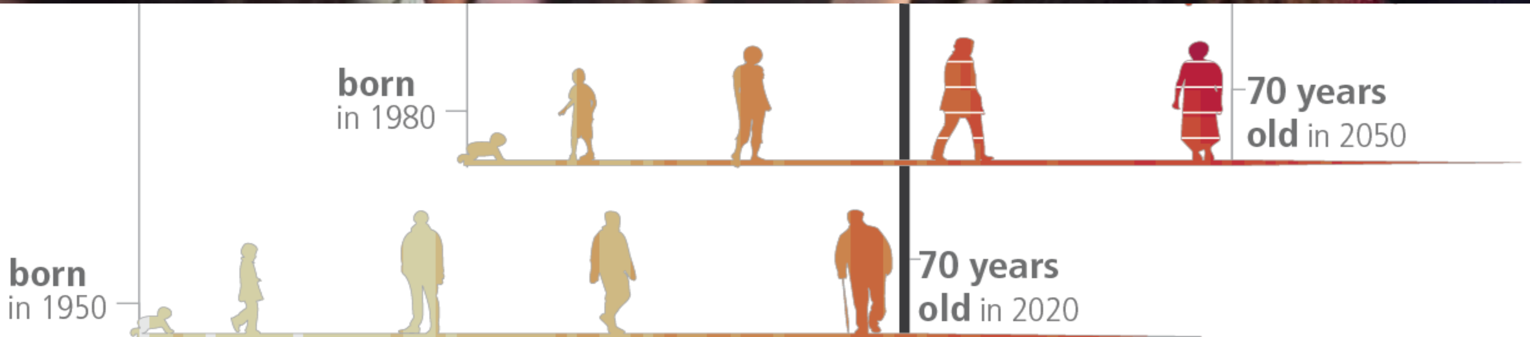
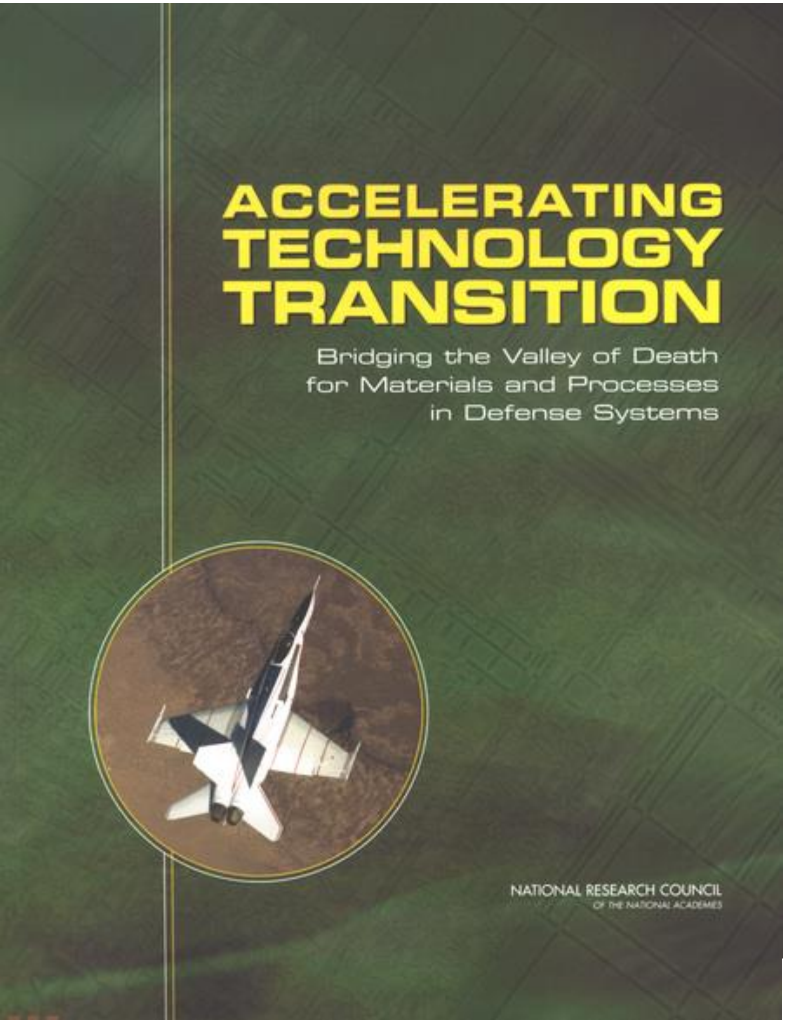


THE NATIONAL ACADEMIES



ACCELERATING TECHNOLOGY TRANSITION

Bridging the Valley of Death for Materials and Processes in Defense Systems

COMMITTEE ON ACCELERATING TECHNOLOGY TRANSITION

DIRAN APELIAN, Worcester Polytechnic Institute, *Chair*
ANDREW ALLEYNE, University of Illinois, Urbana-Champaign
CAROL A. HANDWERKER, National Institute of Standards and Technology
DEBORAH HOPKINS, Lawrence Berkeley National Laboratory
JACQUELINE A. ISAACS, Northeastern University
GREGORY B. OLSON, Northwestern University
RANJI VAIDYANATHAN, Advanced Ceramics Research, Inc.
SANDRA DeVINCENT WOLF, Consultant

- Creating a culture for innovation and rapid technology transition,
- Methodologies and approaches, and
- Enabling tools and databases.

Our Vision

How do we as educators, scientists, and engineers create a sustainable eco-system for educating, training and empowering students to be leaders in sustainability?

iNEMI, Indian Institute of Management - Udaipur collaboration with industry, NGOs, research institutions, govt.

Convergence

- CHIPS Act: $52B – Workforce Development Focus
- SRC Roadmap Sustainability and Energy Efficiency (part of Roadmap for Microelectronics … Packaging Technologies) …
- Corp…
- A… Engineering and Technology (A… social contract – students, educators, companies for jobs. *We are responsible for environmental and societal impacts we design and use*

Workforce Development for Sustainable Electronics

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2.1. Introd

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- **Grand Challenge**

"achieving a 1000x to 1,000,000× increase in computing energy efficiency over the next two decades"

- **Trends/ Drivers**

"...the energy efficiency of computing has improved exponentially, enabled by the scaling provided by Moore's law .... it has also had the effect that orders of magnitude more computing is consumed each decade."

