Session 8 –

AM Scalability, Implementation, Readiness, and Transition

Rainer Hebert
Department of Materials Science and Engineering
Additive Manufacturing Innovation Center in Partnership with Pratt & Whitney
University of Connecticut
Storrs, CT 06269

- Powder-bed metal additive manufacturing in partnership with Pratt & Whitney (joint lab at UConn); collaboration with United Technologies Aerospace Systems → Additive manufacturing through an “aerospace lens”
- Commercial equipment, test-bed (in design phase), characterization equipment (including FEI Center)
- Practical hands-on experience, team projects with computational materials colleagues (Density-functional theory calculations/molecular-dynamics simulations: Pamir Alpay, Avinash Dongare; professional staff)



What is the path for utilizing fundamental results for AM and scaling them for use in productions?

Fundamental results:

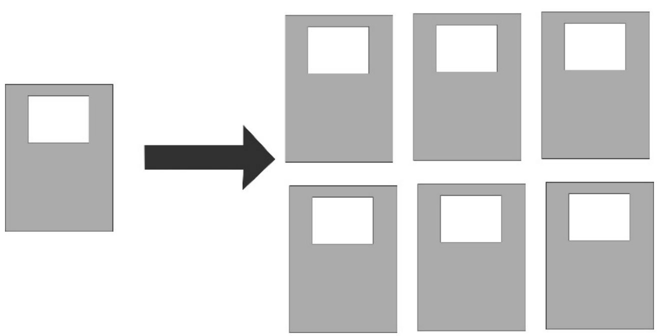
Modeling – Atomic level, macro-level
Theory – Heat transfer, materials theory
Experiments – Controlled input variables

Productions:

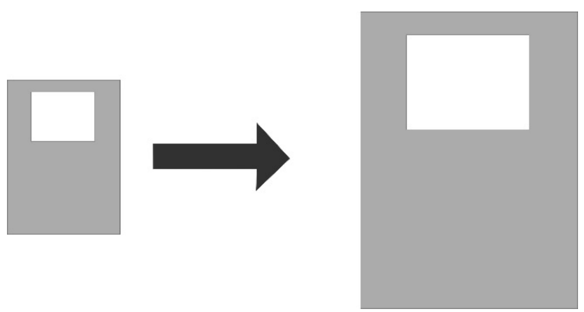
(1) Several (thousands) new parts of the same design
(2) Approved repair technologies; e.g., repair of parts by DoD facilities

Scaling:

Multiple machine operators



Scale up: multiple machines of the same type



Scale up: increase in build volume, throughput

What is the path for utilizing fundamental results for AM and scaling them for use in productions?

Δ (machines)

Δ (processes)

Δ (materials)

→

Δ (microstructures)

Δ (properties)

Variations in input causes variations in AM part properties that need to be minimized

→ Key role of fundamental studies/results is to reduce variations in outcome variables (while meeting specifications)

→ Fundamental studies to characterize variations in input variables

→ Fundamental studies to quantify relations between input and output variables (materials, machines, processes – microstructures)

