



Database Design Strategies for Coordinated Simulation and Testing in Additive Manufacturing

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- Q&C of AM materials and processes (specifically PBF-LB/M)
 - Experimental testing requirements are time and cost drivers
 - In-situ process monitoring is not accepted as a replacement for NDE
 - Insufficient support for integration of computational materials modeling
- Model validation enablers
 - Process-structure: direct observation of melt and solidification processes
 - Structure-property: NDE and mechanical testing (required for Q&C now)
- Our goal:
 - Augment the Q&C process through increasingly mature computational materials models and process monitors in data standardization contexts

Motivation

Key themes and points



Data standards
are not mature

ICME tools are not
incorporated in AM Q&C

We lack a standard
AM data model

A standard AM data model will:

- Bridge the gap between smaller studies and industrial applications
- Facilitate ICME usage in AM Q&C
- Encourage accessibility and reusability of our data

Setting the stage

Data standards in AM Q&C



ASTM F3490-21

Overview of data pedigree

- Establish “Common Data Dictionary” (CDD)
- Aid data-system development to design and update databases
- Improve interoperability and accessibility of AM data

NASA-STD-6030

AM requirements for spaceflight systems

- Governing document for Q&C
- Establish minimum requirements
- Mitigate risk through criticality designation

Key limitations found in either ASTM F3490-21 or NASA-STD-6030

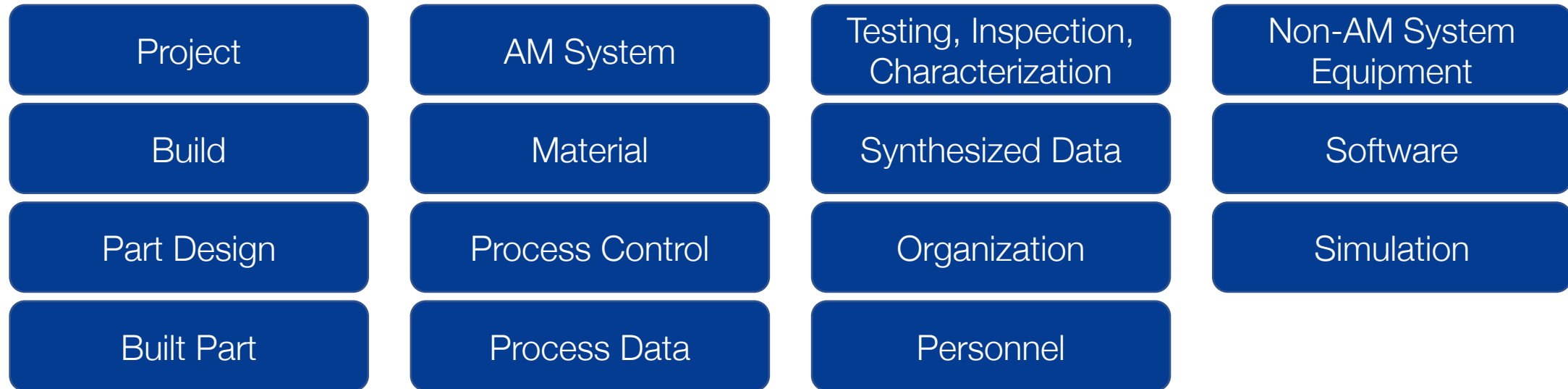
- Virtually no support for ICME tools
- Poor support for in-situ process monitoring for Q&C
- Generalization of testing, inspection, and characterization operations

Setting the stage

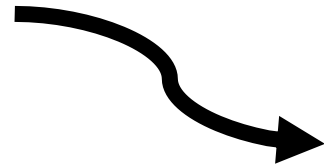
ASTM F3490-21



- Data in the CDD fit into 15 AM Information Modules



- Each module has definitions for
 - Data elements
 - Data type
 - Value range



But the standard falls short of defining a strict schema for the interoperability of these data