"This increasing appetite for computing, with the slowing of scaling for the newer technologies, is why information technology is poised to consume a major fraction of the world's energy in the coming decades"

- **Promising Technologies**

"The combination of advanced packaging, emerging technologies, and codesign with new architectures, devices with algorithms and software will support the SRC Decadal Plan goal of achieving a 1000x to 1,000,000× increase in computing energy efficiency over the next two decades"

"Creating a full stack that includes the chiplet, custom domain-specific accelerator designs, system software, and application drivers that can be modular and usable across computing technology advances especially using cross-disciplinary innovations from materials to complex heterogeneous systems enabled by advanced packaging."

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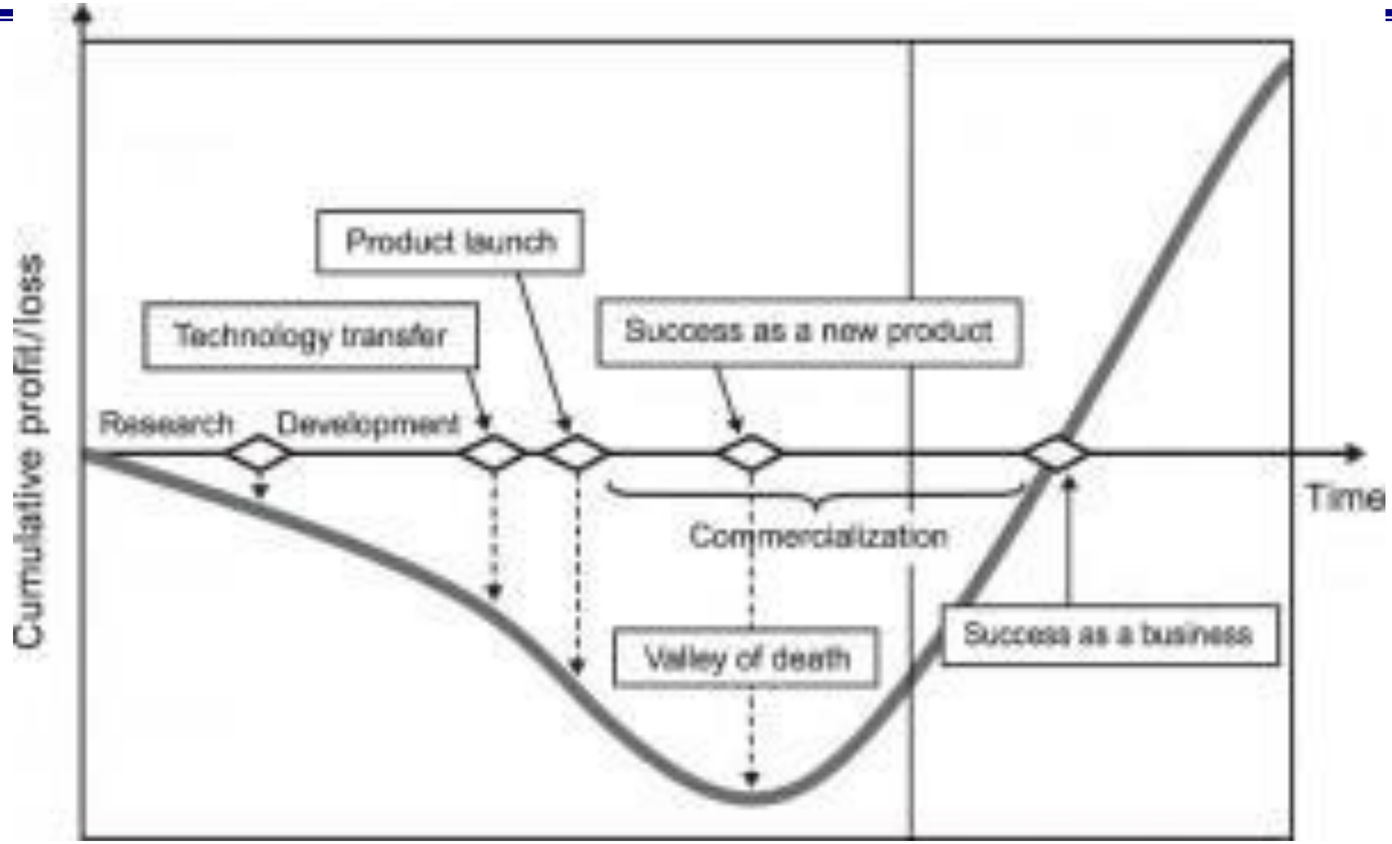

SCALE (Scalable Asymmetric Lifecycle Engagement): A *Workforce Development Prototype* for US Defense Microelectronics

- Creating a culture for innovation and rapid technology transition,
- Methodologies and approaches, and
- Enabling tools and databases.