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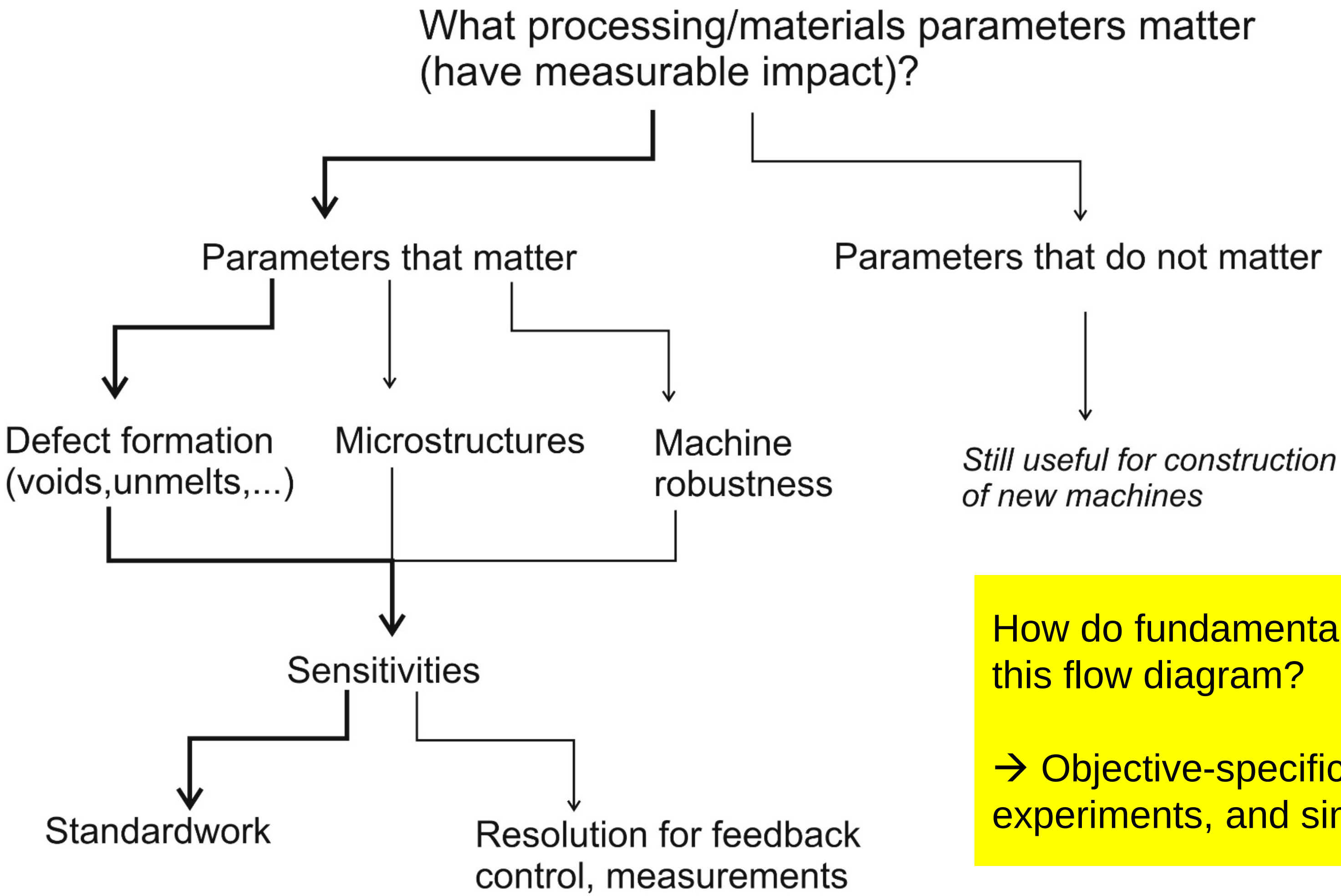

How do fundamental results play into this flow diagram?

→ Objective-specific mix of theory, experiments, and simulations

What is the path for utilizing fundamental results for AM and scaling them for use in productions?

Theory

- Laser theory
- Laser-material interactions
- Heat flow theory
- Theory of thermo-physical properties
- (Rapid) solidification: phase selection, microstructure changes, phase transformations
- Surface chemistry
- Welding theories (e.g., spatter)

Experiment

- Laboratory experiments: Laser optics (beam characteristics, beam path control), raking
- Thermophysical measurements (conductivity, specific heat, wetting angles, surface tension, viscosities)
- Diagnostics (sensors)
- Feedback control

Simulation

- Powder flow (discrete)
- Lattice-Boltzmann
- Density-functional theory
- Molecular-dynamics simulations
- Solidification simulations
- Phase-field modeling

Powder bed raking and heating

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Experiment

- Laboratory experiments: Laser optics (beam characteristics, beam path control)
- Thermophysical measurements (conductivity, specific heat, wetting angles, surface tension)
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Simulation

- **Powder flow (discrete)**
- **Lattice-Boltzmann**
- **Density-functional theory**
- **Molecular-dynamics simulations**
- **Solidification simulations**
- **Phase-field modeling**

Microstructures, properties

What is the path for utilizing fundamental results for AM and scaling them for use in productions?