Setting the stage

NASA-STD-6030



Minimum Q&C requirements set by specific part criticality

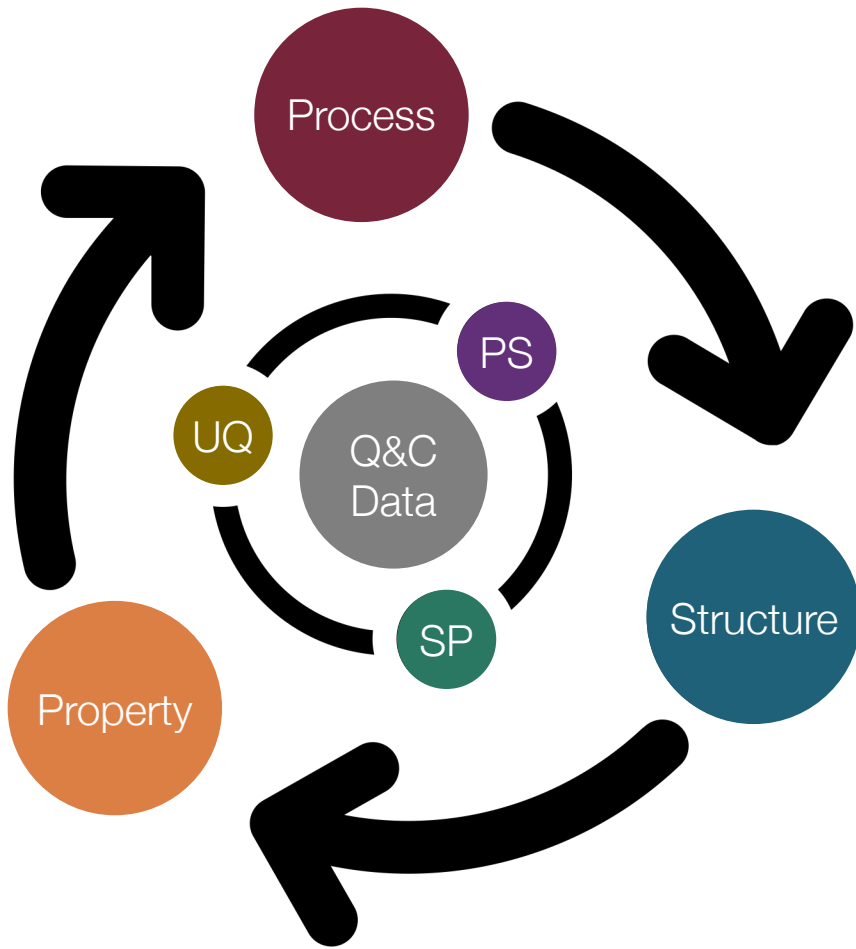
Generally reliant on extensive inspection of witness coupons and NDE of parts

Burden is largely imposed by the development of Qualified Part Processes

- Minimum requirements set all for good reason
- Testing, inspection, and characterization requirements increase the time and cost
- In-situ process monitoring is nice to have but cannot replace required characterizations (X-ray computed tomography)
- From a research perspective, there is uncertainty in how well witness coupons represent critical part regions
- 6030 is strict in prescribed guidance while allowing for specific modifications as needed

Database design strategies

Designing for the research environment



Modeling capabilities

- Thermal history
- Process control
- Microstructure evolution
- Defect formation
- Crack nucleation
- Crack propagation
- Fatigue damage accumulation
- Fatigue time scaling
- Grain-scale constitutive model
- Microstructure and surface

Measurement capabilities

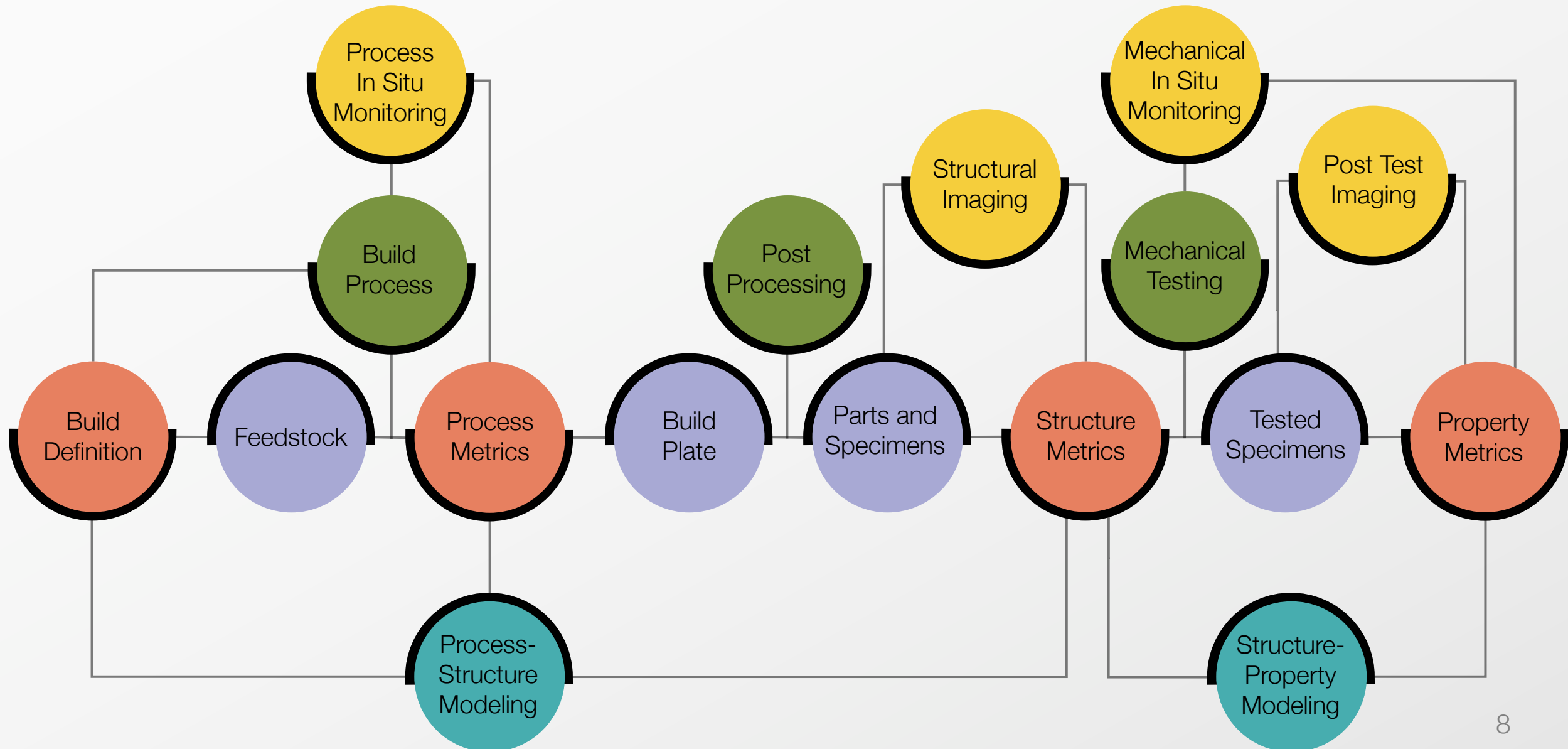
- Melt pool imaging
- Thermal rise
- Optical/ electron microscopy
- Automated serial sectioning
- Electron backscatter diffraction
- In-situ/ ex-situ fatigue loading
- X-ray computed tomography
- High-resolution strain
- Video image correlation

