Design beyond imagination

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Defense Advanced Research Projects Agency

NSF Workshop

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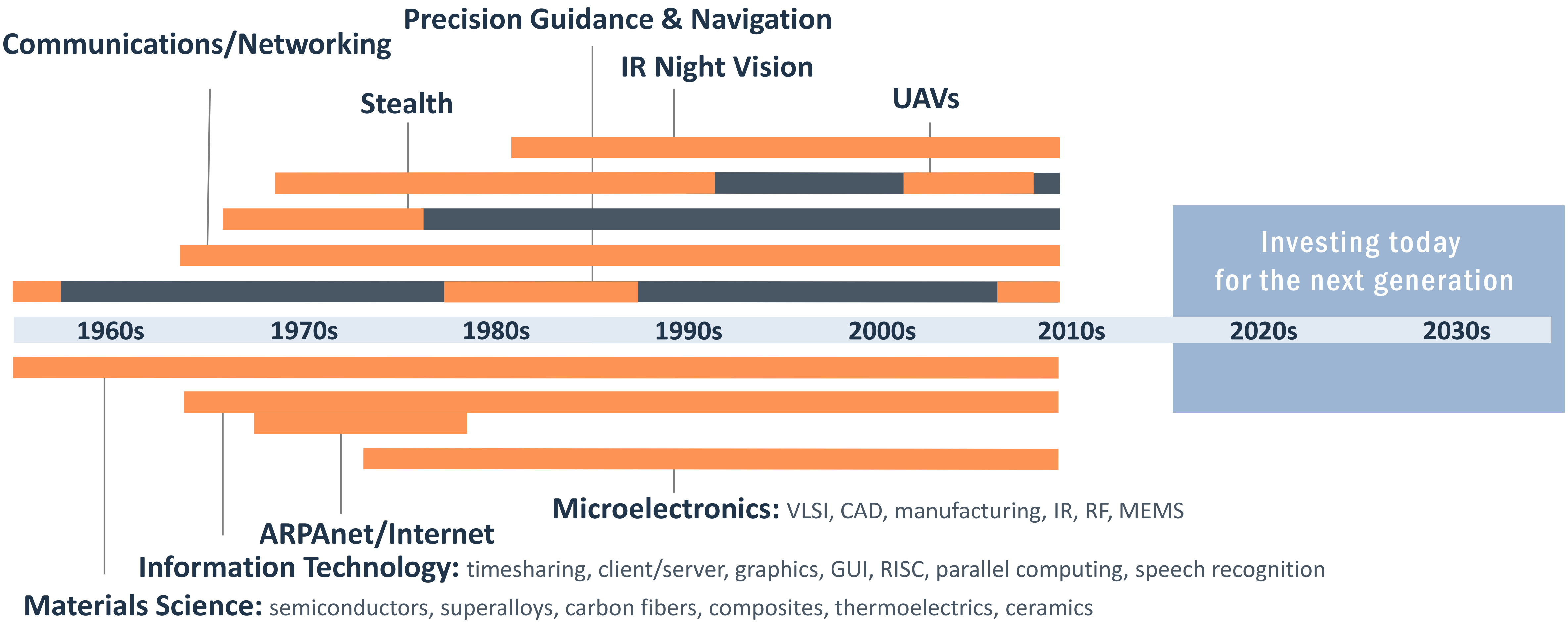
DARPA's Mission: Breakthrough Technologies For National Security



These new capabilities require a healthy ecosystem across Service S&T, universities, and industry

DARPA's role: pivotal early investments that change what's possible

DARPA's Portfolio

Multi-varied threats to the nation

Defend the homeland

Cyber deterrence
Bio threat detection and mitigation
Defense against WMT
Countering hypersonic weapons

Peer competitor confrontations in Europe and Asia

Deter and prevail against high-end adversary

Adaptive lethality for air, land & sea
Control of the EM spectrum
Long range effects
Robust space

Continuous counter-terrorism and counter-insurgency operations

Effectively prosecute stabilization efforts

Gray warfare experimentation
Behavior modeling & influence
3D city-scale operations
Warrior performance

Foundations

Understanding complexity, composable systems, advanced materials and electronics, trusted hardware and software, human-machine symbiosis, 3rd wave artificial intelligence, data and social science, new computing, and engineered biology

Increasing the pace of developing technologies and capabilities for the US and allied warfighter

DARPA Technical Offices

BTO — BIOLOGICAL TECHNOLOGIES OFFICE

Biology for Security
- Outpacing Infectious Disease
- Neurotechnology
- Gene Editing & Synthetic Biology

DSO — DEFENSE SCIENCES OFFICE

- Frontiers in Math, Computation & Design
- Limits of Sensing & Sensors
- Complex Social Systems
- Anticipating Surprise

I2O — INFORMATION INNOVATION OFFICE

- Symbiosis: Partner with Machines
- Analytics: Understand the World
- Cyber: Deter Cyber Attack

MTO — MICROSYSTEMS TECHNOLOGY OFFICE

- Electromagnetic Spectrum
- Tactical Information Extraction
- Globalization

STO — STRATEGIC TECHNOLOGY OFFICE

Win In Any Environment via Adaptive Kill Webs
- Sensing
- Comms, Command, Control
- Effects

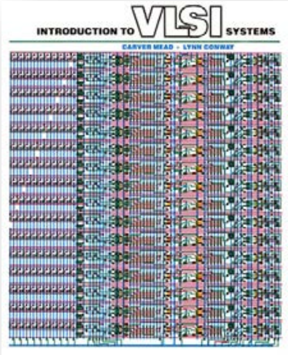
TTO — TACTICAL TECHNOLOGY OFFICE

Enterprise Disruption: Platforms, Systems, and Technologies that Enable New Warfighting Constructs

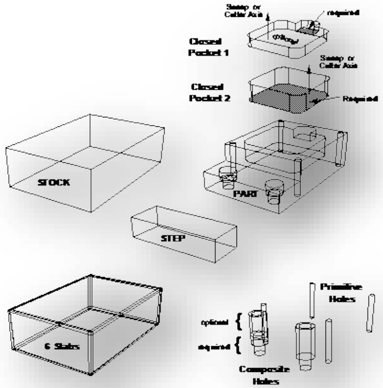
Crosscutting Themes
- Eliminate High-Value Assets
- Exploit Cross-Domain Seams
- Enable Decision-Making Asymmetry

My background: Design and manufacturing

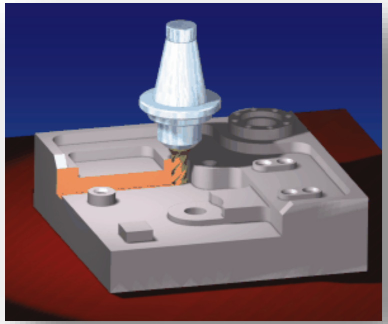
Materials is the common thread between design and manufacturing



VUB: EE/ME

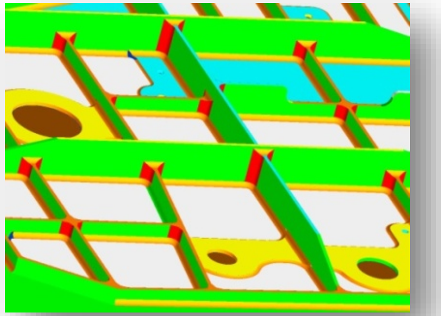


UofR: CAD → CAM

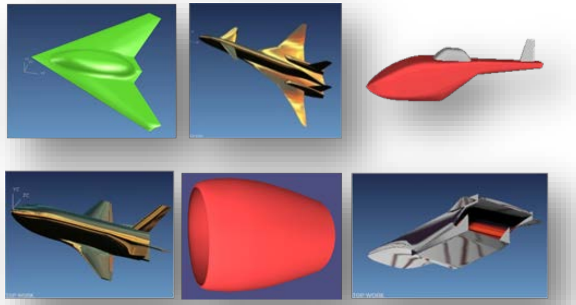


Unigraphics: CAM

Boeing



NC Automation



MDO

Composites

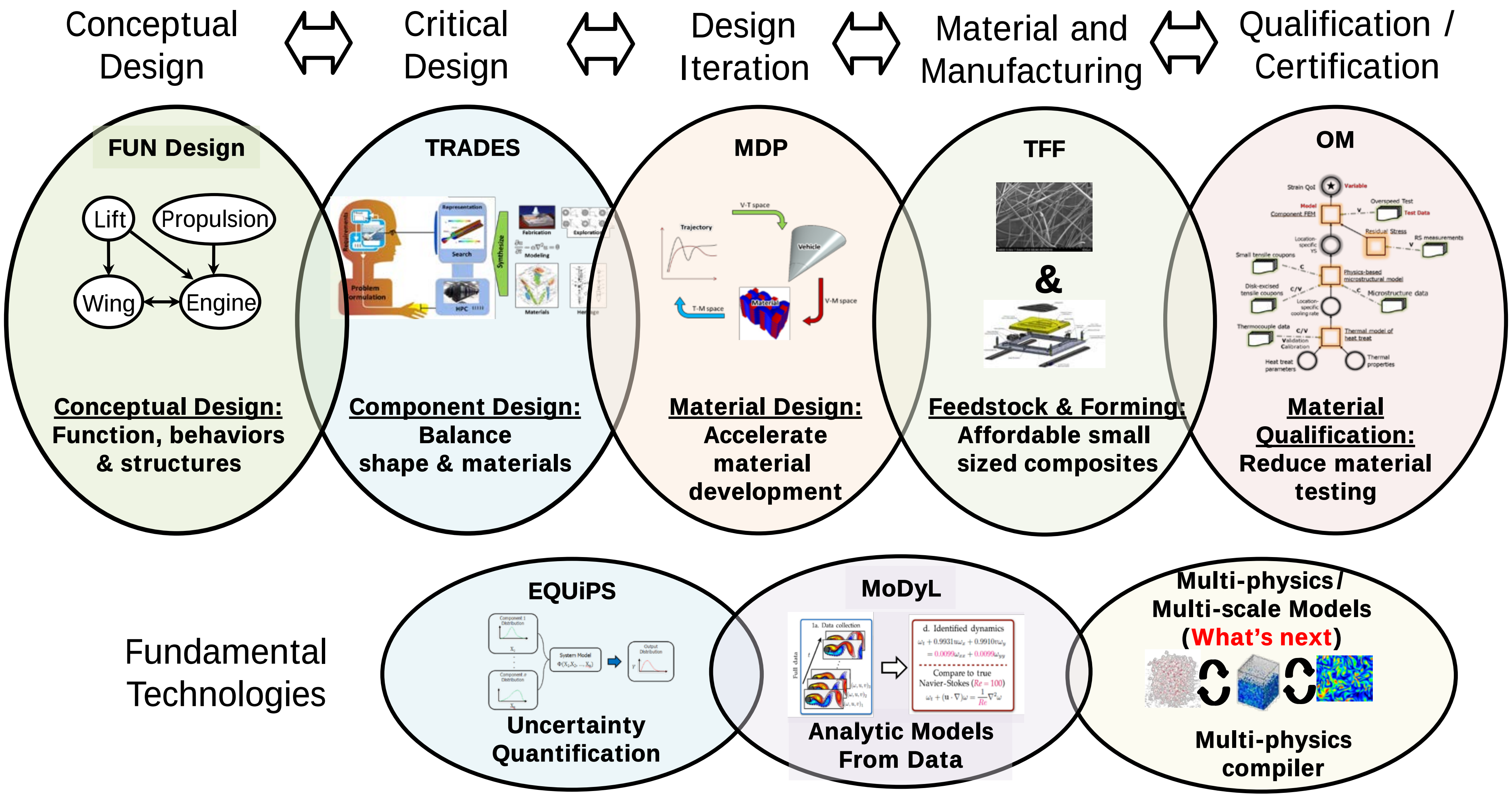
My interests: Design and build things better and faster

Discover radically new designs?

Leverage advanced materials & manufacturing?

What's next?

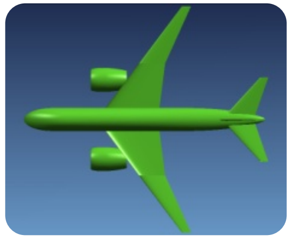
DARPA portfolio spans design-to-manufacturing cycle

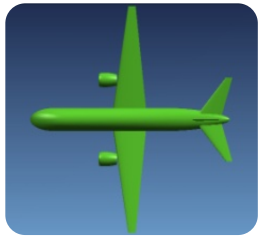
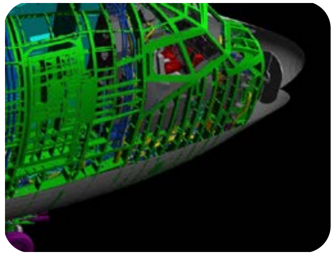


Design is accomplished in stages

Stage	Output
conceptual design function → behavior → structure	configuration Locks in >70% of life-cycle cost
preliminary design Optimal size, shape, position, materials	embodiment
detailed design manufacturing	parts & assembly



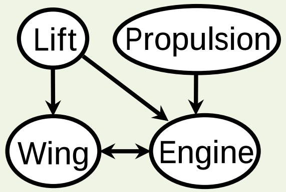



FUNdamental Design: Can computers find new design architectures?