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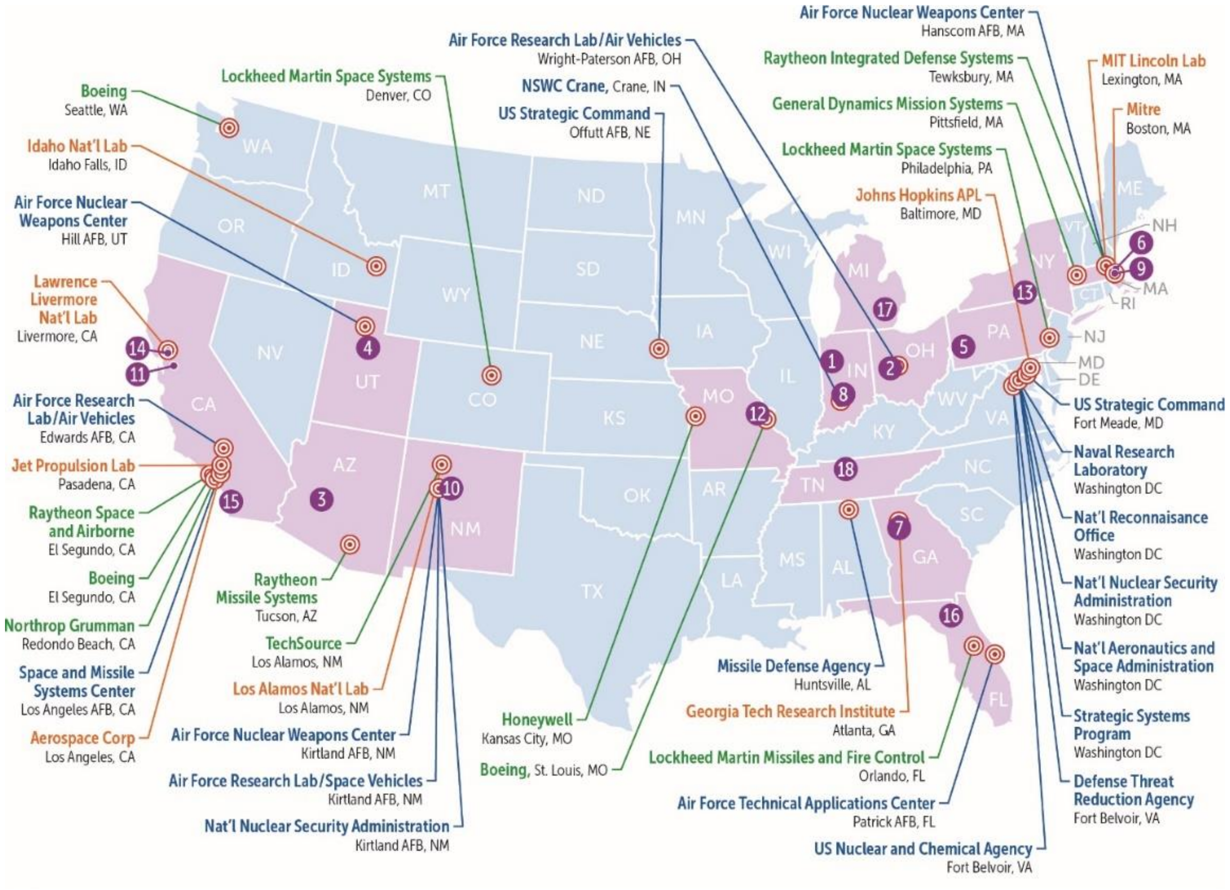
SCALE will provide DOD/GOV/DIB with a more effective pipeline and an asymmetric microelectronics workforce advantage



SCALE scalability demonstrated by PPAP National Network

Technical Verticals

Radiation-hardened technology:
1. Vanderbilt
2. Air Force Institute of Technology
3. St. Louis University
4. Brigham Young University
5. Arizona State University
6. Georgia Tech
7. Purdue University
8. Indiana University
9. New Mexico State University
10. UT-Chattanooga

Supply Chain Awareness:
1. Purdue University
2. University of Florida

Heterogeneous integration and advanced packaging:
1. Purdue University
2. Georgia Tech
3. SUNY-Binghamton
4. Arizona State University

System on Chip:
1. Ohio State University
2. Georgia Tech
3. Purdue University
4. UC-Berkeley

Embedded Systems Security:
1. Indiana University
2. IUPUI
3. Notre Dame

SCALE Pathways for Undergraduate Trainees

First Year
Core curriculum

Fall & Spring: Introduce Microelectronics (ME) modules into core courses, **Spring:** Recruiting - Open House/Call Out, research projects, seminars, workshops, bootcamp
Summer: **Possible DOD/GOV/DIB Internship or REU**

Second Year
Core curriculum

Fall & Spring: Introduce ME modules in disciplinary core courses, research projects, seminars, workshops
Spring: Open House, Application, selection, & sign-up, **Orientation & field trips**
Summer: **Likely DOD/GOV/DIB Internship or REU**

Third Year
Core curriculum

Fall & Spring: Multi-disciplinary core courses for program (1Cr, 3Cr), Mentored team-based research, Defense Microelectronics Research Fellowship **– Research mentors & seminars**
Summer: **Guaranteed internship with DOD/GOV/DIB facilities**

Fourth Year
Core curriculum

Fall: Focused topical area course for team-based project (Capstone Senior Design, Focused Area, or interdisciplinary), Mentored team-based research, Defense Microelectronics Research Fellowship, technical electives relevant to focus topics - **Research mentors & seminars, work with interns to select technical electives useful for future employment**

Spring: Interdisciplinary course for focused topical area, Mentored team-based research, Defense Microelectronics Research Fellowship, technical electives relevant to focused topic - **Research mentors & seminars, work with interns to select technical electives useful for future employment**

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Summer: Graduation ⇨ hired by DOD/DIB, admitted to graduate school for DOD topic research

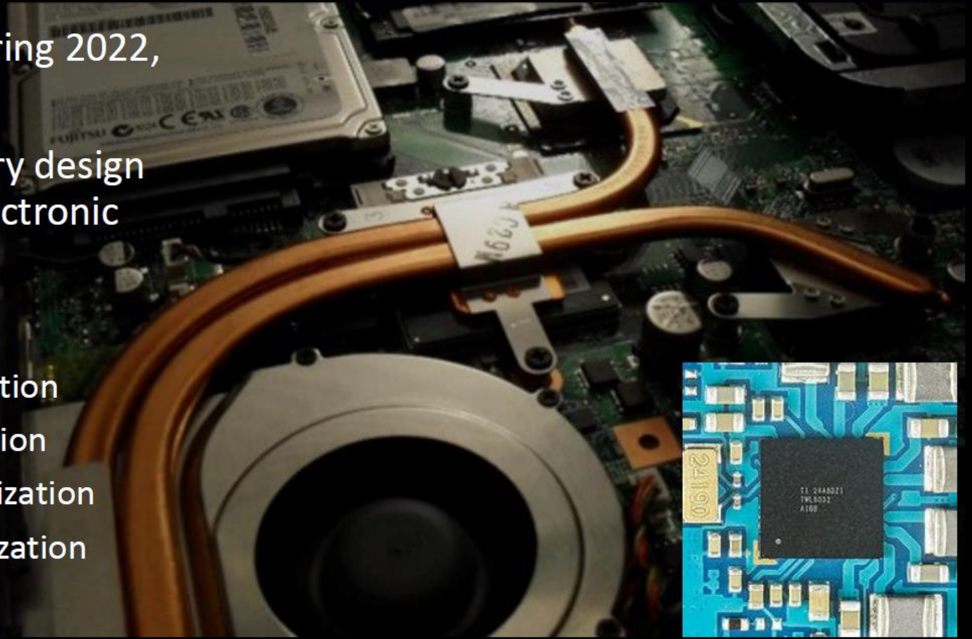
DoD and universities defined the fundamental knowledge, skills, and abilities (KSAs) needed across all microelectronics fields.