We develop schema around the data we have

PS: Process-structure relationship
SP: Structure-property relationship
UQ: Uncertainty quantification
Q&C: Qualification and certification

Database design strategies

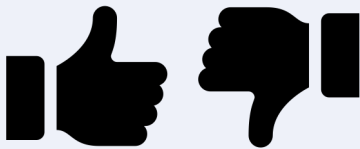
Designing for the research environment



Database design strategies

FAIR data in the AM domain



	Maturity in AM	Examples
Findable		• Published papers • Existing data repositories
Accessible		• “Data available upon reasonable request” • Machine-specific data not always available
Interoperable		• Data cleaning and preparation are expensive • Lack of common data representation
Reusable		• Often too many uncontrolled variables • Lack of common data representation (again!)



Not always searchable by specific parameters, though

Database design strategies

Standard data model



Data standards
are not mature

ICME tools are not
incorporated in AM Q&C

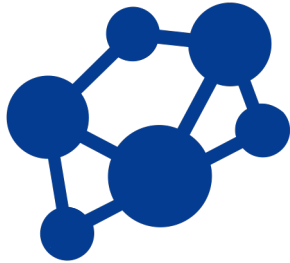
We lack a standard
AM data model

A standard AM data model will:

- Bridge the gap between smaller studies and industrial applications
- Facilitate ICME usage in AM Q&C
- Encourage accessibility and reusability of our data

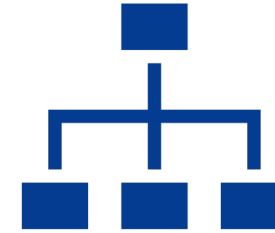
Database design strategies

Choosing a data model structure



Relational

- Complex structure
- Well-suited for production-scale work
- Focus of the work is to build a generalizable data model