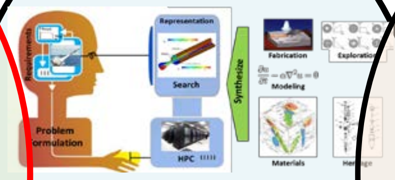
Conceptual Design ⟺ Critical Design ⟺ Design Iteration ⟺ Material and Manufacturing ⟺ Qualification / Certification

FUN Design



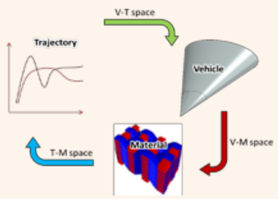
Conceptual Design:
Function, behaviors & structures

TRADES



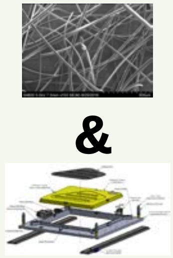
Component Design:
Balance shape & materials

MDP



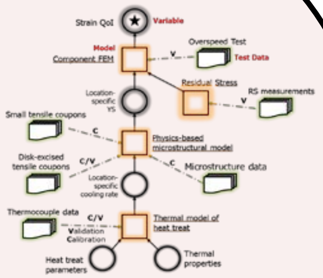
Material Design:
Accelerate material development

TFF



Feedstock & Forming:
Affordable small sized composites

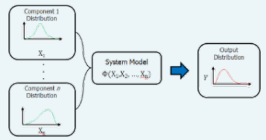
OM



Material Qualification:
Reduce material testing

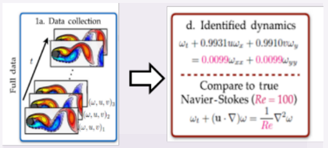
Fundamental Technologies

EQUiPS



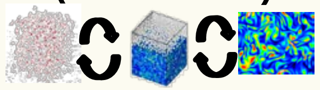
Uncertainty Quantification

MoDyL



Analytic Models From Data

Multi-physics / Multi-scale Models (What's next)



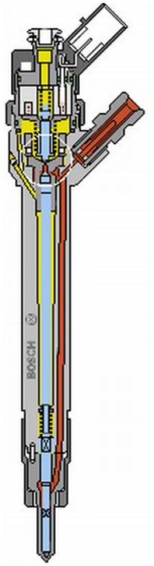
Multi-physics compiler

FUN(damental) Design: Rethink conceptual design

Establish conceptual design building blocks to enable exploration and discovery of novel & optimized designs

Enable generation of new designs

Carburetor
(Holley 0-82750 4150 Street HP 750 CFM Four Barrel Vacuum Secondary)



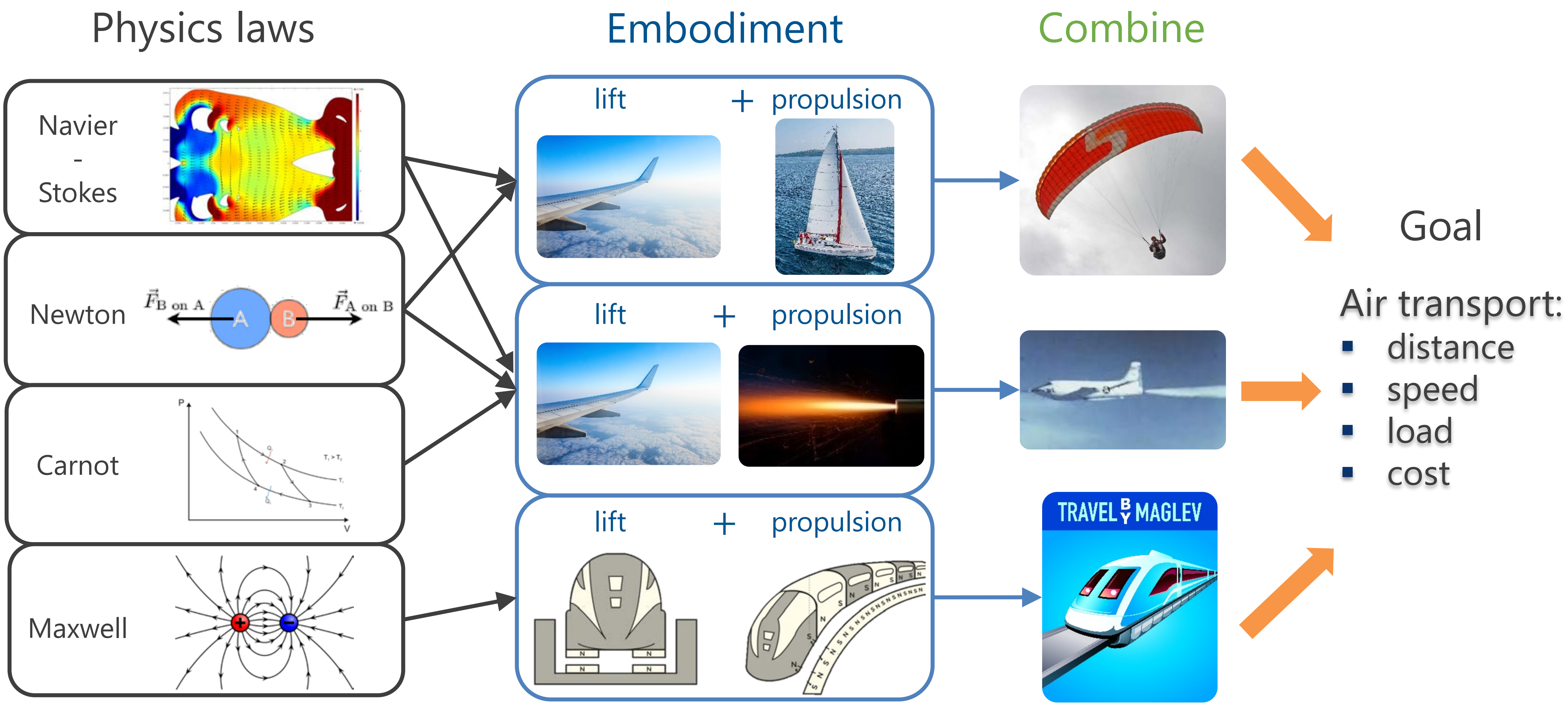
Fuel Injector
(Bosch)

Carburetors and fuel injectors perform the same function but in dramatically different physical realizations

Combine best of designs

+

FUN Design: How do you make computers reason about physics to achieve a goal?

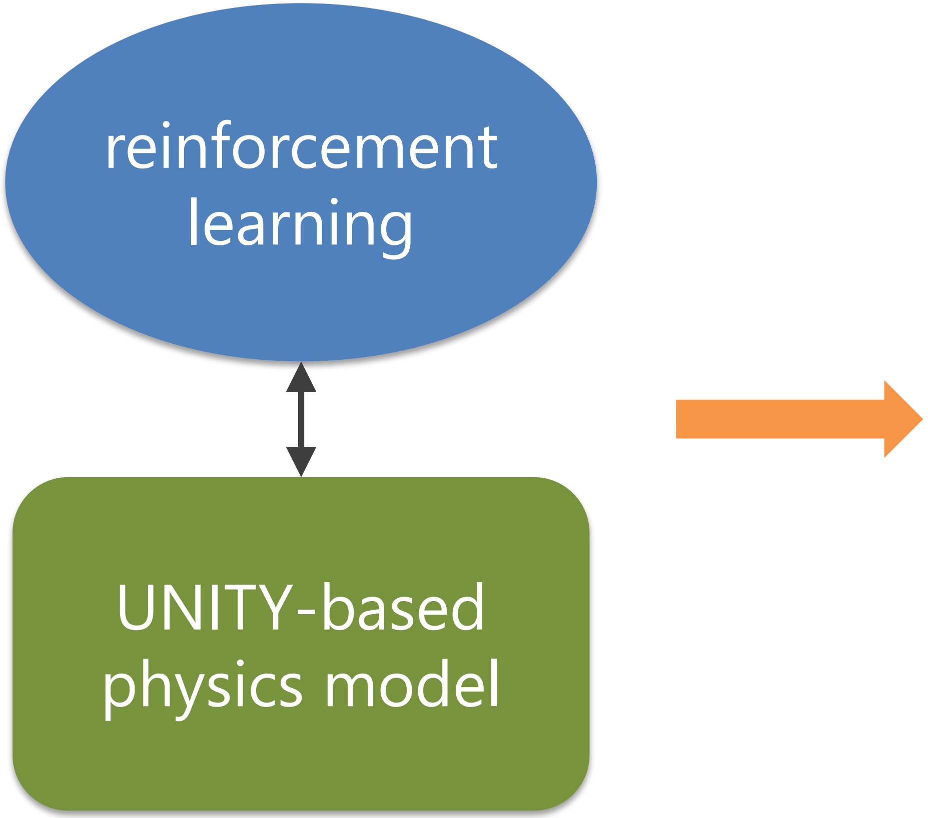


www.energy.gov/articles/how-maglev-works

PSU uses AI to explore physics to find new behaviors

Penn State: Yukish

Reinforcement learning & gaming simulation to discover new behaviors and modes of transportation



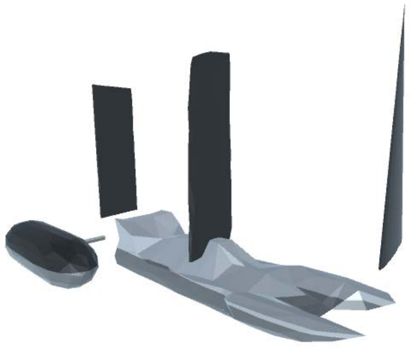
Discovered skipping flight path that repeatedly crosses the boundary layer to extract energy