Co-created and co-delivered by Purdue, Georgia Tech, Arizona State, Vanderbilt, SUNY/Binghamton,

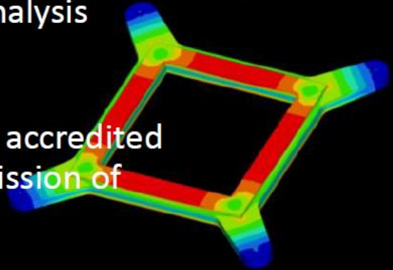
Asynchronous
Scaleable

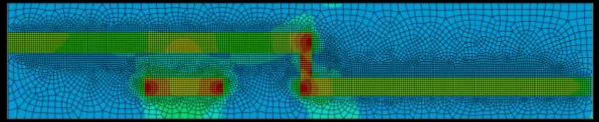
ME 597 ECE 595 MSE 597

Introduction to Electronics Packaging and Heterogeneous Integration



- Instructor: Ganesh Subbarayan, Spring 2022, 3 credits
- Learn the basics of multi-disciplinary design and characterization of modern electronic components and assemblies
- Topics:
  - Electrical Design and Characterization
  - Thermal Design and Characterization
  - Mechanical Design and Characterization
  - Material Selection and Characterization
  - Package Fabrication
  - Statistical Modeling and Data Analysis
- Prerequisites:
  - Junior-level standing in an ABET accredited engineering curriculum or permission of course instructor





David N Halbrooks
Email: dhalbroo@purdue.edu

Common Pool Resources

Commons: A resource shared by many people who depend on it for their livelihoods

- In context of products, there are multiple “commons”
  - the environment - creating pollution and wasting embedded resources
  - the products themselves, their components, and retaining value to society

Natural

- **Fisheries**
- **Forests**
- **Groundwater**
- **Irrigation Systems**
- **Rivers**
- **Air**

Man-Made

- **E-waste**
- **Paper**
- **Plastic**
- **Food**
- **Products**
- **Minerals**

Common Pool Resources

Commons: A resource shared by many people who depend on it for their livelihoods

Our students as a "commons"

It is up to us to work together and with them to help them become leaders in sustainability

ty

Avoid

"The Tragedy of the Commons"

- **Forests**
- **Groundwater**
- **Irrigation Systems**
- **Rivers**
- **Air**

- **Paper**
- **Plastic**
- **Food**
- **Products**
- **Minerals**

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https://www.facultyfocus.com/articles/course-design-ideas/group-work-collaborative-activities/

Organizing Framework – Ostrom - 2009 Nobel Prize

PERSPECTIVE

SCIENCE VOL 325 24 JULY 2009

A General Framework for Analyzing Sustainability of Social-Ecological Systems

Elinor Ostrom[1,2*]

A major problem worldwide is the potential loss of fisheries, forests, and water resources. Understanding of the processes that lead to improvements in or deterioration of natural resources is limited, because scientific disciplines use different concepts and languages to describe and explain complex social-ecological systems (SESs). Without a common framework to organize findings, isolated knowledge does not cumulate. Until recently, accepted theory has assumed that resource users will never self-organize to maintain their resources and that governments must impose solutions. Research in multiple disciplines, however, has found that some government policies accelerate resource destruction, whereas some resource users have invested their time and energy to achieve sustainability. A general framework is used to identify 10 subsystem variables that affect the likelihood of self-organization in efforts to achieve a sustainable SES.

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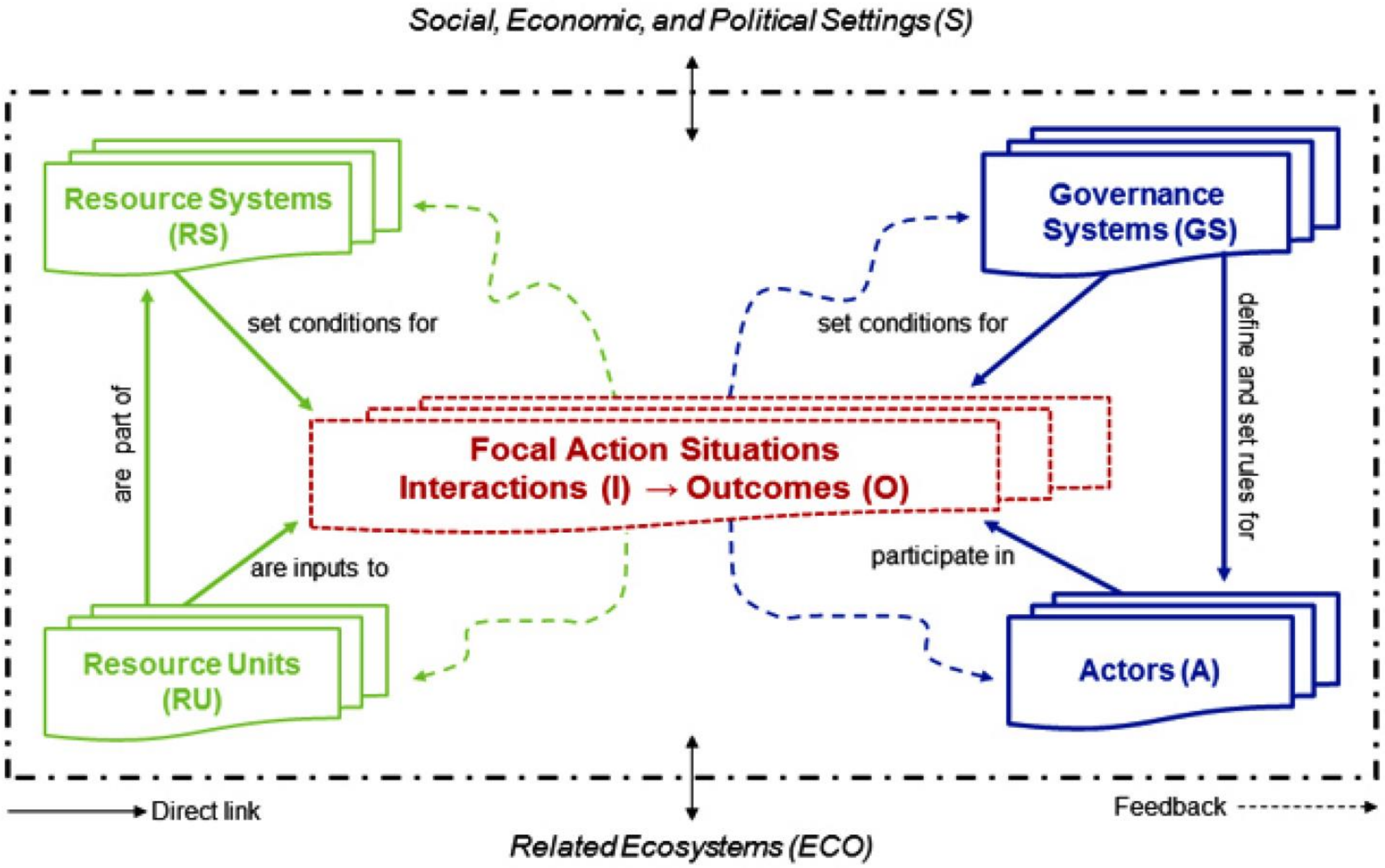
Framework for Sustainable Systems for the Commons (Ostrom)