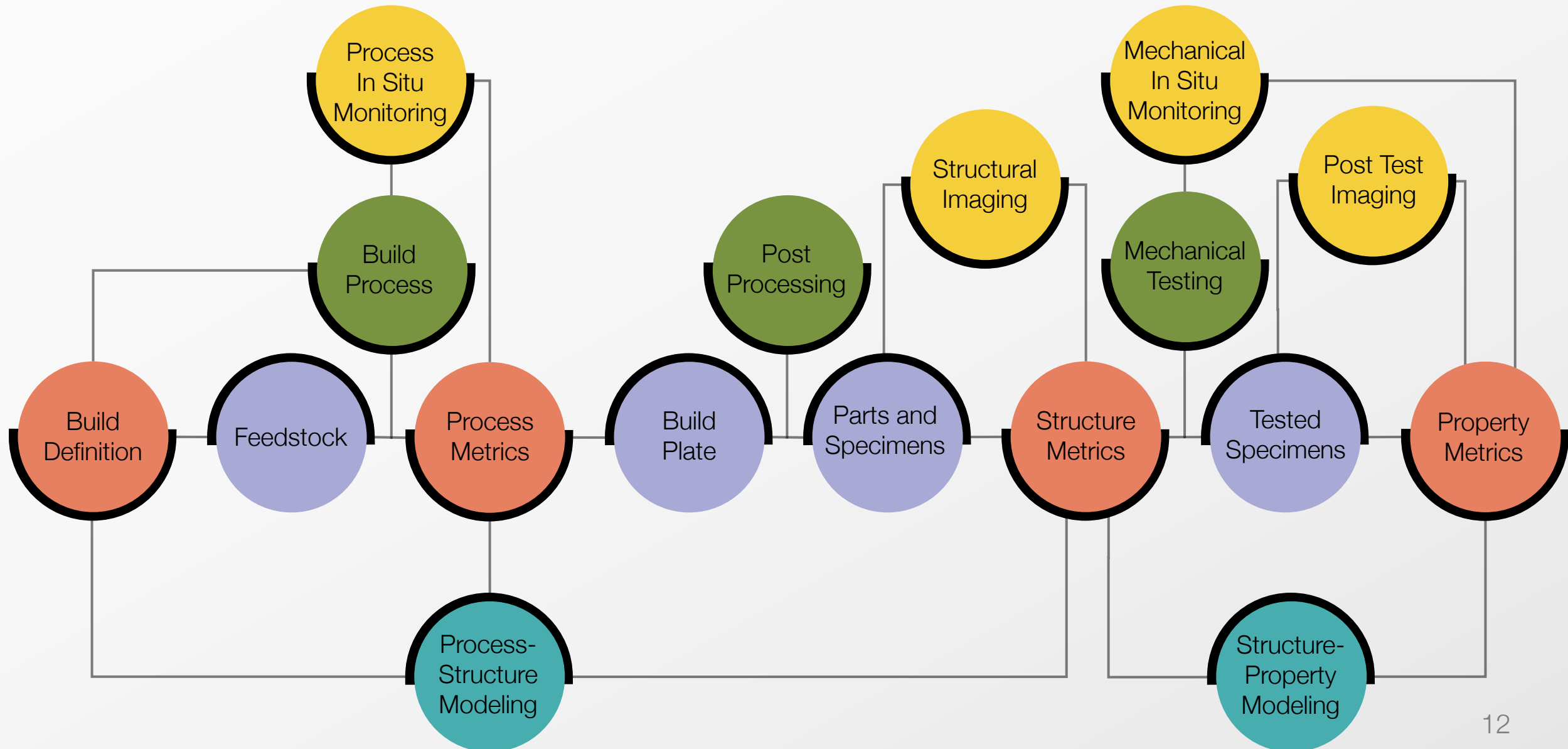


Hierarchical

- Simple structure
- Well-suited for singular studies
- Data hierarchy often developed for a specific application

Database design strategies

Foundation of an AM data model





We want to use an
AM data model to

- Ask complex questions
- Filter and sort by key attributes
- Minimize data storage overhead
- Access tidy data formats
- Maintain data integrity

Relational data models
support this through

- Efficient queries
- Built-in features for sorting
- Elimination of redundant data
- Transform and export functions
- Schema enforcement

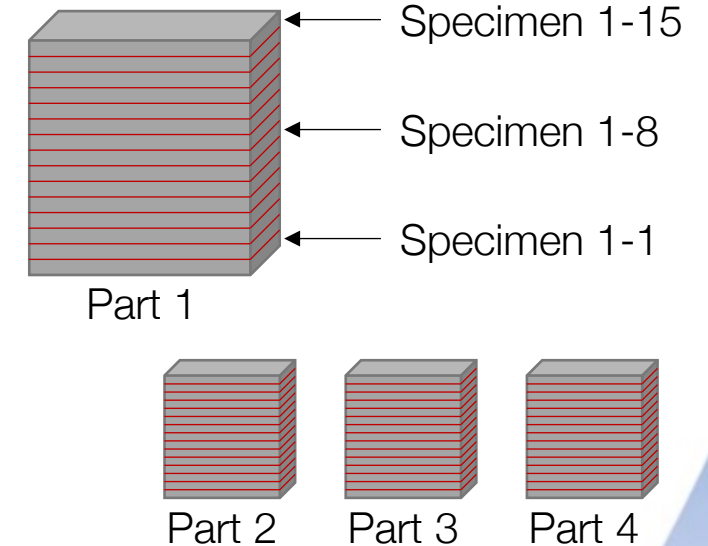
Relational Databases

Structured Query Language (SQL)