View in presentation mode to see video

PSU: AI generated boats

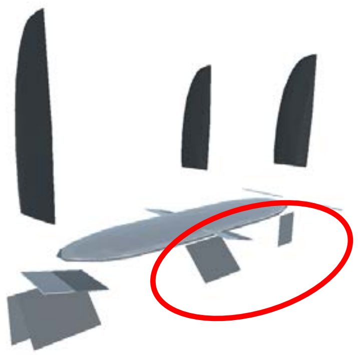
Penn State: Yukish

Initial design: Flat bottom



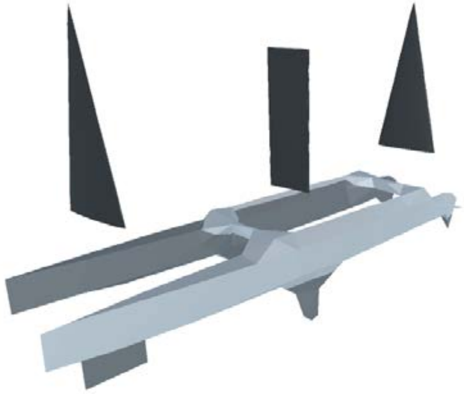
Capsizes

AI discovered keel & leeboards for stability

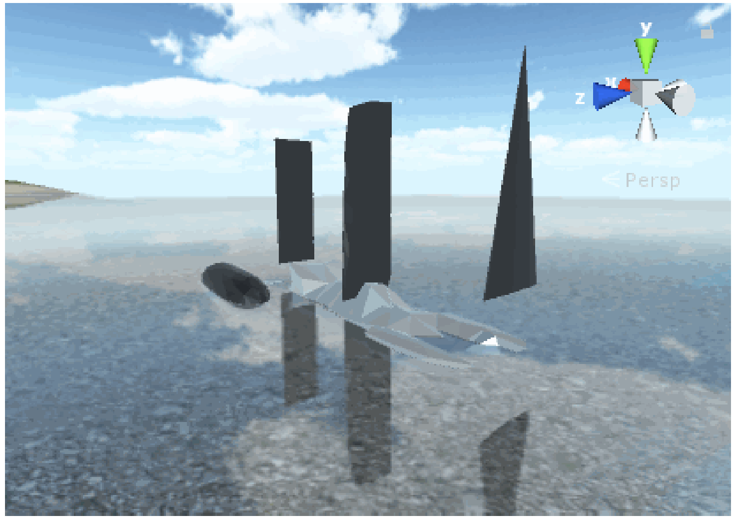


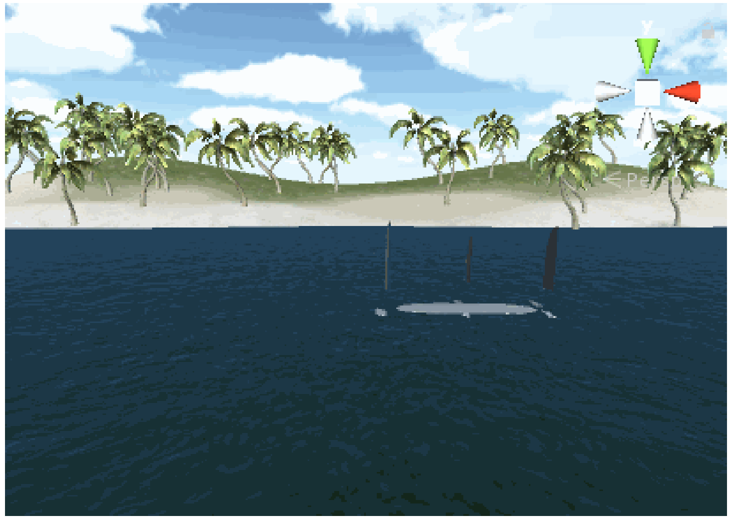
Capsizes with high waves

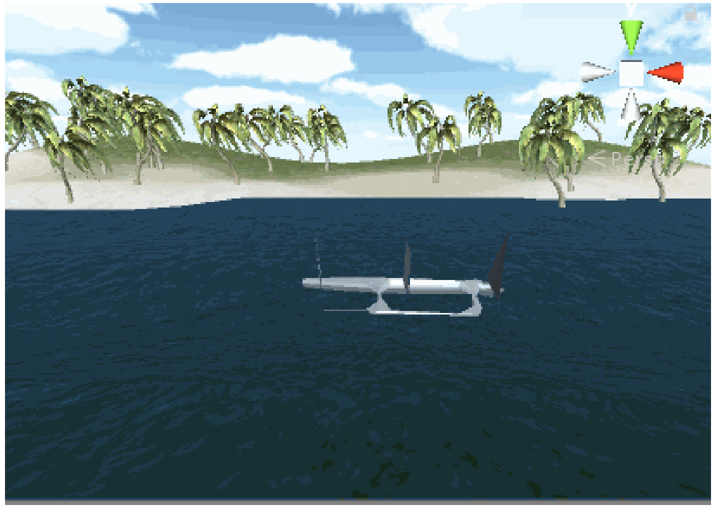
AI discovered dual hull



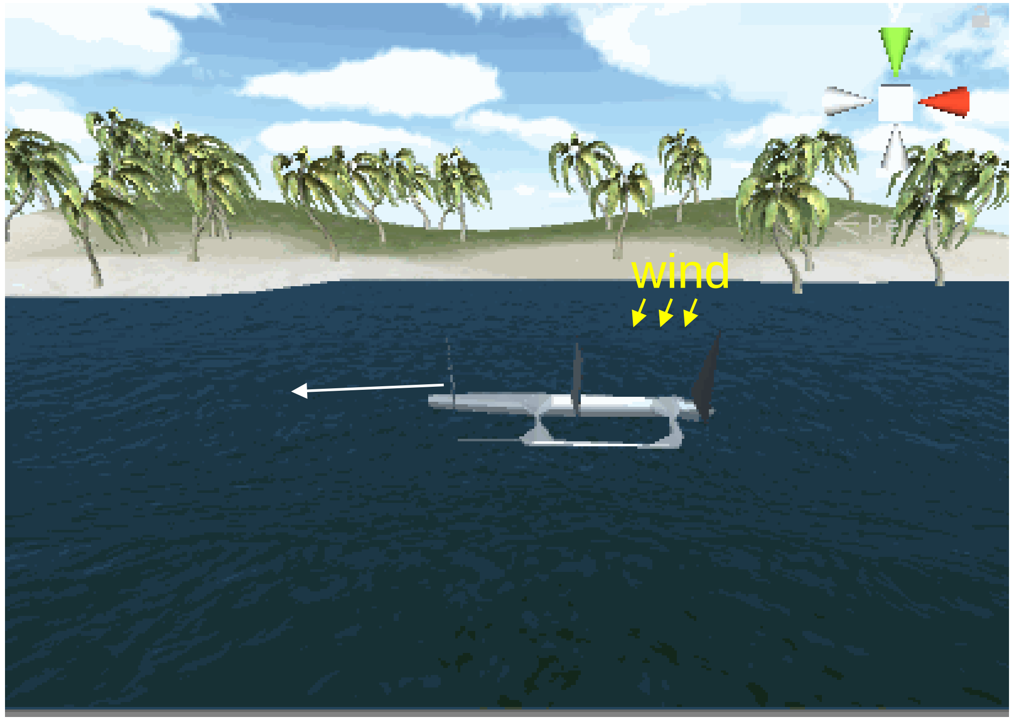
Crosswind travel with waves







Verification…



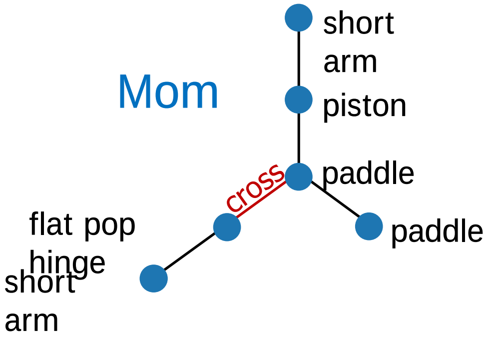
Verification

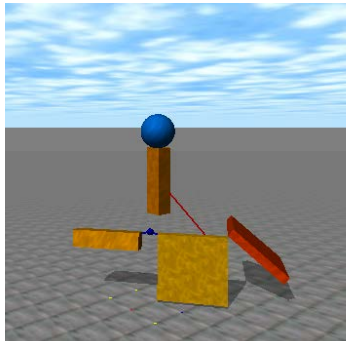
Metron: Leverage algebra of operads to mate and mutate designs

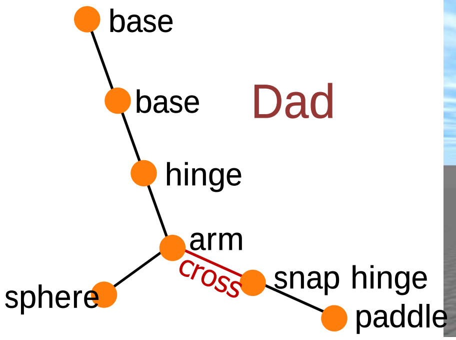
Imitate nature to cross link designs and improve species