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Social, economic, and political settings (S)

S1 – Economic development
S2 – Demographic trends
S3 – Political stability
S4 – Other governance systems
S5 – Markets
S6 – Media organizations
S7 – Technology

*** Required for sustainable systems**

Resource systems (RS)

RS1 – Sector
RS2 – Clarity of system boundaries
* RS3 – Size of resource system
RS4 – Human-constructed facilities
* RS5 – Productivity of system
RS6 – Equilibrium properties
* RS7 – Predictability of system dynamics
RS8 – Storage characteristics
RS9 – Location

Resource units (RU)

* RU1 – Resource unit mobility
RU2 – Growth or replacement rate
RU3 – Interaction among resource units
RU4 – Economic value
RU5 – Number of units
RU6 – Distinctive characteristics
RU7 – Spatial and temporal distribution

Governance systems (GS)

GS1 – Government organizations
GS2 – Nongovernment organizations
GS3 – Network structure
GS4 – Property-rights systems
GS5 – Operational-choice rules
* GS6 – Collective-choice rules
GS7 – Constitutional-choice rules
GS8 – Monitoring and sanctioning rules

Actors (A)

A1 – Number of relevant actors
A2 – Socioeconomic attributes
A3 – History or past experiences
A4 – Location
* A5 – Leadership/entrepreneurship
* A6 – Norms (trust-reciprocity)/social capital
* A7 – Knowledge of SES/mental models
* A8 – Importance of resource (dependence)
A9 – Technologies available

Action situations: Interactions (I) → Outcomes (O)

I1 – Harvesting
I2 – Information sharing
I3 – Deliberation processes
I4 – Conflicts
estment activities
I6 – Lobbying activities
I7 – Self-organizing activities
I8 – Networking activities
I9 – Monitoring activities
I10 – Evaluative activities

O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability)
O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability)
O3 – Externalities to other SESs

Related ecosystems (ECO)

1 – Climate patterns ECO2 – Pollution patterns ECO3 – Flows into and out of focal SES

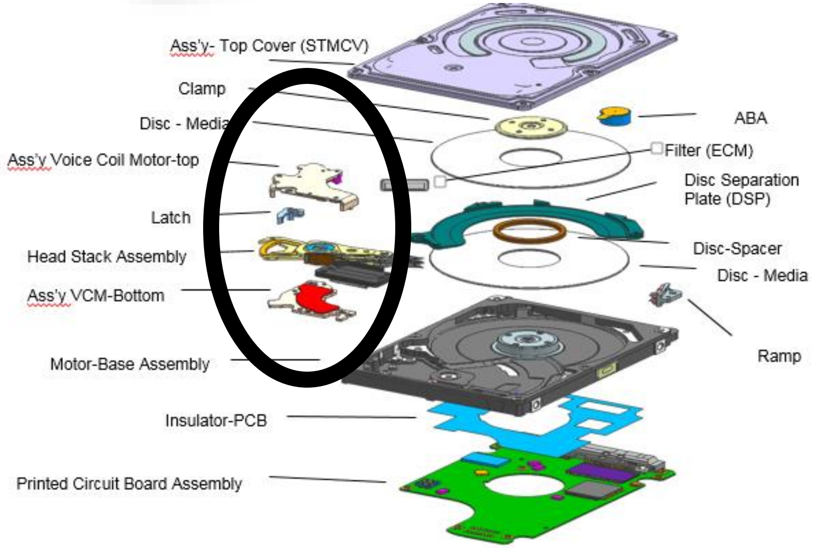
Think of Atul Gowande and The Checklist Manifesto