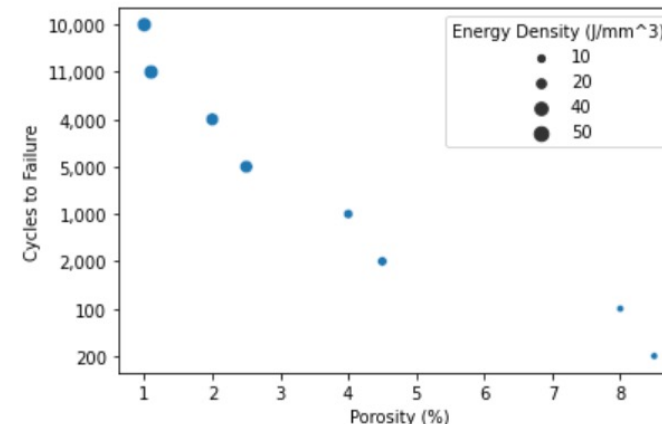
SQL is a language designed to move complex data linkages into tidy data for easy querying

	Specimen	Porosity (%)	Cycles to Failure	Energy Density (J/mm ³)	Power (W)	Velocity (mm/s)	Air Flow Direction	Temperature (K)
0	1	1.0	10,000	50	100	1000	x	273
1	2	1.1	11,000	50	100	1000	x	273
2	3	2.0	4,000	40	80	1000	x	273
3	4	2.5	5,000	40	80	1000	x	273
4	5	4.0	1,000	20	40	1000	x	273
5	6	4.5	2,000	20	40	1000	x	273
6	7	8.0	100	10	20	1000	x	273
7	8	8.5	200	10	20	1000	x	273



Since the data is tidy, with one line of code, we can plot

```
scatterplot(  
  data=read_csv('specimen.csv'),  
  x='Porosity (%)',  
  y='Cycles to Failure',  
  size='Energy Density (J/mm3)'  
)
```



Relational Databases

Structured Query Language (SQL)



Tidy Specimen Table

	Specimen	Porosity (%)	Cycles to Failure	Energy Density (J/mm^3)	Power (W)	Velocity (mm/s)	Air Flow Direction	Temperature (K)
0	1	1.0	10,000	50	100	1000	x	273
1	2	1.1	11,000	50	100	1000	x	273
2	3	2.0	4,000	40	80	1000	x	273
3	4	2.5	5,000	40	80	1000	x	273
4	5	4.0	1,000	20	40	1000	x	273
5	6	4.5	2,000	20	40	1000	x	273
6	7	8.0	100	10	20	1000	x	273
7	8	8.5	200	10	20	1000	x	273

Redundancy from [part](#) association

Redundancy from [build](#) association

Relational Databases

Structured Query Language (SQL)

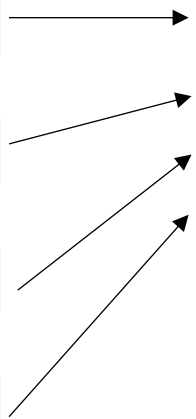


New Specimen Table

	Specimen	Porosity (%)	Cycles to Failure	Part
0	1	1.0	10,000	0
1	2	1.1	11,000	0
2	3	2.0	4,000	1
3	4	2.5	5,000	1
4	5	4.0	1,000	2
5	6	4.5	2,000	2
6	7	8.0	100	3
7	8	8.5	200	3

Part Table

	Power (W)	Velocity (mm/s)	Air Flow Direction	Temperature (K)
0	100	1000	x	273
1	80	1000	x	273
2	40	1000	x	273
3	20	1000	x	273



Relational Databases

Structured Query Language (SQL)



New Specimen Table

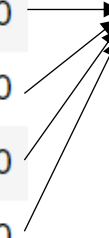
	Specimen	Porosity (%)	Cycles to Failure	Part
0	1	1.0	10,000	0
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4	5	4.0	1,000	2
5	6	4.5	2,000	2
6	7	8.0	100	3
7	8	8.5	200	3

Part Table

	Power (W)	Velocity (mm/s)	Build
0	100	1000	0
1	80	1000	0
2	40	1000	0
3	20	1000	0

Build Table

	Air Flow Direction	Temperature (K)
0	x	273



Relational Databases

Structured Query Language (SQL)



New Specimen Table

	Specimen	Porosity (%)	Cycles to Failure	Part
0	1	1.0	10,000	0
1	2	1.1	11,000	0
2	3	2.0	4,000	1
3	4	2.5	5,000	1
4	5	4.0	1,000	2
5	6	4.5	2,000	2
6	7	8.0	100	3
7	8	8.5	200	3