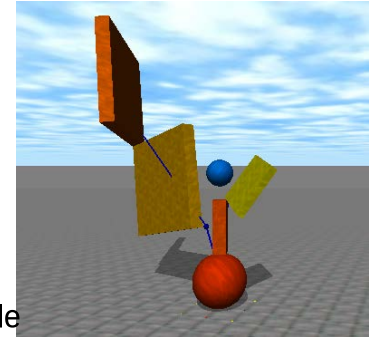
Source: METRON

Parents

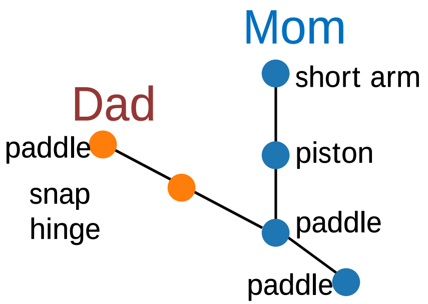


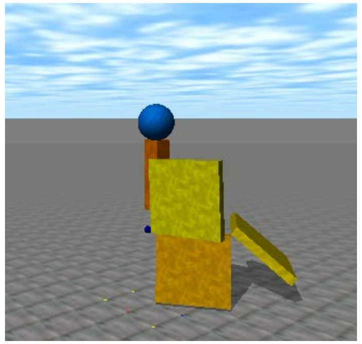


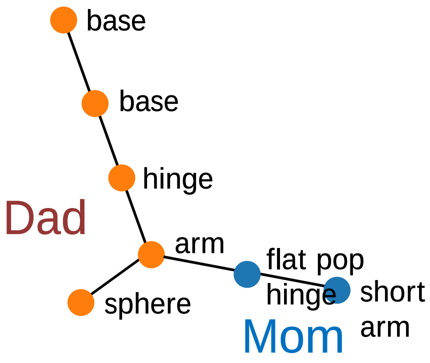


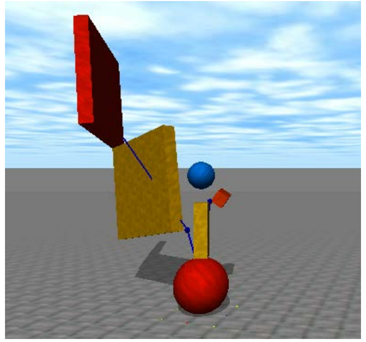


Children

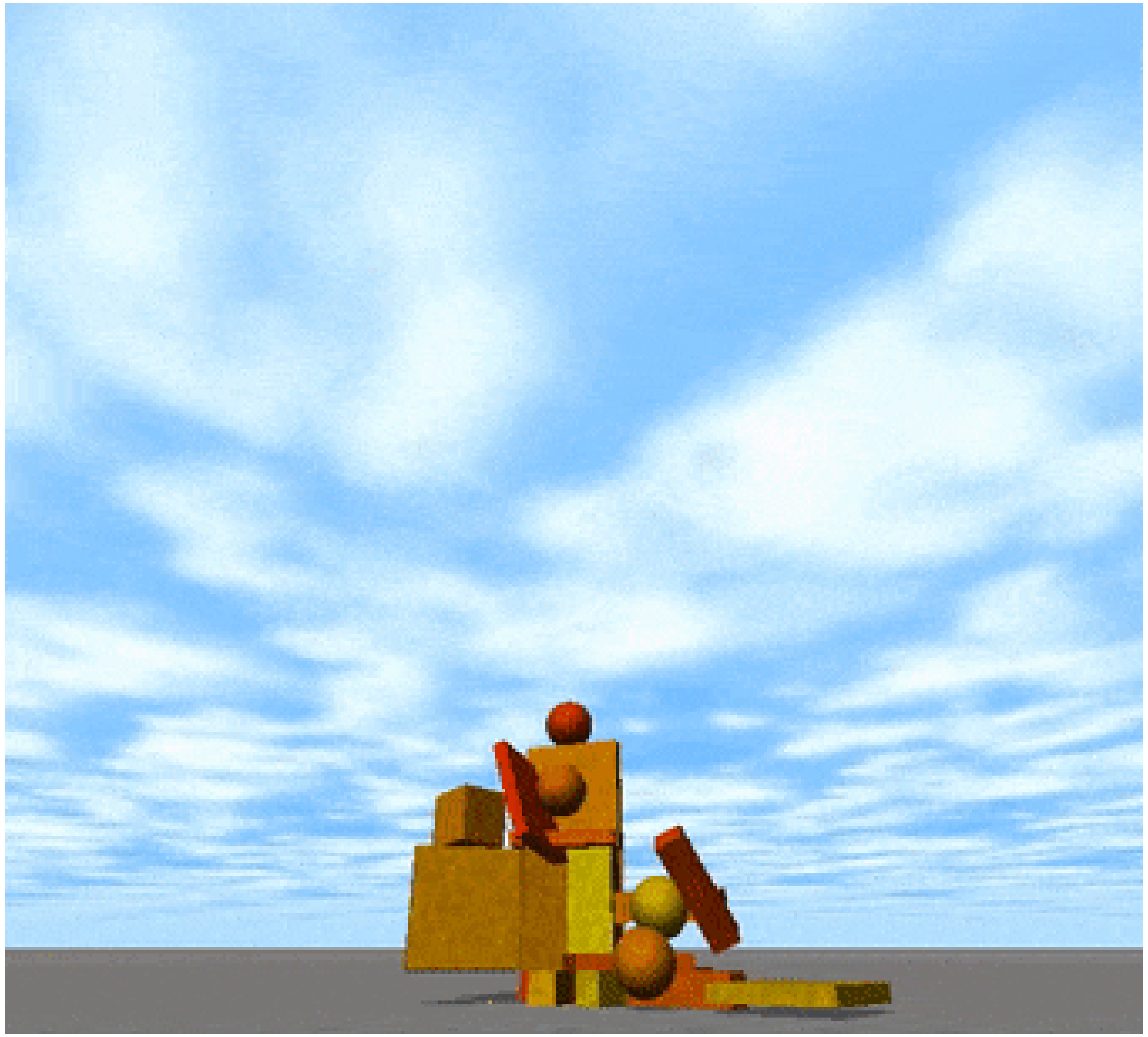








“Blooper Real”: Exploding Junk



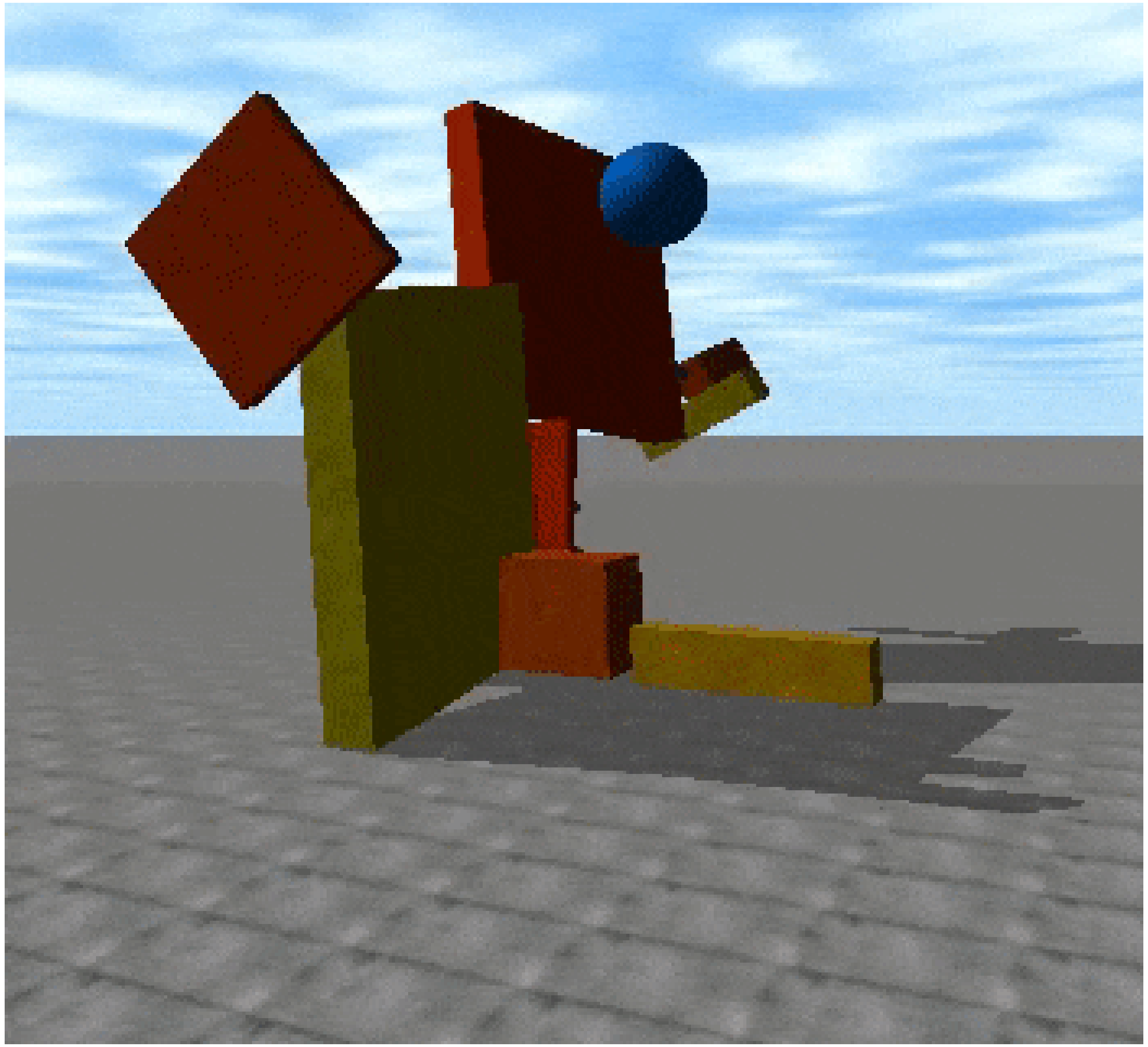
View in presentation mode to see video

AI discovered that negative distances (a bug in the program) resulted in infinite energy to fire the projectile.

It’s a clear demonstration that AI can exploit different physics to find unanticipated areas in design space

Metron: Godfrey

Blooper Real: AI discovers how to cheat

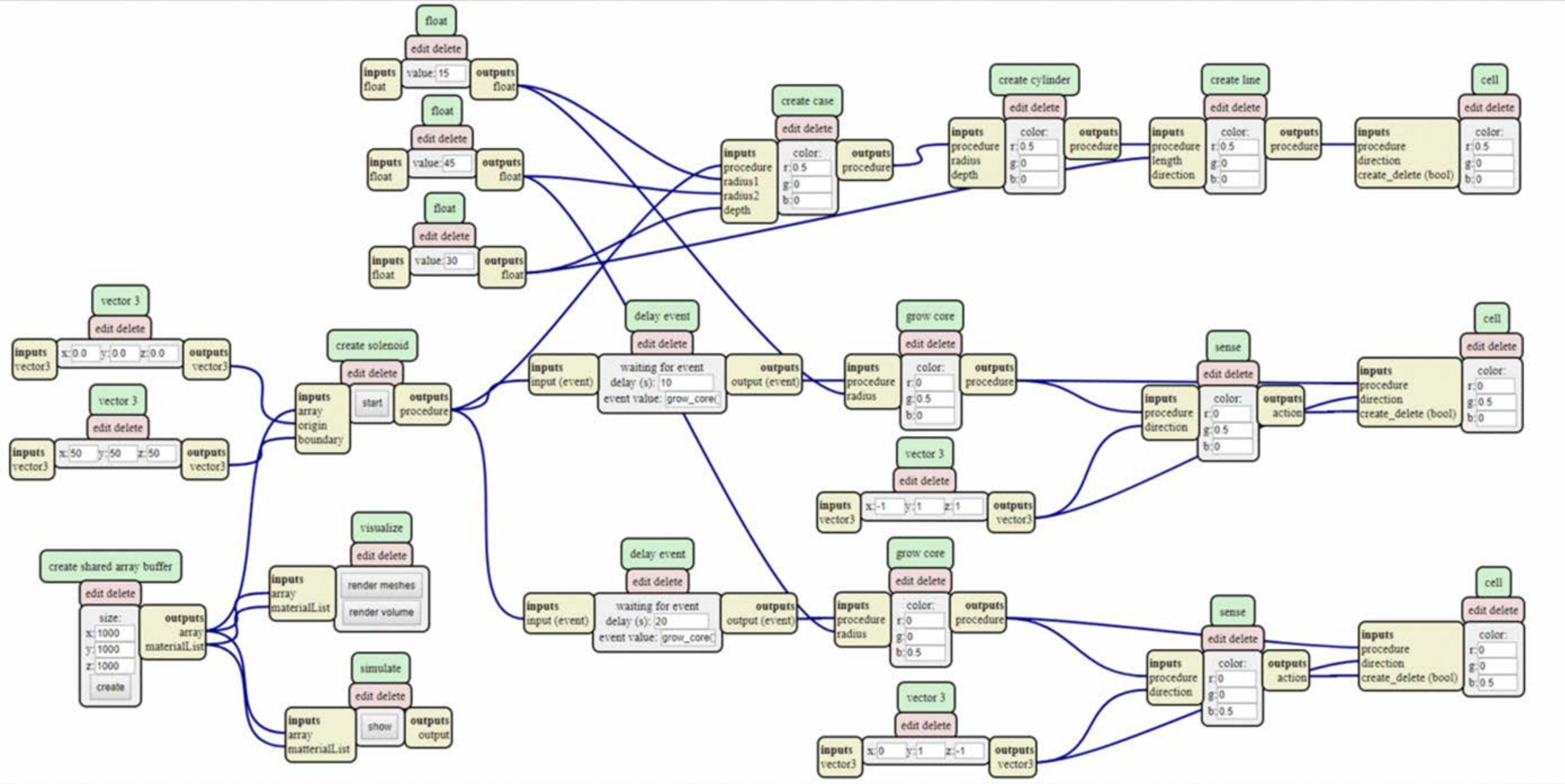


AI exploits loophole in rules to cheat!

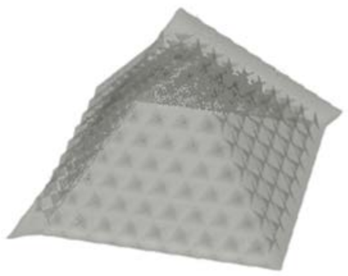
MIT: Use search over algorithms to design

MIT: Gershenfeld

Explore conceptual design space by searching over algorithms with self modifying graphs analogous to natural evolution



Designs are implicitly represented by algorithms with rewrite rules

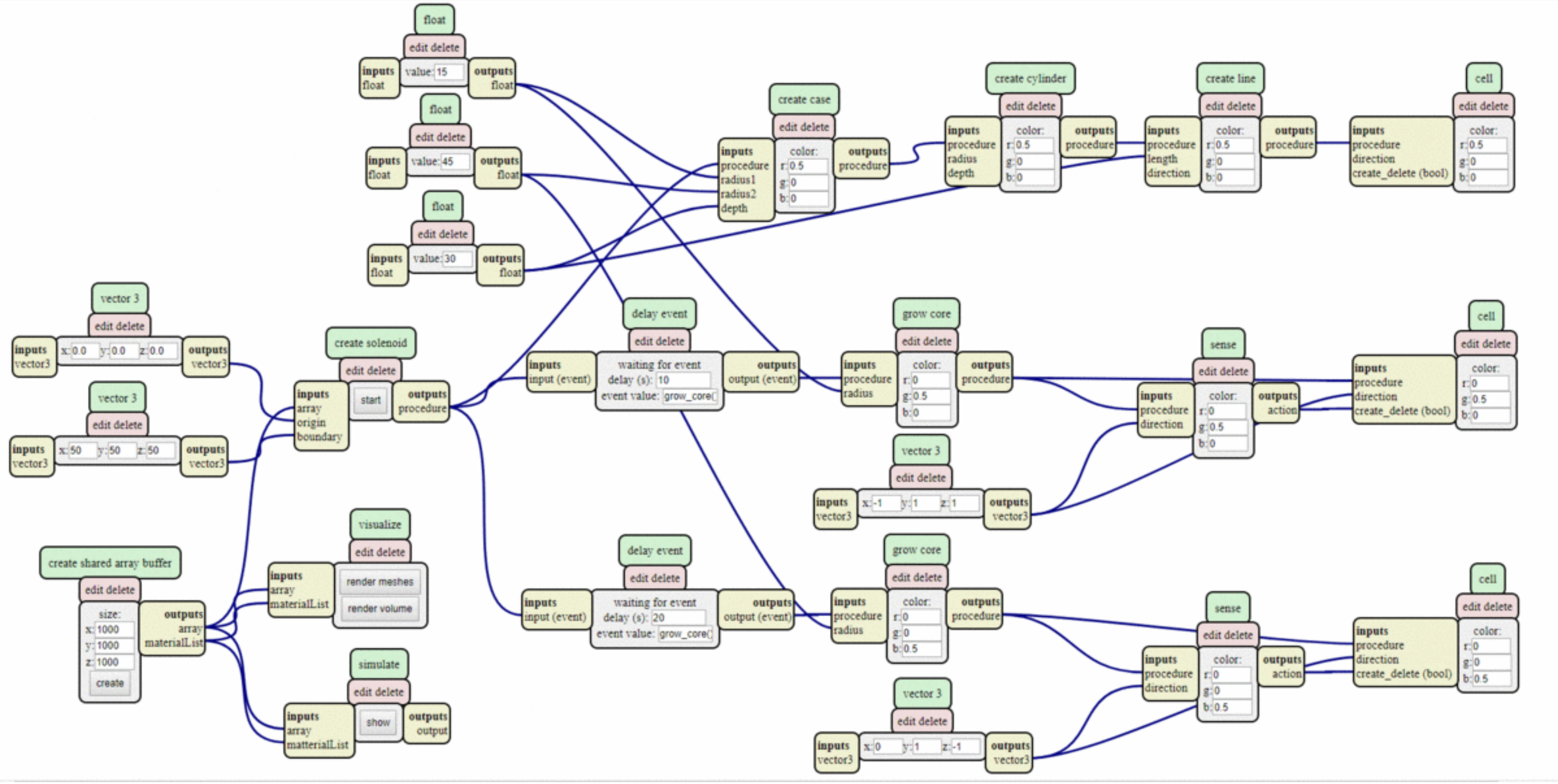


Growing a solenoid

MIT: Use search over algorithms to design

MIT: Gershenfeld

Explore conceptual design space by searching over algorithms with self modifying graphs analogous to natural evo