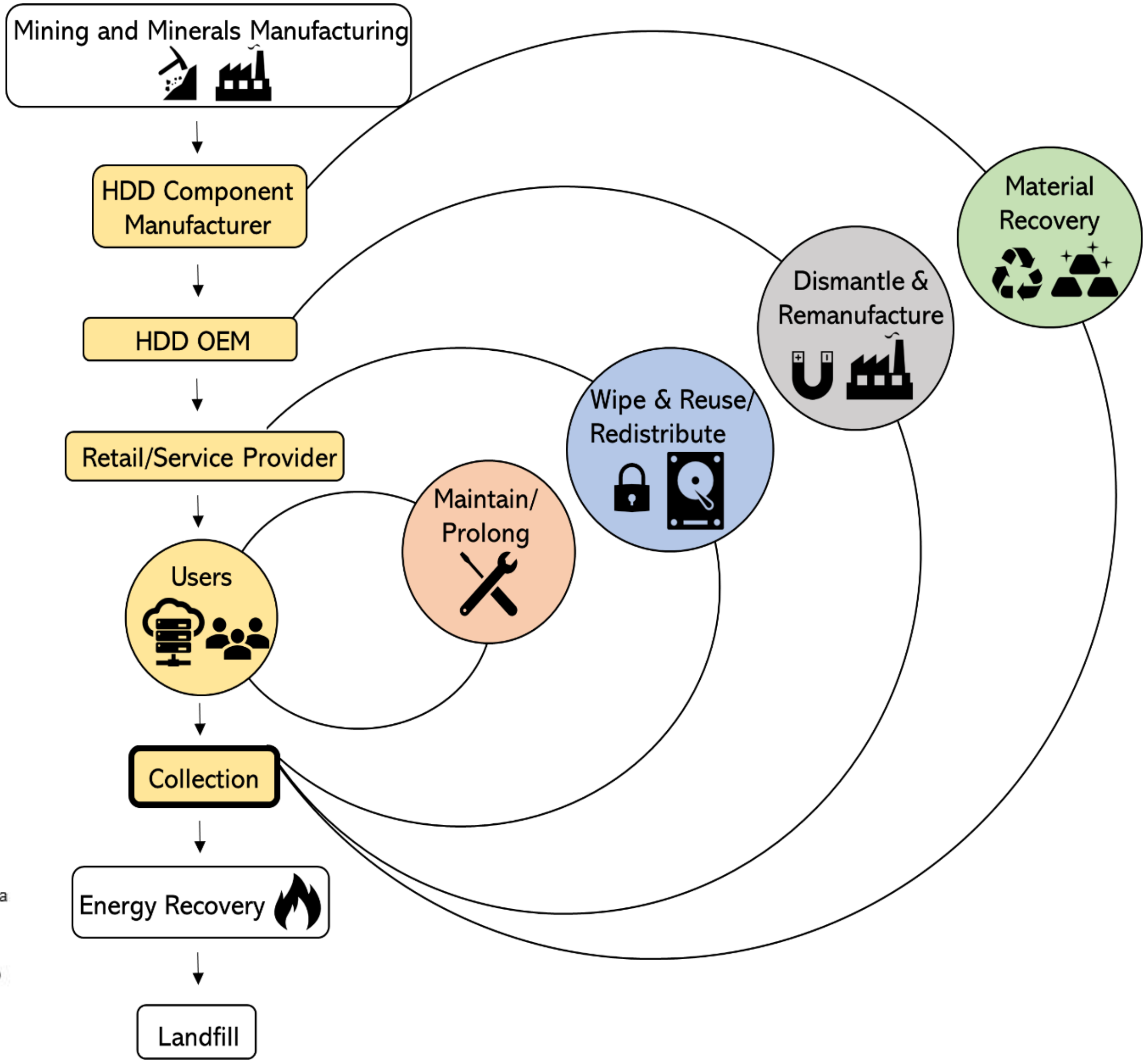
Creating a Circular Economy for Hard Disk Drives – A Shared Vision

Project Leaders:
Carol Handwerker (Purdue University)
Bill Olson (Seagate)

iNEMI
Advancing manufacturing technology

Creating a Circular Economy for Hard Disk Drives





Creating a Circular Economy for Hard Disk Drives

iNEMI Phase 2 project started in October 2017, completed September 2018

- **In-kind funding model**
- **System collaboration model:** self-assembling and self-managing group setting common goals **(Ostrom framework)**
- **Demonstration of circular economy for HDDs:** supply chain, economics, logistics, reducing life cycle costs

Members:

Ames Lab, Cascade Asset Management, **Cisco,**
Critical Materials Institute, Echo Environmental, **Google,**
Green Electronics Council, IBM/Geodis, Idaho National Lab, **Microsoft,** Momentum Technologies, Oak Ridge National Labs, Purdue University, **Seagate**, Teleplan, University of Arizona, Urban Mining Company

Members:
their goals, the positions they hold and the moves they can make

Members in the project had a common goal

HDD Manufacturers – Seagate

HDD Users – Cisco, Google, Microsoft

Authorized After-market Service Providers – Teleplan

Recyclers and IT Asset Management Companies –Geodis/IBM, Cascade Asset Management, Echo Environmental

Secondary Market Buyers and Sellers of HDDs– connected through recyclers and large HDD users

Magnet Manufacturers – connected through Seagate

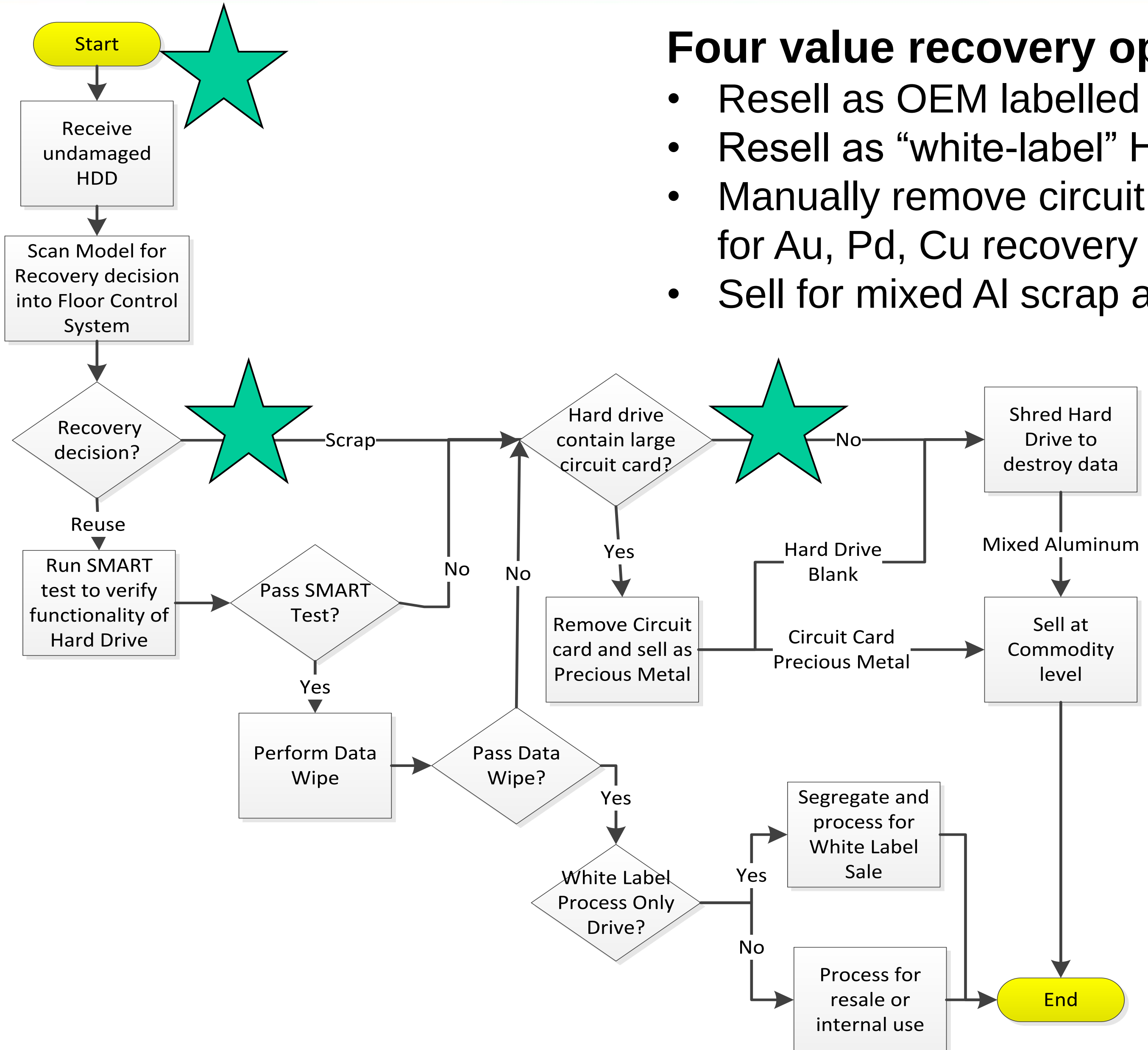
Smelters and Other Materials Recovery Organizations- Momentum Technologies, Urban Mining Corporation