New Part Table

	Power (W)	Velocity (mm/s)	Build
0	100	1000	0
1	80	1000	0
2	40	1000	0
3	20	1000	0

Build Table

	Air Flow Direction	Temperature (K)
0	x	273

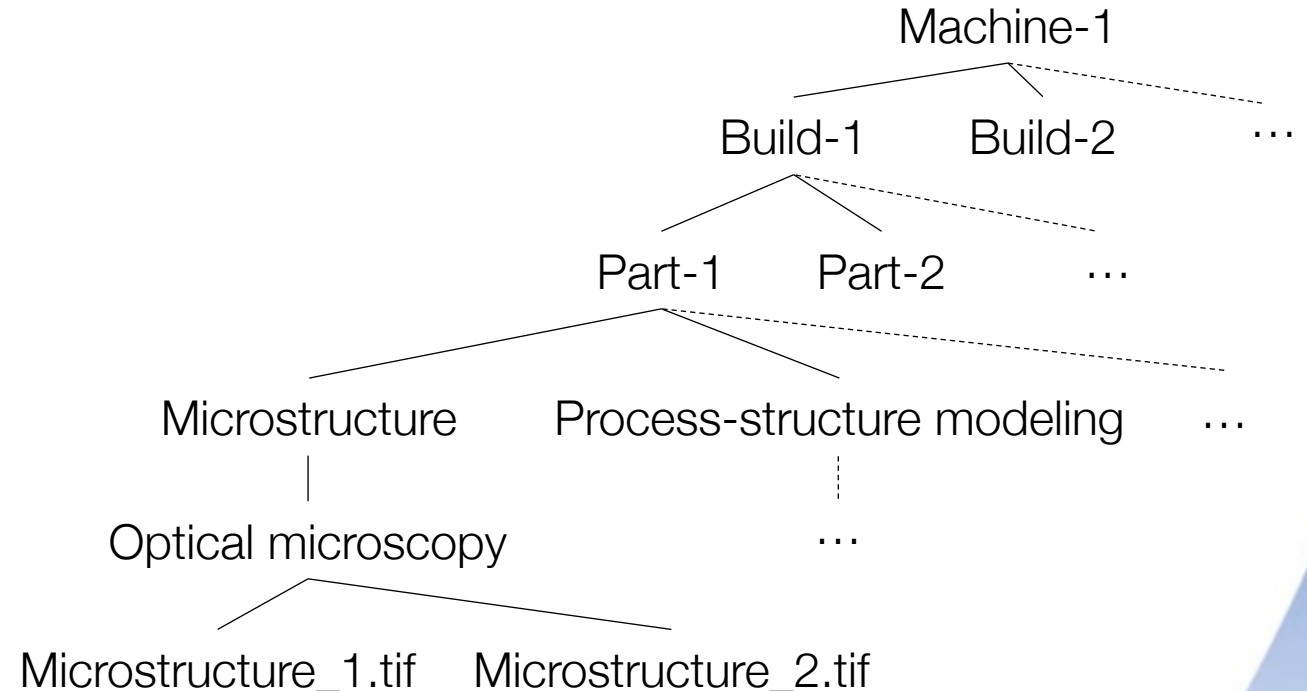
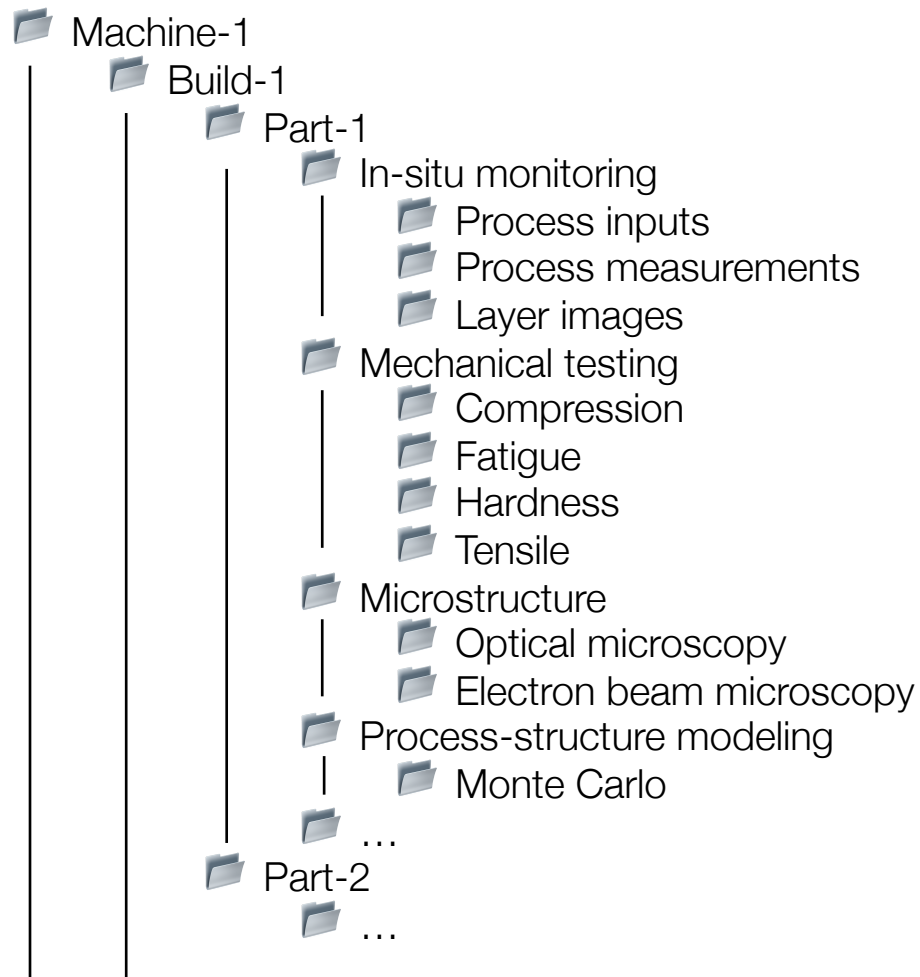
So how can we put it all back together?