Microstructures

Defect formation

Machine/processing/materials parameters that matter

Short-term (<2 years)

Intermediate (5 years)

Long-term (10 years +)

What are the roadblocks that hinder the scaling of AM technologies into production and use in systems?

"Roadblock": Significantly obstructing progress toward scaling of AM technologies; more severe than challenges

(1) Incomplete understanding of relations between materials-/processing-parameters, machine characteristics, part properties (and variations)

Individual phenomena that occur during the additive processes known qualitatively. But correlations and quantitative predictions for the overall process remain formidable task.

(2) Process transparency (some machines, not all)

- Machine parameters "coded" → difficult to integrate with modeling
- Beam motion, settings not known in detail

What are the roadblocks that hinder the scaling of AM technologies into production and use in systems?

(3) Manual calibrations (some machines)

Trend toward automated calibration, alignment routines, but questions about alignment and calibration accuracies and precision will remain.

(4) Machine sensing capabilities

Limited capabilities to measure additive process in-situ. But also limited understanding what exactly needs to be sensed and measured and at what resolution.

What are the roadblocks that hinder the scaling of AM technologies into production and use in systems?

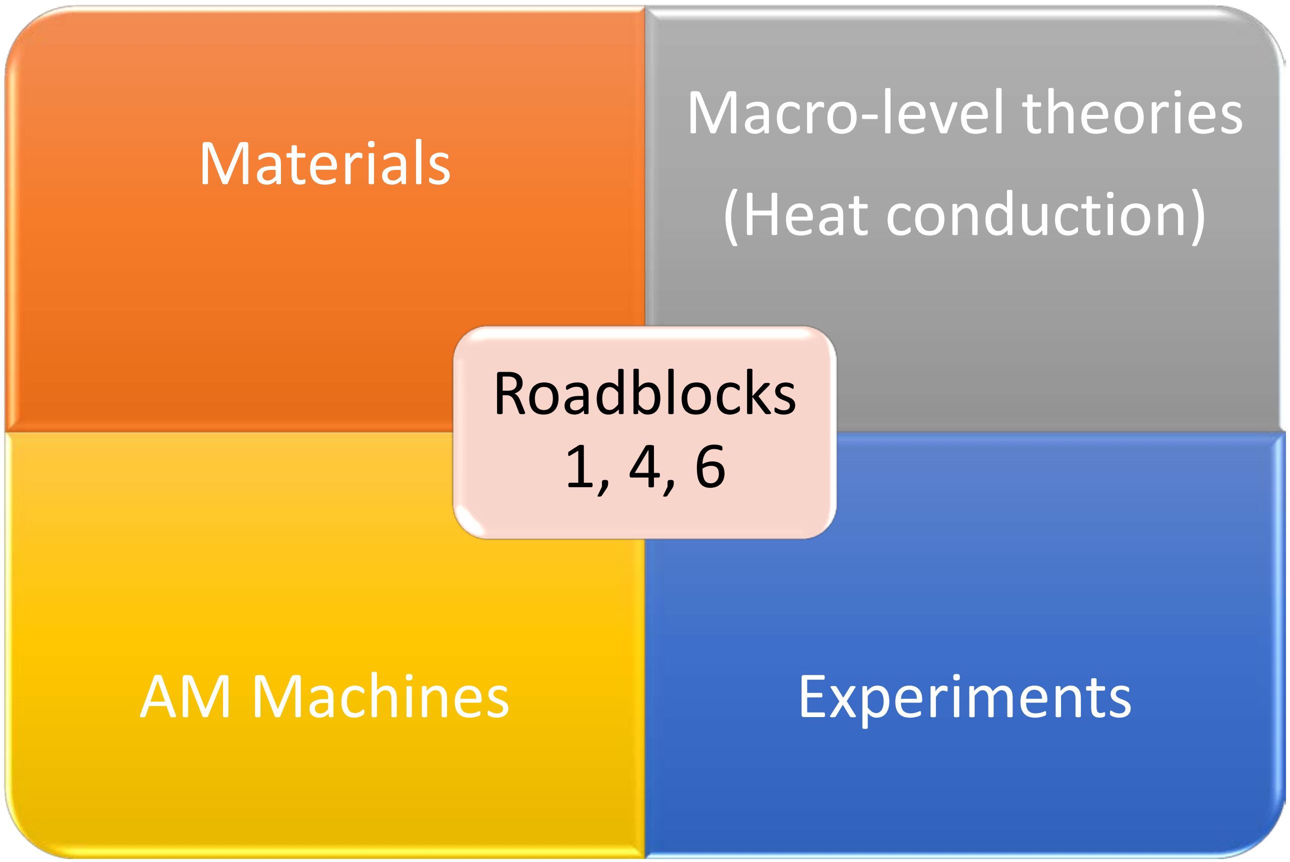
(5) Fast machine evolutions

- Updates in software, hardware not aligned with timelines for AM qualification.
- Drive to sell and improve machines, will be accelerated when IPs expire.

(6) Some drivers to promote scaling of AM technology counter-productive for demanding applications

Increased beam power to accelerate throughput, anticipated new machine at lower cost could increase output variations