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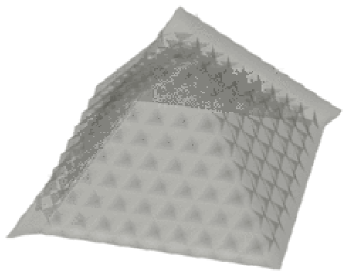
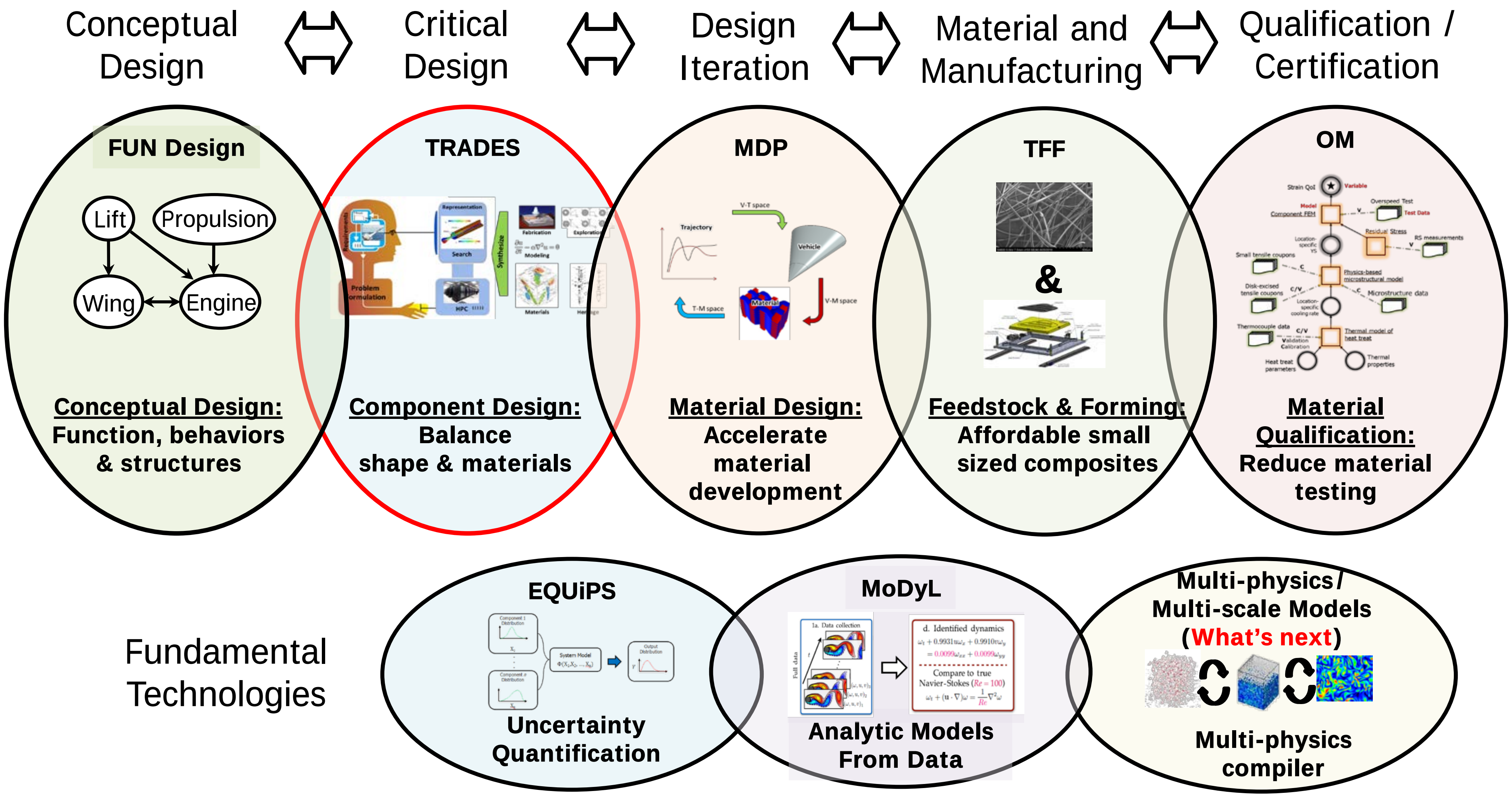


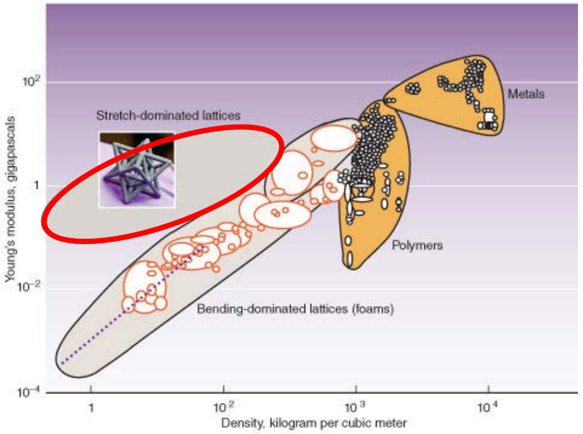
Growing a solenoid

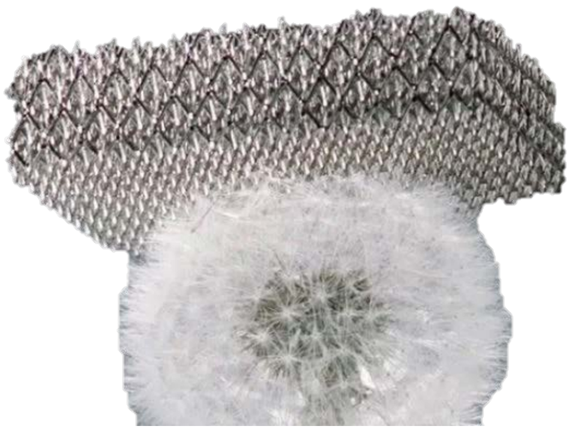
TRADES: Develop the math and algorithms to balance shape with materials for component design, basically next gen CAD systems



Breakthroughs in manufacturing enable precise control over material placement creating non-natural material behaviors

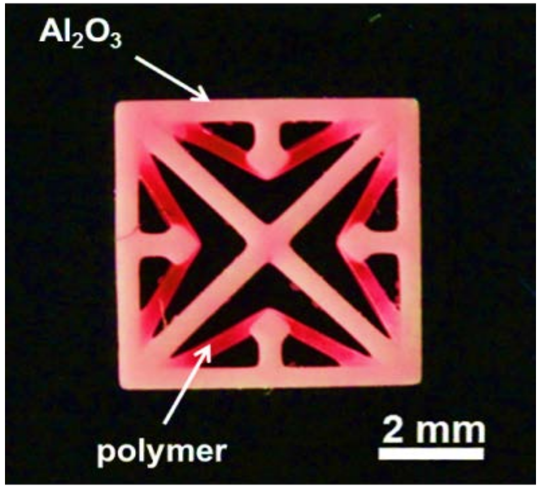
Material behaviors not found in nature

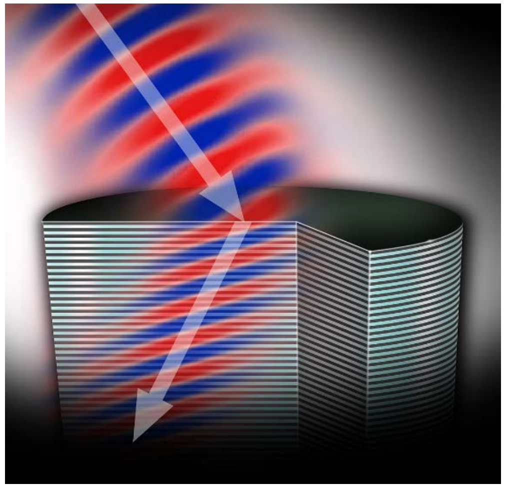




Super light weight structures

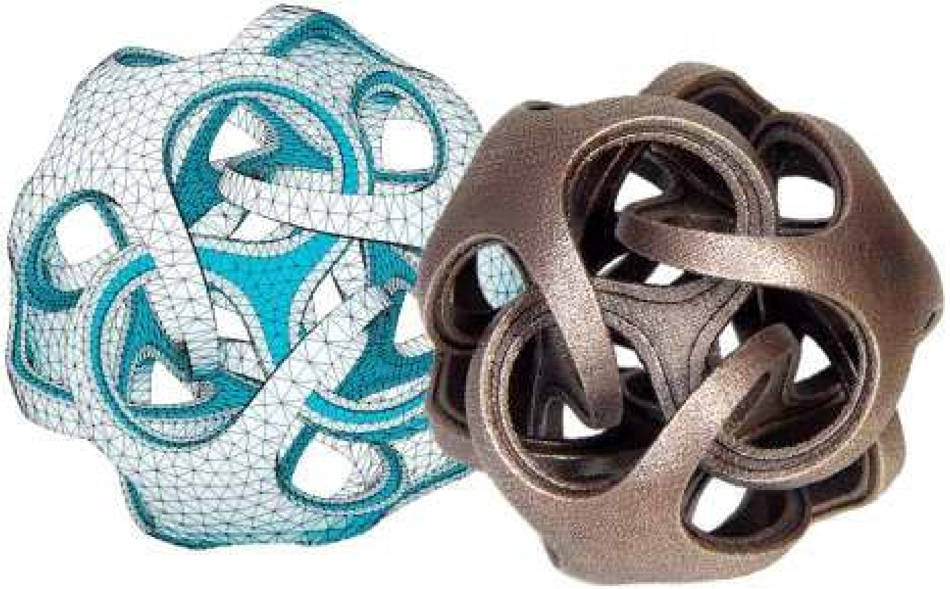
Negative thermal expansion





Negative refractive index

Complex shapes that were impossible or too expensive are now feasible



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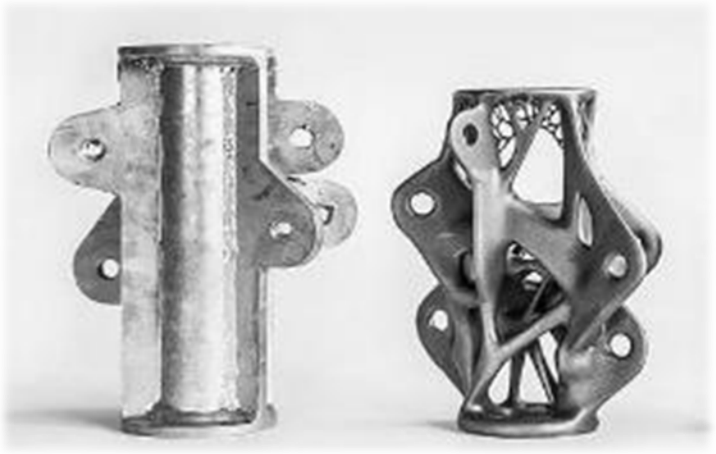
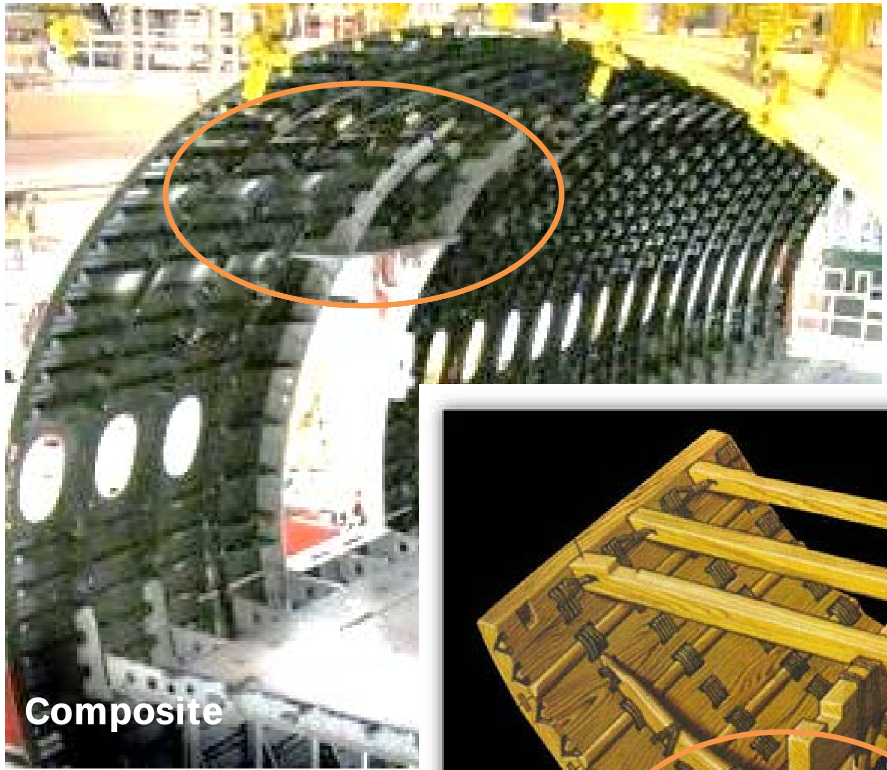
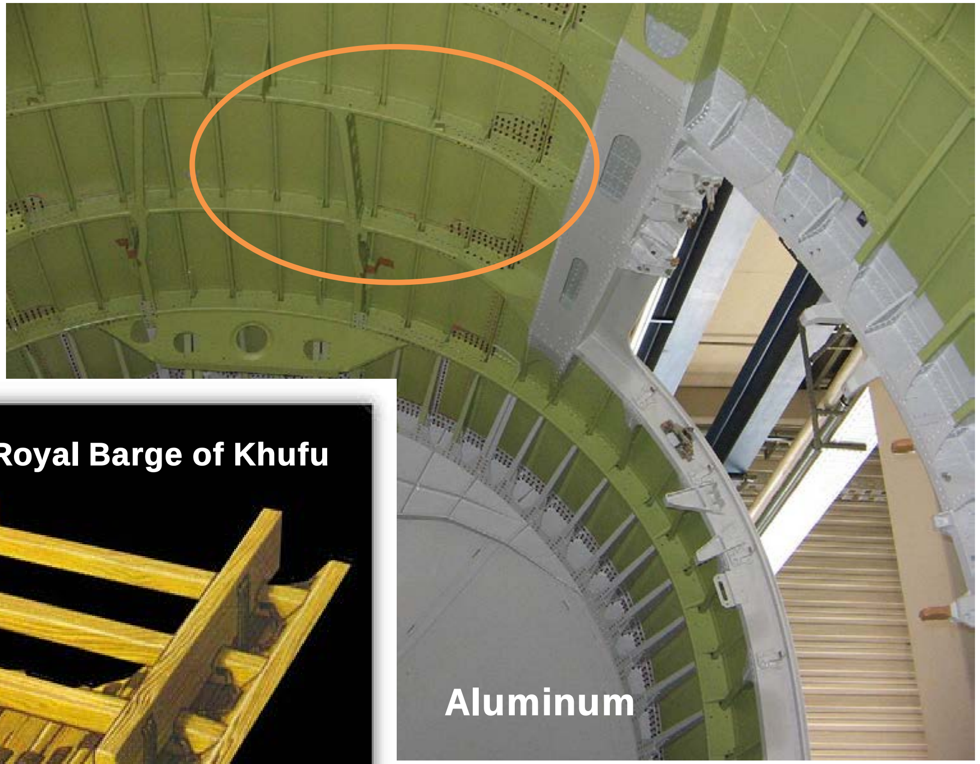
A more practical example