SQL Joins →

```
select * from specimen
join part on specimen.part = part.id
join build on part.build = build.id;
```

Relational Databases

Comparison to a Hierarchical Data Structure



But suppose we want to know if the part location on the build plate affects the microstructure?

Relational Databases

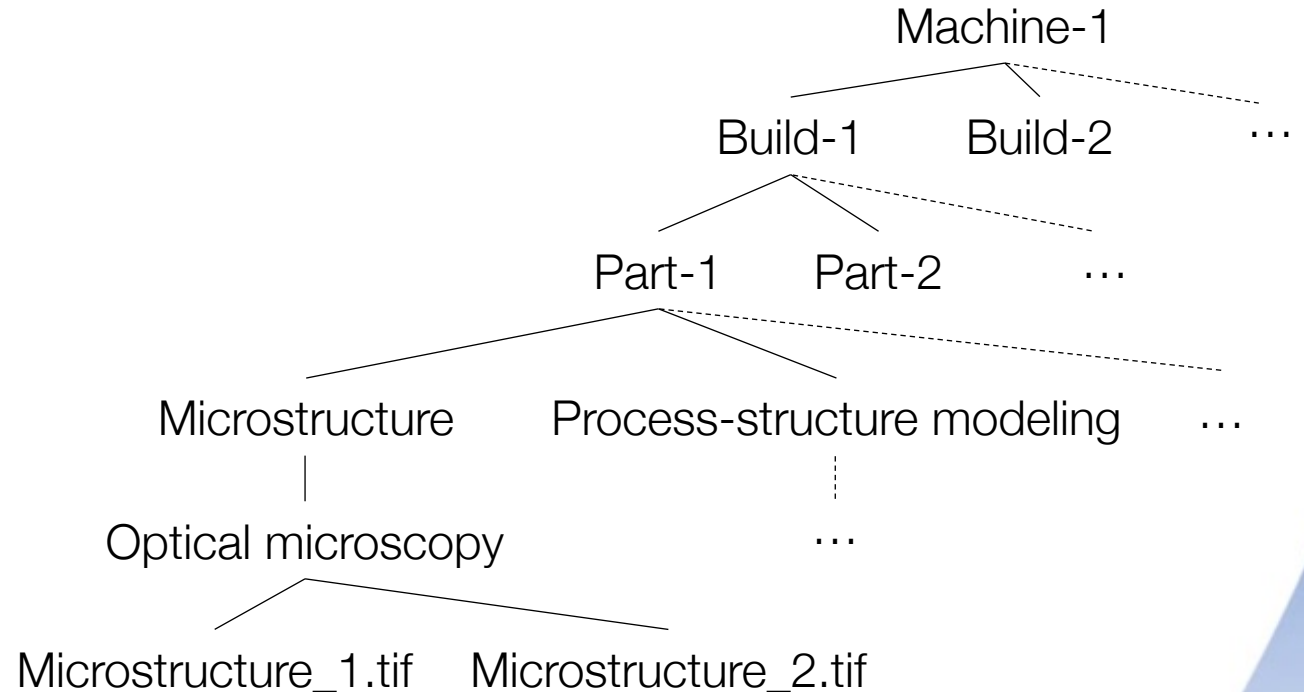
Comparison to a Hierarchical Data Structure



Pseudo-SQL Query

```
select images
from optical_microscopy as om
join part on om.part = part.id
join build where part.build = build.id
where build.x > 1 and build.x < 10;
```