After First-Market Users - consumers, data center, enterprise, cloud, computer – connected through HDD Users + AM Service Providers

Technology Developers – research organizations (national labs, universities, all the above) – CMI – Ames, INL, ORNL, Purdue

Standards organizations – GEC (EPEAT)

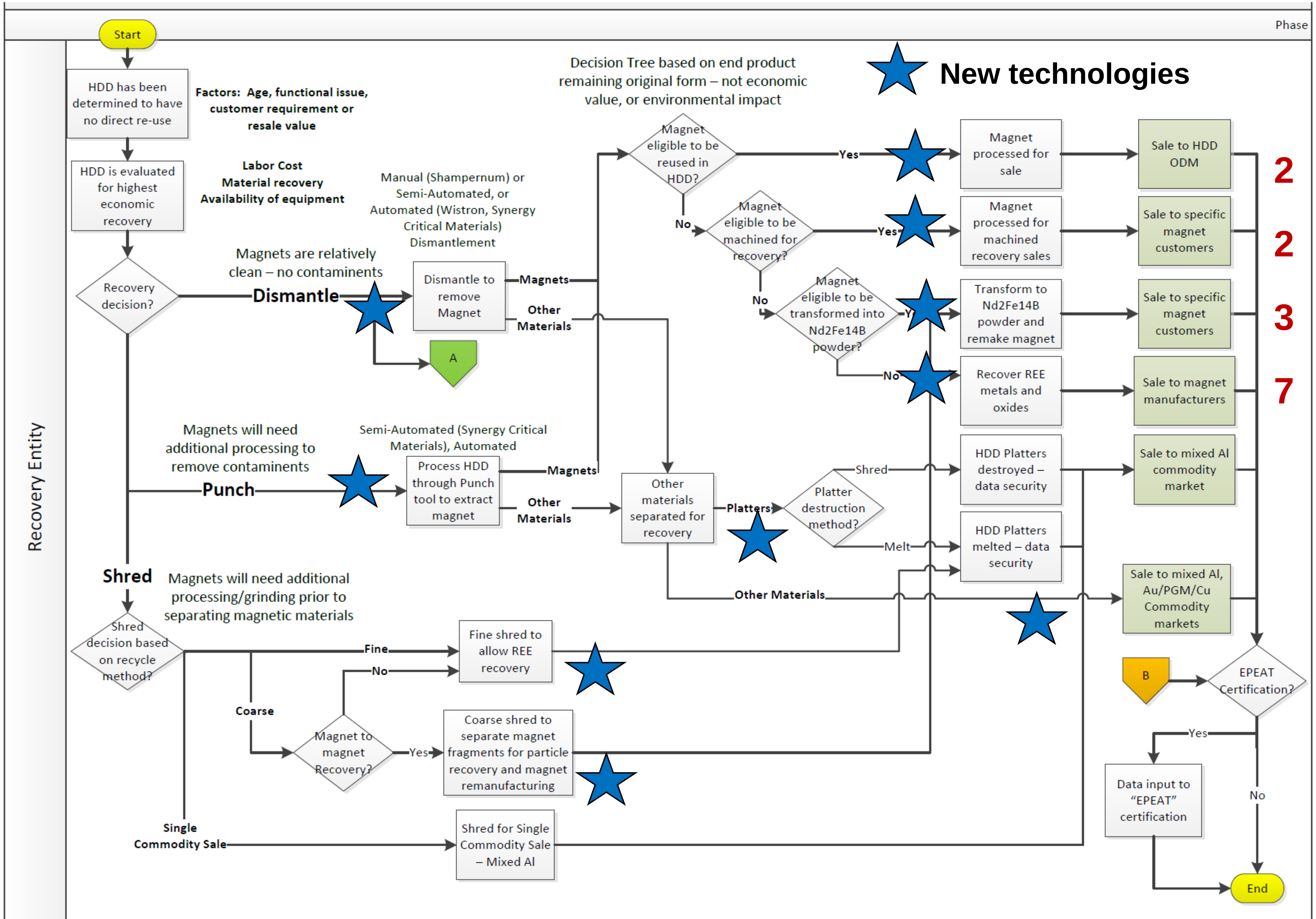
Decision Tree for Value Recovery from Used HDDs



Four value recovery options:

- Resell as OEM labelled HDD
- Resell as "white-label" HDD
- Manually remove circuit boards and sell for $7-$9/lb for Au, Pd, Cu recovery
- Sell for mixed Al scrap at $0.25/lb as shred or whole