Do any of these roadblocks represent problems/issues that can be best addressed through additional fundamental research?



Do any of these roadblocks represent problems/issues that can be best addressed through additional fundamental research?

Materials:

- **Generate materials data specific to AM** (experiments, first-principles calculations, simulations): Surface tensions, viscosities of liquid alloys; impurity effects; specific heats, thermal conductivities; absorption coefficients.
- **Modeling of processing aspects** (theory: thermodynamics, kinetics; simulations: Lattice-Boltzmann)

Macro-level, heat flow theory:

- **Modeling of processing aspects** (powder raking; heat flow: fluid-dynamics, theory)

Do any of these roadblocks represent problems/issues that can be best addressed through additional fundamental research?

Experiments:

- **Physically simulate aspects of the AM machines and processing** (raking, laser optics, powder particle melting, atmosphere effects,…)
- **Improve machine control aspects** (future: feedback capabilities)

AM machines:

Sensing capabilities: thermal measurements at frequencies > 1 MHz, with "heat source finder"

What are future applications, markets and industry partners that may leverage the fundamental research and scale it into production?

I. Hybrid materials: Combinations of different materials applied during one and the same process, e.g., ceramics with metals, different metals, polymers with ceramic, metal particles.	
Applications	Metal-ceramic combinations for energy applications (fuel cells), for sensing applications, coatings.
Markets	Energy, aerospace, biomedical
Industries	Industries in power generation (land-based, aerospace), major biomedical companies
Fundamental research: Multi-component diffusion, phase transformations, interface chemistries and microstructures,…	

What are future applications, markets and industry partners that may leverage the fundamental research and scale it into production?