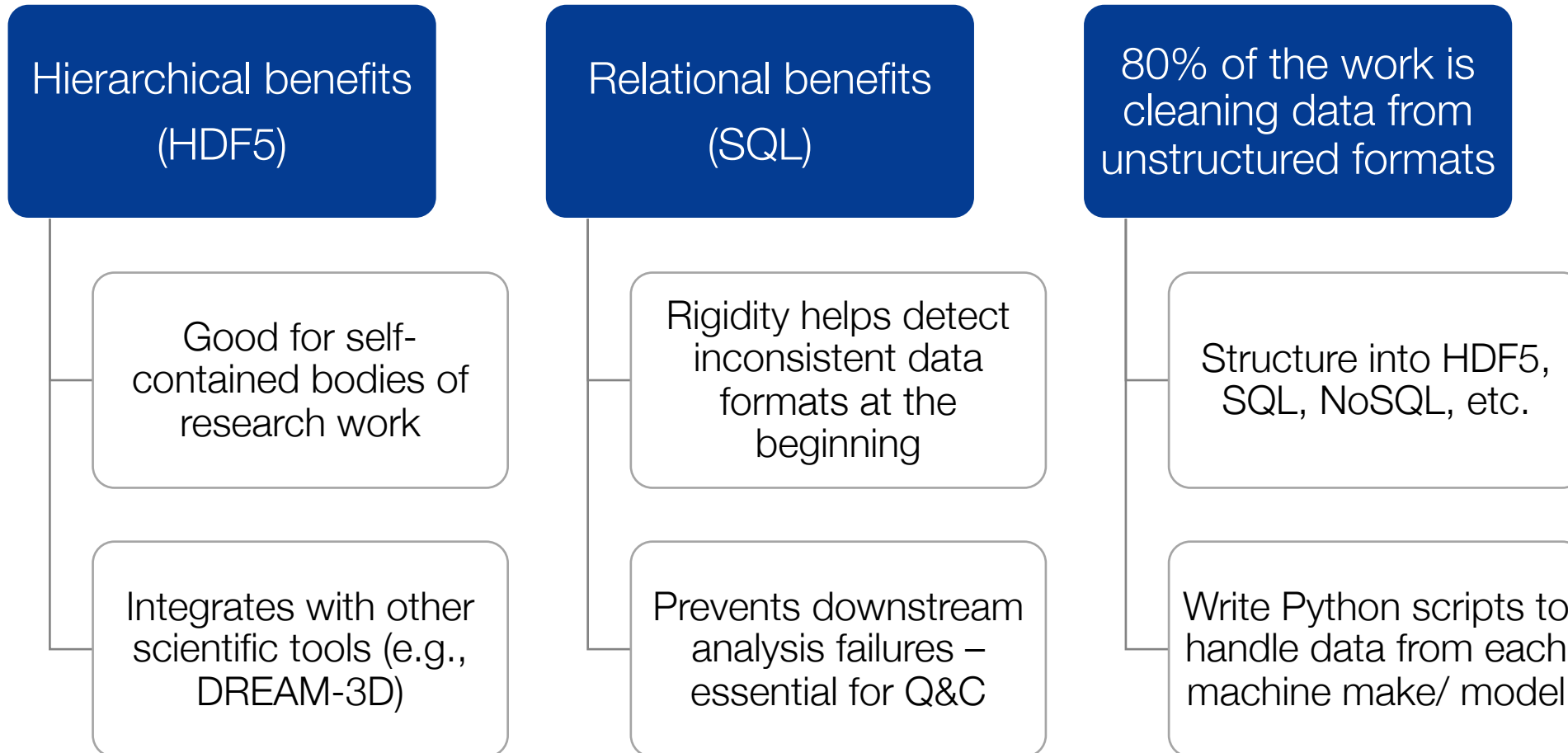
	images	part	build_location_x
0	microstructure_10.tif	1	1.4
1	microstructure_11.tif	1	2.0
2	microstructure_39.tif	2	2.6
3	...	...	...



But suppose we want to know if the part location on the build plate affects the microstructure?

Database design strategies

Organizing data



Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the software and hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available.



- Significant ongoing works:
 - HyperThought – Air Force Research Laboratory
 - Granta MI – ANSYS
 - Manufacturing Demonstration Facility - Oak Ridge National Laboratory
 - Additive Manufacturing Material Database – National Institute of Standards and Technology
 - Materials Commons – University of Michigan
 - Globus – University of Chicago
- Relevant standards mentioned today:
 - ASTM F3490-21
 - NASA-STD-6030



Relational models have longer term return on investment

Offers FAIR benefits



Data standardization addresses the academic-industry gap

Hierarchical structures are adequate
Relational structures offer a more targeted maturation pathway



Improving ICME maturity increases Q&C acceptance

Relational data structures offer ease of querying suitable for streamlined model validation and calibration