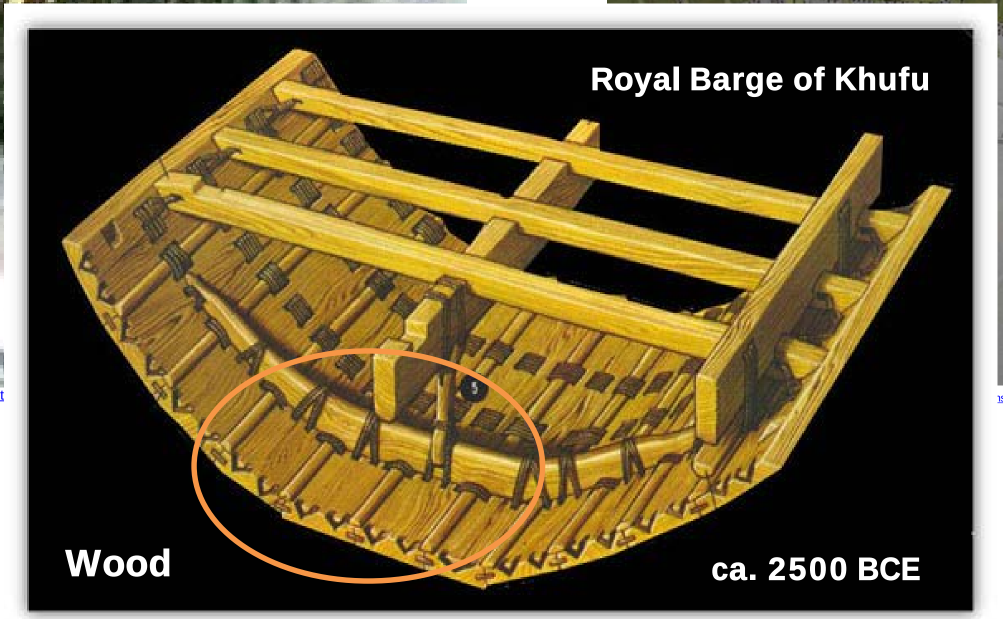
Reality: We don't really know how to leverage these advances



http://www.airbus.com/newsevents/news-events-single/detail/the-first



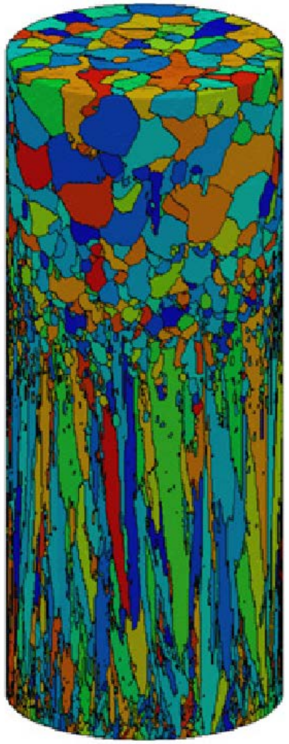
s.wikimedia.org/wiki/File:Airbus_A340_Int%C3%A9rieur_Fuselage_Arri%C3%A8re.JPG



http://nautarch.tamu.edu/class/316/khufu/

The basic problem with “manufactured” materials

3D printing results in different material structures than bulk materials

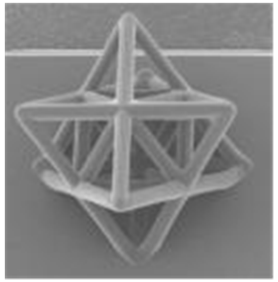


Even within the same print, the material structure changes due to thermal history

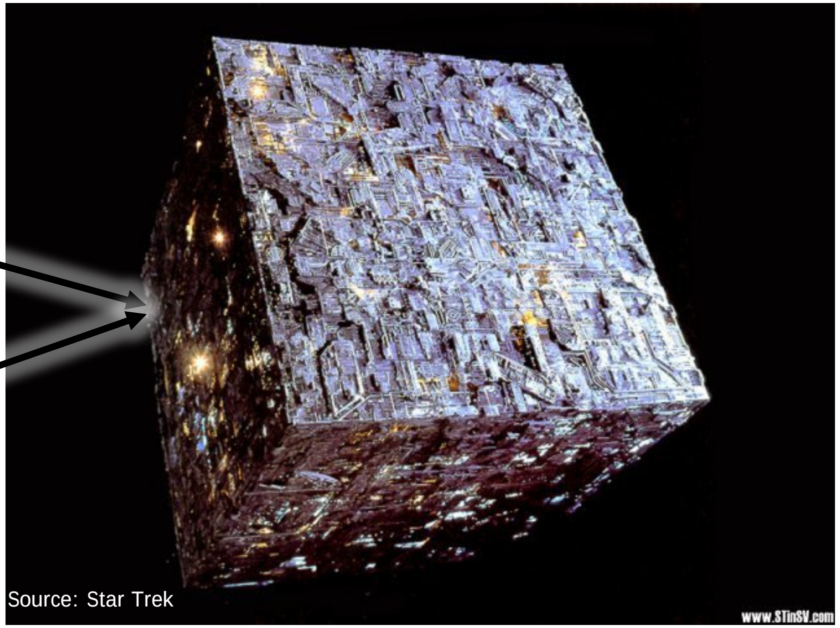
Carozzani et.al., Modelling Simul. Mater. Sci. Eng. **20** (2012)

How would you compensate for this?

We have also reached the limits of our design tools & our minds



.01 mm



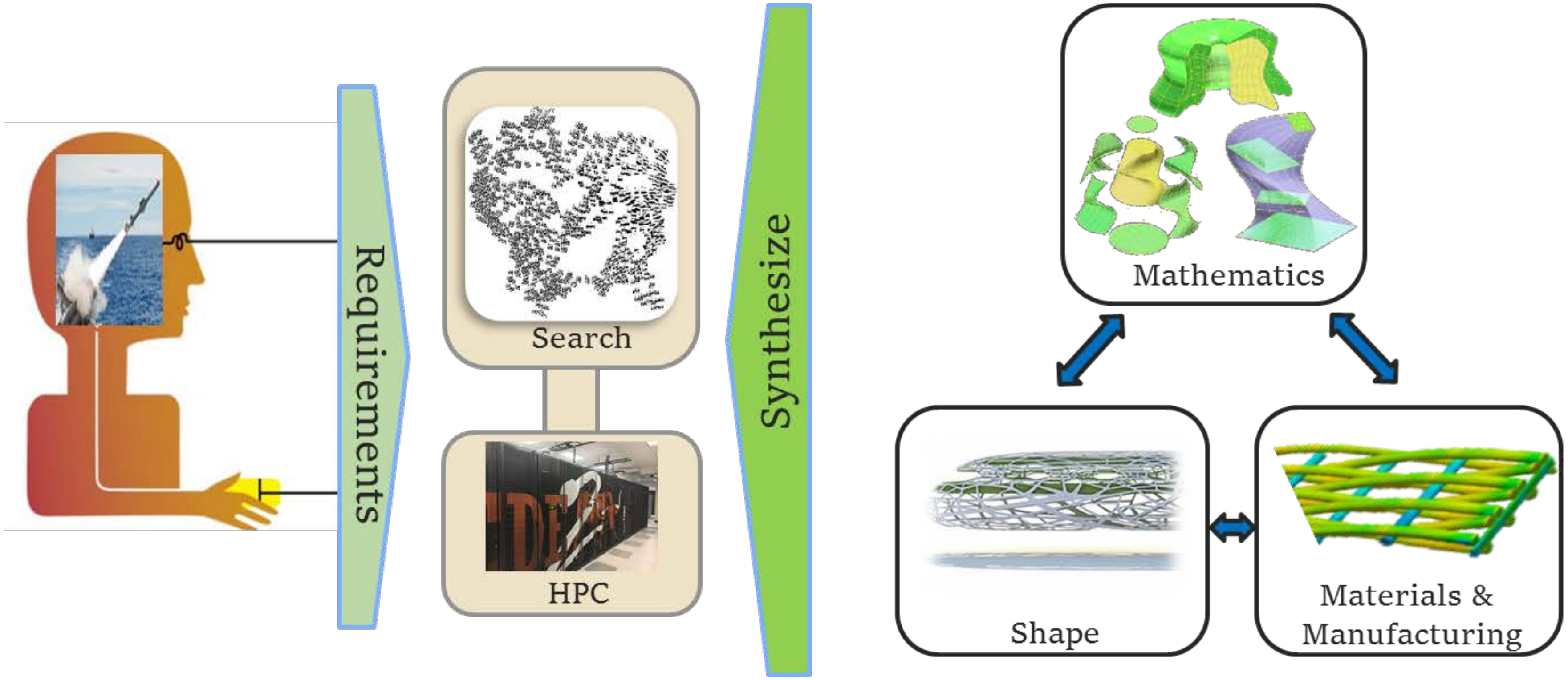
1 m

> 100,000 GBytes

RAM on most PCs: <128 GBytes

TRAnsformative DESign (TRADES): Make computers a true collaborative partner with human designers to synthesize designs unimagined today.

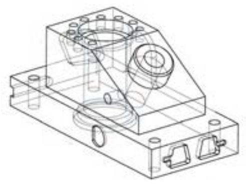
- Design tools have not kept up with advances in materials and manufacturing
- Complexity of design space exceeds existing systems and human capabilities



TRAnsformative DESign: How do you balance shape and materials?

State of the art

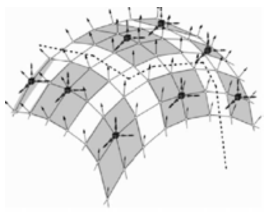
Modeling: Efficiently describe shape, material and their variations



Explicit
Data centric
≤3D

→ Multi-resolution (Animation)
Functional/Generative (CS)
≥3D (Math)

Analysis: Compute physical properties directly & reliably



Discretization
Finite element analysis

→ Direct analysis (Math)
Query based methods (CS)

Synthesis: Generate and find the best designs

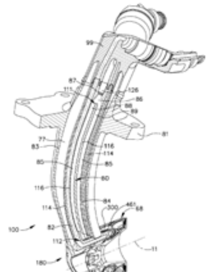


FIG. 3

Record

→ Optimization & Uncertainty (Math)
Design as coding (CS)
Machine learning (AI)

Seamless integration

Future

Example program metrics to measure success

TRADES program metrics:

- Modeling, complexity, and response speed assessed against industry incumbents using nominal HPC cluster
- Multi-physics, interoperability and required computer-human interaction assessed against state of the art design tools

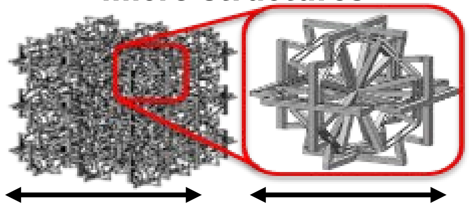
Program Metric	State of the Art	Threshold	Objective
Usable level of detail in physical scale difference	$\leq 10^5$	$>10^6$	$>10^8$
Object complexity (Shape + Material)	No material, 10^5 to 10^9	$>10^{12}$	$>10^{15}$
Computational efficiency (e.g., Simulating high fidelity physics)	Hours to weeks	minutes	seconds
Multi-physics design	Indirect through design-test	Sequential	Coupled
Material architecture and shape generation for multi-physics challenge problems	Does not exist	>2 Physics	>3 Physics, with uncertainty
Interoperability	Manual intervention	Automated	Direct
Computer-human interaction	Experienced (> 10 yrs) professional required to generate and model non-trivial design solutions	Semi-professional required	Non-professional

The type of challenges addressed by TRADES: multi-scale, multi-material, multi-physics

Model shape & materials at scale:

Problems:

Model 1 m^3 of micro structures

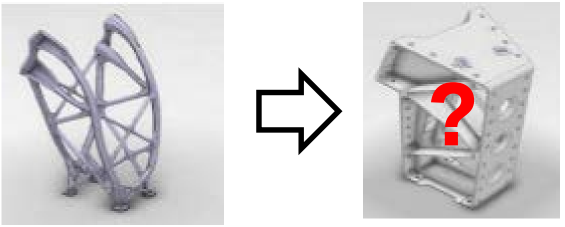


1 m

- .01 mm

Model a femur

Material substitution



Ti-6Al-4V

Al 7075

Challenge:

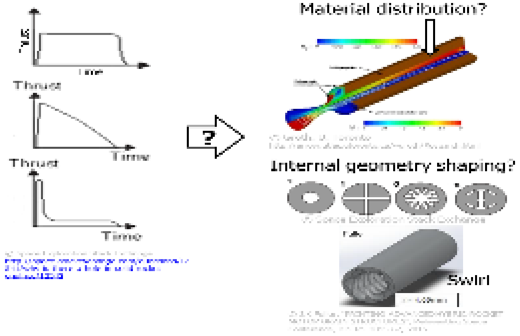
- Complexity exceeds SOA
  - Required = 100,000 GBytes
  - Available = <128 Gbytes
- Semi-stochastic material distributions

Reshape object with different material

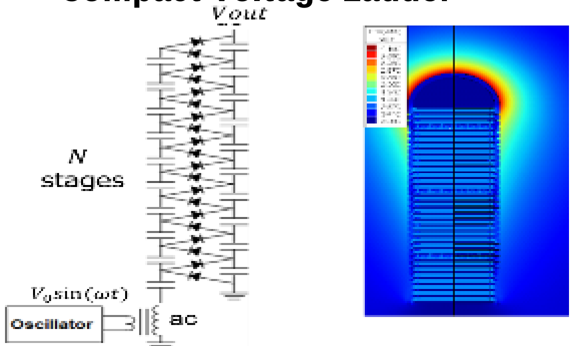
Synthesize shape and materials subject to multiple (non-traditional) physics:

Problems:

Solid Rocket Motor



Compact Voltage Ladder



Challenge:

Balance propellant distribution to eliminate solid rocket motor casing

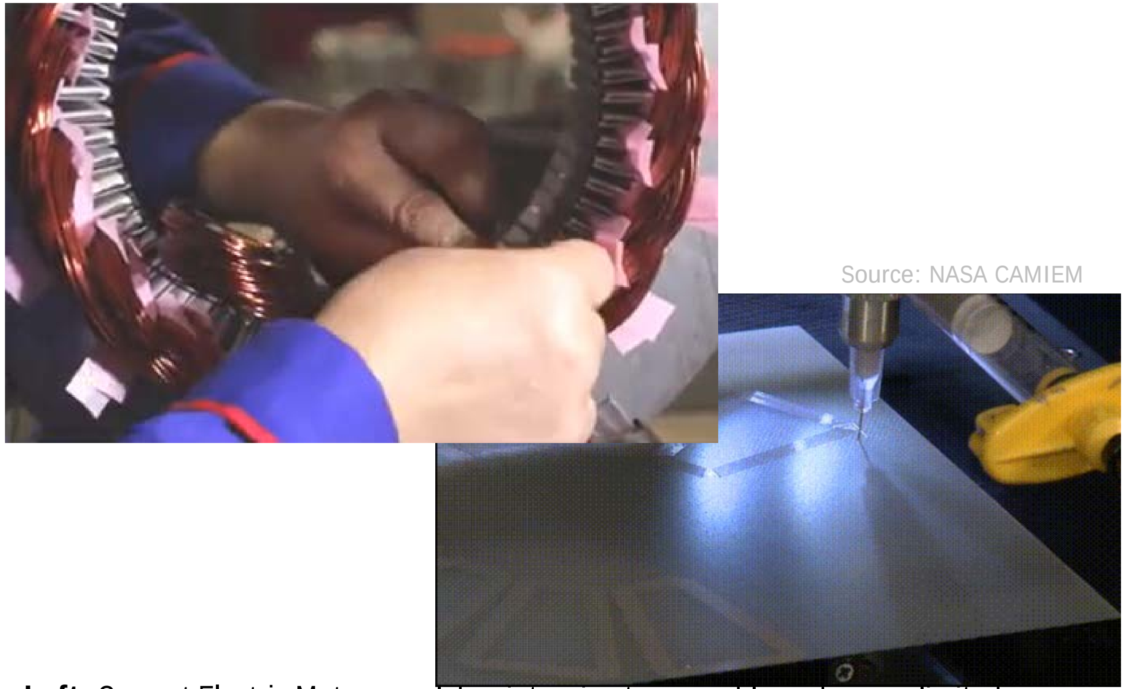
Design compact 4MV voltage ladder by optimizing dielectric distribution

Final challenge problems released to force generality and evaluate viability of approach

Focus: Incorporating variability and uncertainty in shaping & material

Challenge Problem 5: Printable Electric Motor

Objective: Design a 3D printed Electric Motor with the optimal layout of conductors, magnetic materials and cooling ducts



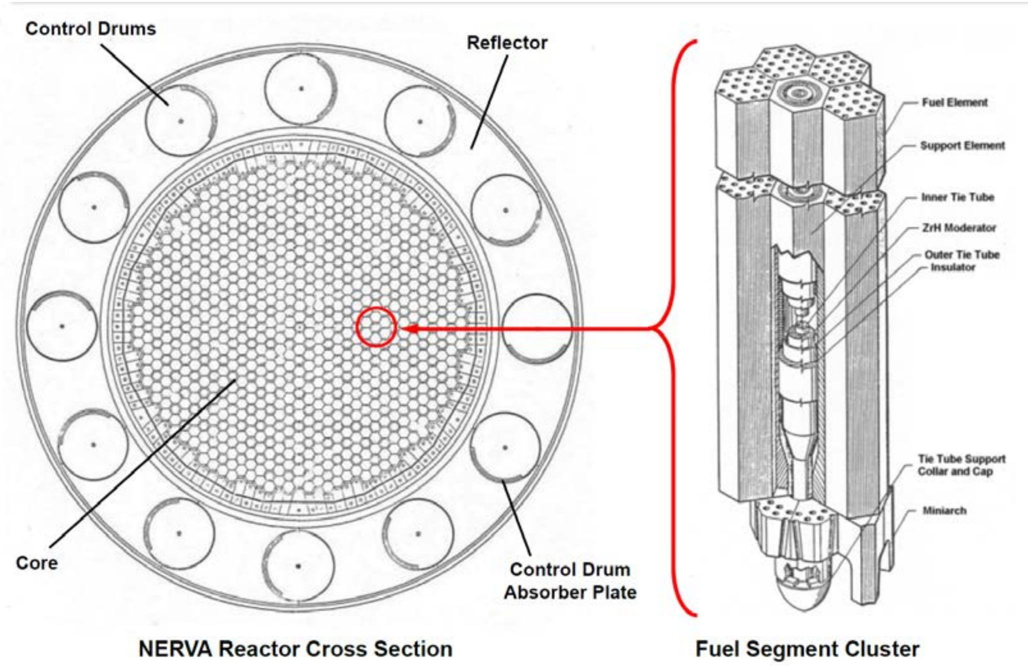
Source: NASA CAMIEM

Left: Current Electric Motors are labor intensive to assemble and power limited
Right: The ability to print electric motors can increase efficiency and power density

Challenge: Manage variability of EM field as a result of uncertainty in shape and material

Challenge Problem 6: Nuclear Thermal Rocket (NTR)

Objective: Design and optimize flow-path for NTR reactor to maximize thrust



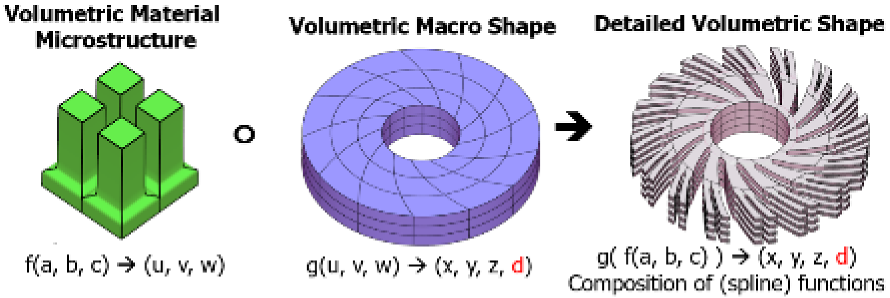
Source: NASA

Challenge: Maintain controllable fission while accommodating material variability

TRADES highlights: New representations enable efficient multi-scale modeling

High-dimensional math

U Utah (Technion, Syracuse U, MIT): Riesenfeld

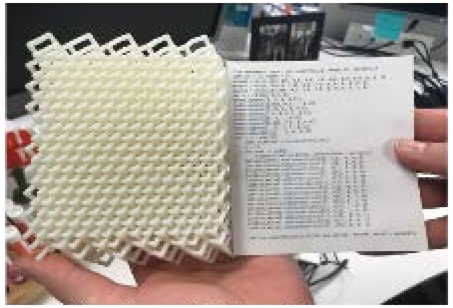


Approach: Leverage higher dimensional mathematics to combine shape & materials in volumetric design & analysis

Accomplishment: Unified representation of shape and architected materials

Design as a program

Siemens (GA Tech, MI State, PARC): Musuvathy



A lattice and its parameterized procedural representation

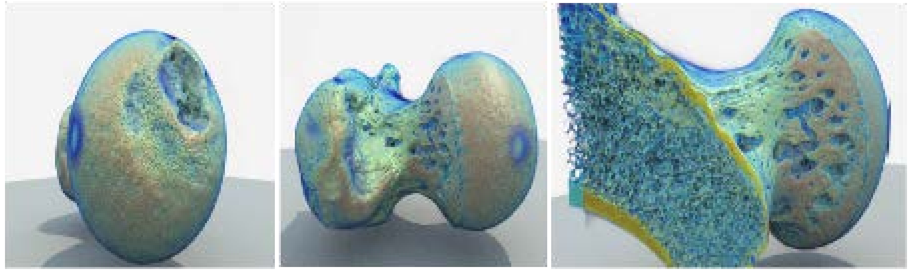
Lattice model inspired by NASA spring tire and modeled with parameterized procedures

Approach: Represent shape and material structures as programs to express designs that are **1,000,000x** more complex

Accomplishment: Interactive computations on massive structures lattice $(10^{12} — 10^{15}$ beams) on SOA workstation

Sparse voxel representations

PARC (Intact, Intact, OSU): Nelaturi



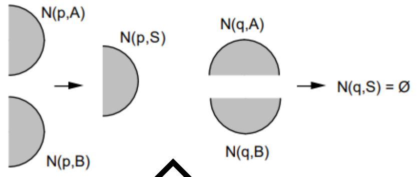
Approach: Leverage sparse representation techniques from animation to represent fine details in the context of large components

Accomplishment: >100x reduction in memory requirements and speed up in computations

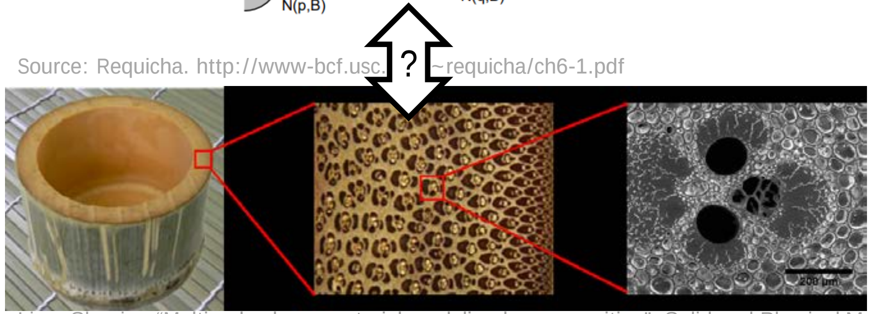
TRADES highlights: Rethinking solid modeling at scale

Multi-scale point membership classification

ICSI: Shapiro



Source: Requicha. http://www-bcf.usc.edu/~requicha/ch6-1.pdf



Liua, Shapiro, "Multiscale shape-material modeling by composition", Solid and Physical Modeling, 2018

Approach:

- Material and geometry are no longer independent
- PMC depends on the scale of the neighborhood
- Material properties correspond to the (homogenized) averages

Impact:

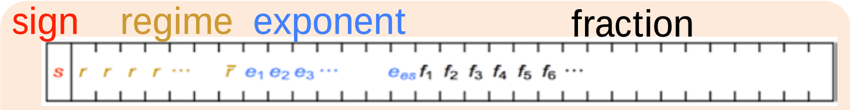
- Supports virtually unlimited resolution
- Mathematical rigorous approach to extend solid modeling

Challenges:

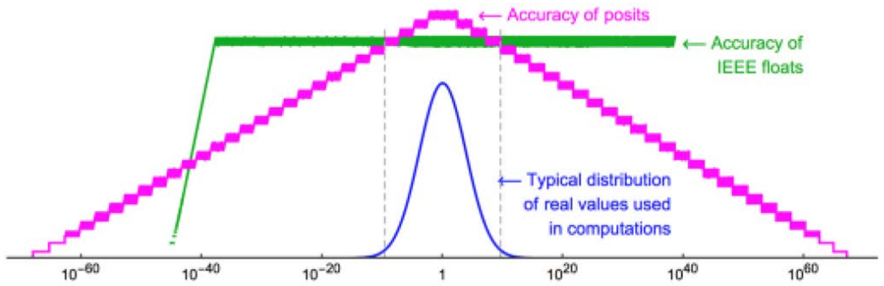
- Lots of unanswered questions, tie with material homogenization