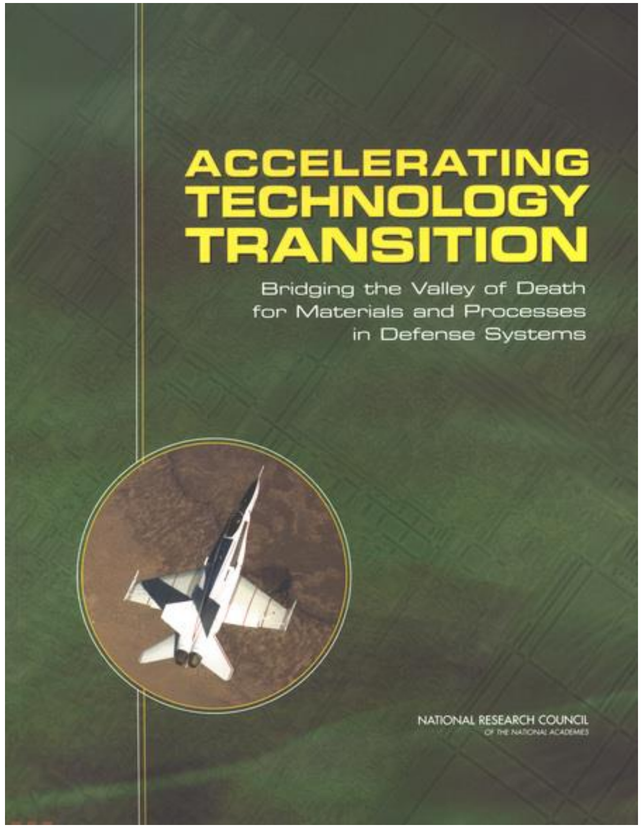
In iNEMI Project – 9 pathways



A New Model for Managing the Commons

- Students as a Commons
- Educators create the eco-system
- Not just what we teach, but
  - how we focus on shared
  - how we build and r... ...te trust
  - how we imple... ... eco-system sustainab...
  - …
- W... ...e tools to use and models to test

Next Steps: Propose a series of Workshops



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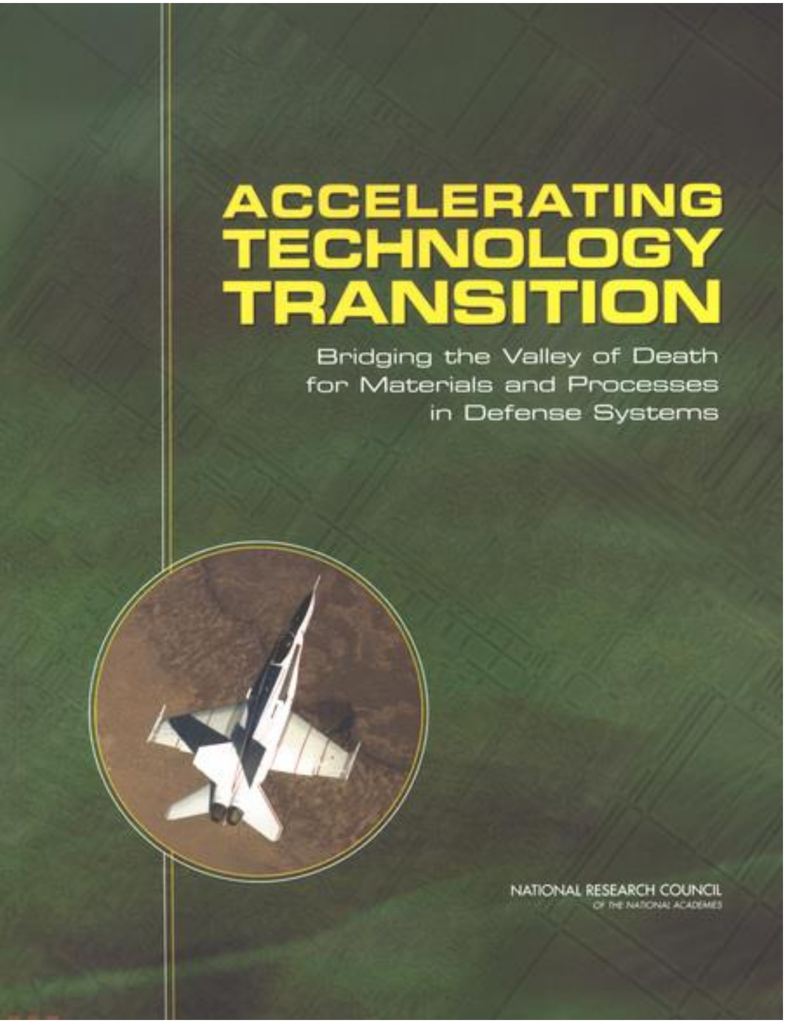

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Extra Slides

Resulting Demonstration Projects

Demonstration Project	Leaders	Key Finding
HDD Coil Magnet Assembly Direct Reuse	Seagate/Google	HDD magnet assemblies can be effectively harvested and used to build new hard drives
HDD Direct Magnet Reuse	Oak Ridge National Laboratory	HDD magnets can be recovered undamaged in large numbers (>1MM/yr) and used in useful products (beyond HDD)
Magnets from Dismantled HDD	Urban Mining Company	Can harvest magnets from a range of HDDs in a commercially viable way
Oxides from EoL HDD Magnets	Momentum Technologies/Ames Lab	Demonstrated ability to produce REOs from different recovery paths with high purity
Moving from "Reuse or Shred" to "Reuse and Recover"	Microsoft/Google/Idaho National Lab	Identified economic and environmental values from wiping and resale/reuse

- **Project Page with final report, presentations, papers: https://www.inemi.org/value_recovery_2**
- **Environmental impacts of a circular recovery process for hard disk drive rare earth magnets**, K. Frost, I. Sousa, J. Larson, H. Jin, I. Hua, Resources, Conservation and recycling October 2021
- **Life cycle assessment of emerging technologies on value recovery from hard disk drives**, Jin, H., Frost, K., Sousa, I., Ghaderi, H., Bevan, A., Zakotnik, M., Handwerker, C.A., Resources, Conservation & Recycling, 157 (2020) Article Number: 104781

We posit

Two Additional Necessary Factors for Success

Actors have ***shared* goals** for the SYSTEM as well as individual goals for themselves that are explicitly articulated

Actors recognize that others**’ individual goals** are important -

so that when there are disagreements or things get “hard”, we continue to work together to meet our shared goals

This is explicitly what we developed in the iNEMI Value Recovery project

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