II. New materials: New materials, specifically developed for additive manufacturing applications, resulting in components with improved properties.	
Applications	High-temperature structural applications, light-weight applications.
Markets	Aerospace, automotive, transportation
Industries	Industries producing materials (alloys), e.g., ALCOA
Fundamental research: Alloy development for AM, thermodynamics & kinetics, phase diagrams	

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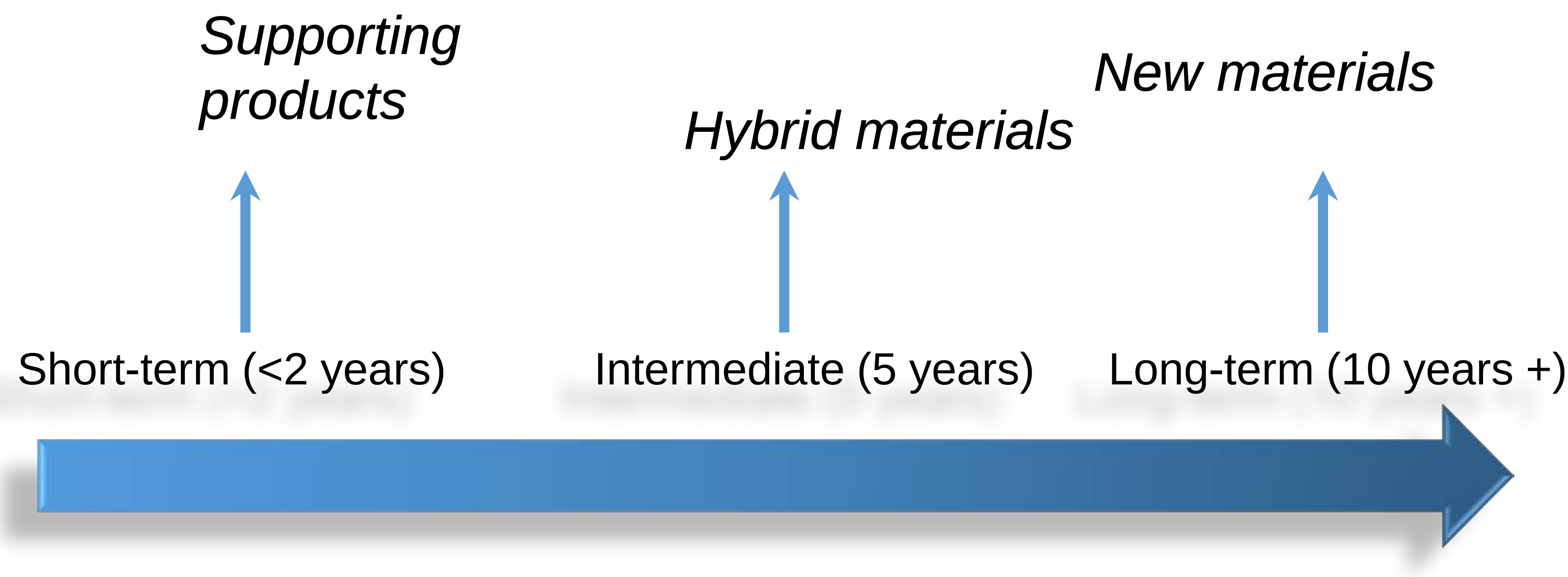
III. Supporting products: Industries gear up to support the transition of additive manufacturing into production. From the obvious (powder) to the unsuspected (e.g., electron microscopy)—the transition of additive manufacturing to new applications and production levels seem to spur developments in supporting applications.	
Applications	Measuring (of AM machines, of AM-produced parts), control (of AM machines).
Markets	Precision engineering, software,
Industries	Software companies offering simulation software for “traditional” processing, manufacturers of analysis equipment (thermal, optical, microstructure,…)
Fundamental research: The products emerging from the relevant industries are used intrinsically for fundamental AM research	

What are future applications, markets and industry partners that may leverage the fundamental research and scale it into production?

Industrial applications



Final remarks

- Fundamental research can be turned off instantaneously (stop funding).
- Fundamental research cannot be turned on instantaneously (takes years to build up expertise).
- Some of the fundamental research relevant to additive manufacturing has been neglected for many years (decades), unclear if still available (in the US).
- Massive effort required to stem the challenges for transitioning AM into production.
- Strong focus currently on TRL 4-6, maybe underestimating the real issues for transitioning AM into production.