More accurate & energy efficient computations

Etaphase: Mullen



Subregion sizes are *dynamic* and *self-defining*



Posits maximize accuracy near values used in real computations

Approach: New representation of real numbers (known as POSITS) provide tapered accuracy with more precision around typical distribution of real values used in computations

Impact: New representation is over 30x more accurate than the comparable IEEE Standard for floating point operations allowing 32 bit posits to get 64 bit float accuracies POSITS also reduce power consumption which are important for server farms and could result in a 4x weight savings for batteries in portable devices

Limitations: Floats are current industry standard – will be difficult to disrupt industry with small investment

TRADES analysis highlights: Novel approaches enable interoperable and parallel analysis

Query based analysis

PARC (Intact, Intact, OSU): Nelaturi

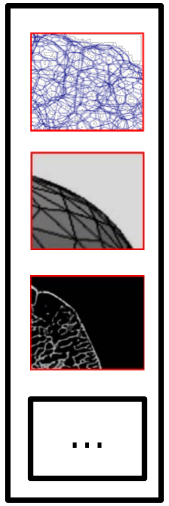
Representation

Boundary Rep

Tessellated

Image Stack

Many others

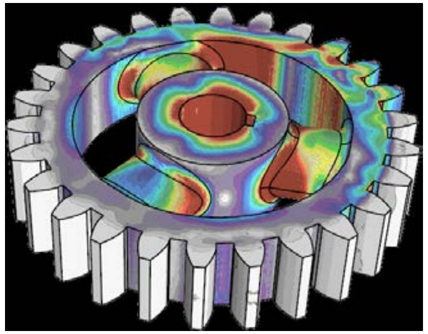


Query Object

Moments

$$\int_{\Omega} x^i y^j z^k \rho \, d\Omega$$

Analysis



Approach:

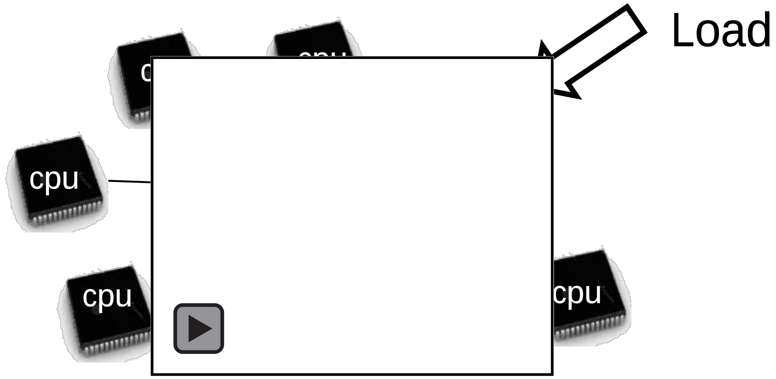
1. Reformulated analysis in terms of moments
2. Query object to evaluate moments

Accomplishment: 51% reduction in human effort during modeling & simulation process

Impact: Interoperable and scalable analysis without representation conversion to enable automated design exploration

"Swarm computing"

Columbia U: Lipson



Minimize mass

Approach: Use ideas from swarm computing to parallelize analysis and simulation: "one processor per node"

Accomplishment: 12,500 X faster than SOA CPU based analysis & simulation.

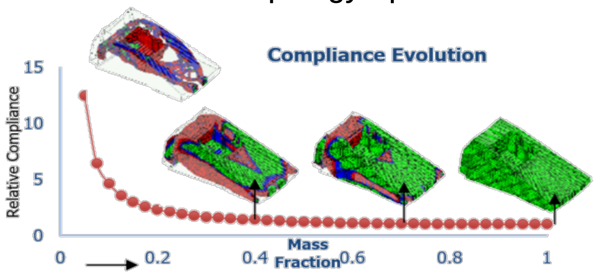
Impact: Rethinking how to leverage massive amounts of computing resources to solve scientific problems at large scales

TRADES Synthesis Highlights: Incorporation of manufacturing constraints and uncertainty in synthesis

Topology optimization with manufacturability

PARC (Intact, OSU): Nelanturi

Pareto topology optimization



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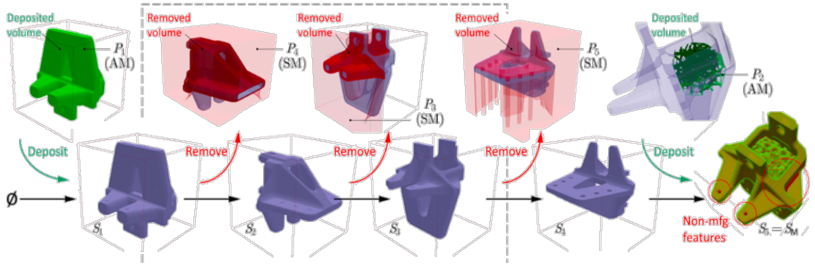
Manufacturability Assessment



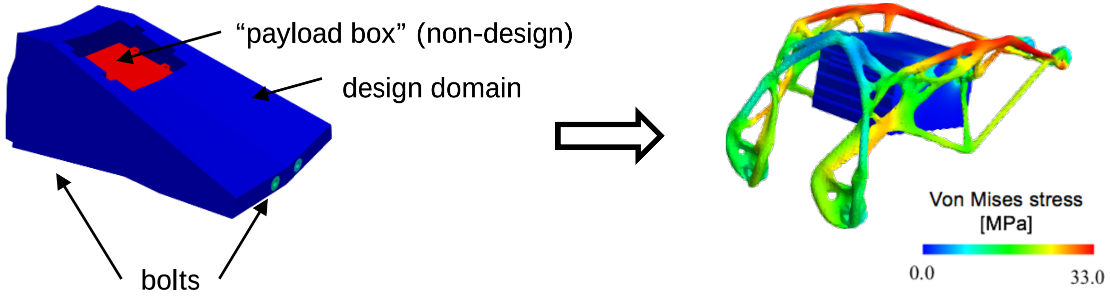
Approach: Combine gradient based topology optimization with manufacturing analysis

Accomplishment: 10x faster synthesis while guaranteeing feasibility

Impact: Generate manufacturable designs directly

Multi-objective topology optimization under uncertainty

CU Boulder (UTRC): Maute



Sandia Bracket Challenge: Find optimal distribution of Ti-6Al-4V such that a combination of mass and strain energy is minimized subject to constraints

Accomplishment: Fully immersed description of geometry (no need for conforming mesh) and hierarchical adaptive mesh refinement.

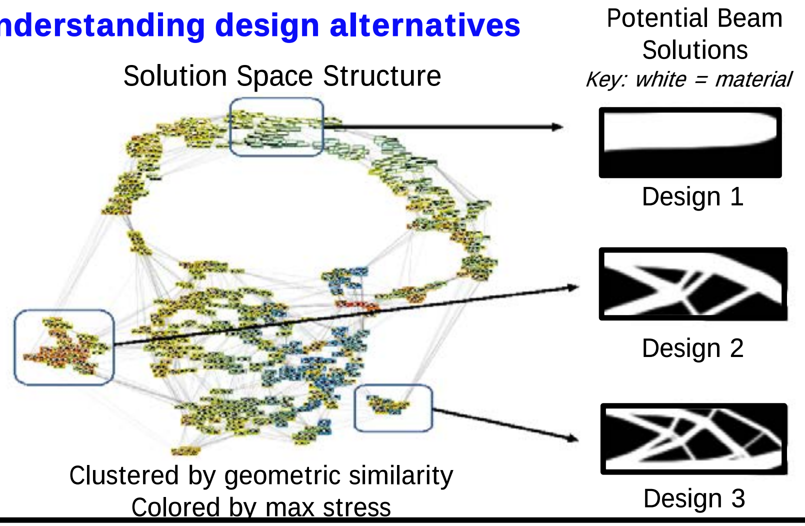
Impact: Allows 1000X reduction of computational cost for design under uncertainty, and topology optimization for complex structures in less than one day.

Limitations: Direct resolution of length scales limited to 10^4

Synthesis Accomplishments: Navigating complex trade spaces and accelerating discovery with Machine Learning

Understanding design alternatives

U Utah: Kirby



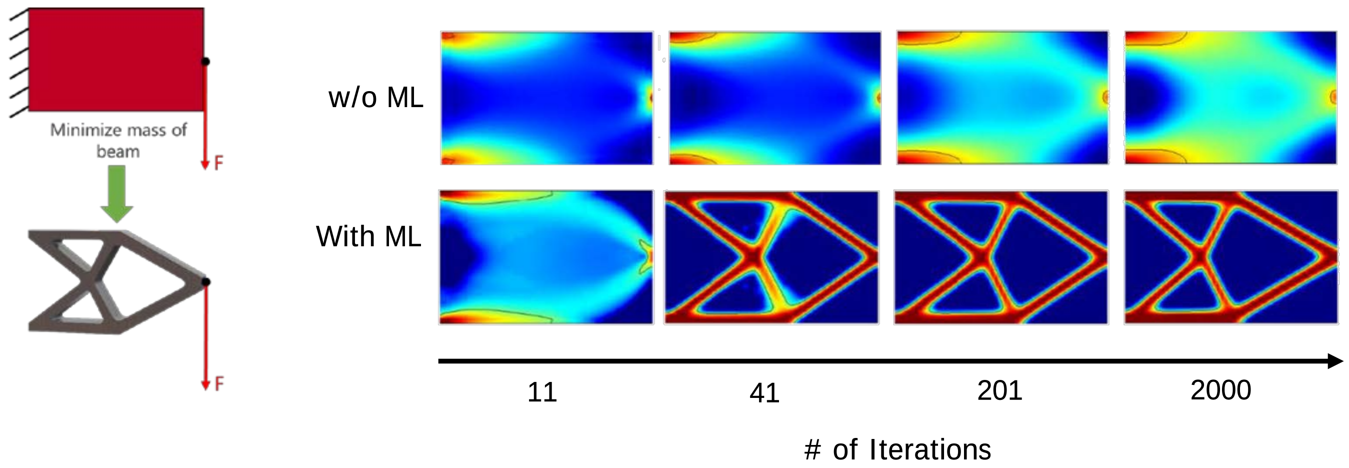
Approach: Cluster and connect synthesis solutions by shape similarity and Quantities of Interests (e.g., max stress)

Accomplishment: New perspective on navigating complex trade spaces

Impact: Provide insights into alternative but viable solutions to enable design refinement and explorations

Machine Learning (ML) to accelerate synthesis

U Col (UTRC): Maute

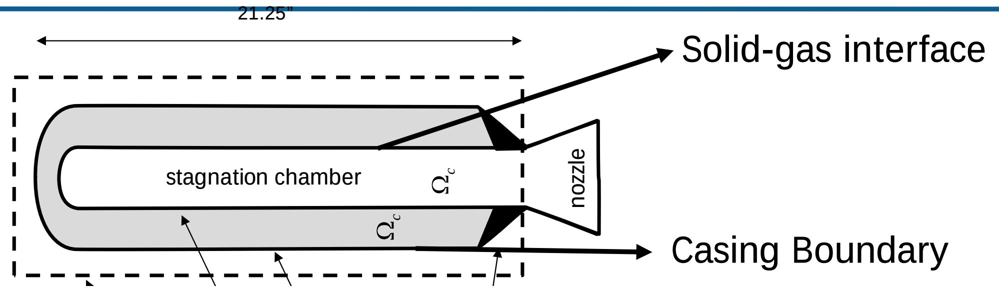


Approach: Utilize Machine Learning (ML) to accelerate convergence to a design solution

Accomplishment: Accelerate synthesis by ~2 orders of magnitude

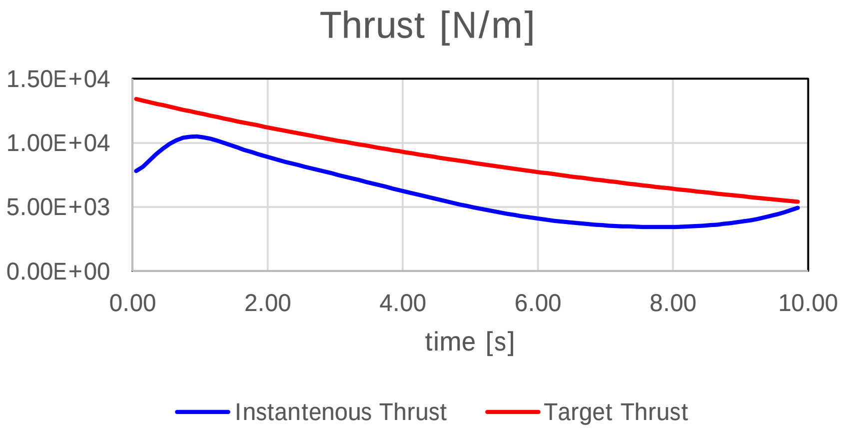
Impact: Enable rapid exploration of design alternatives; refine ML as the design collection grows

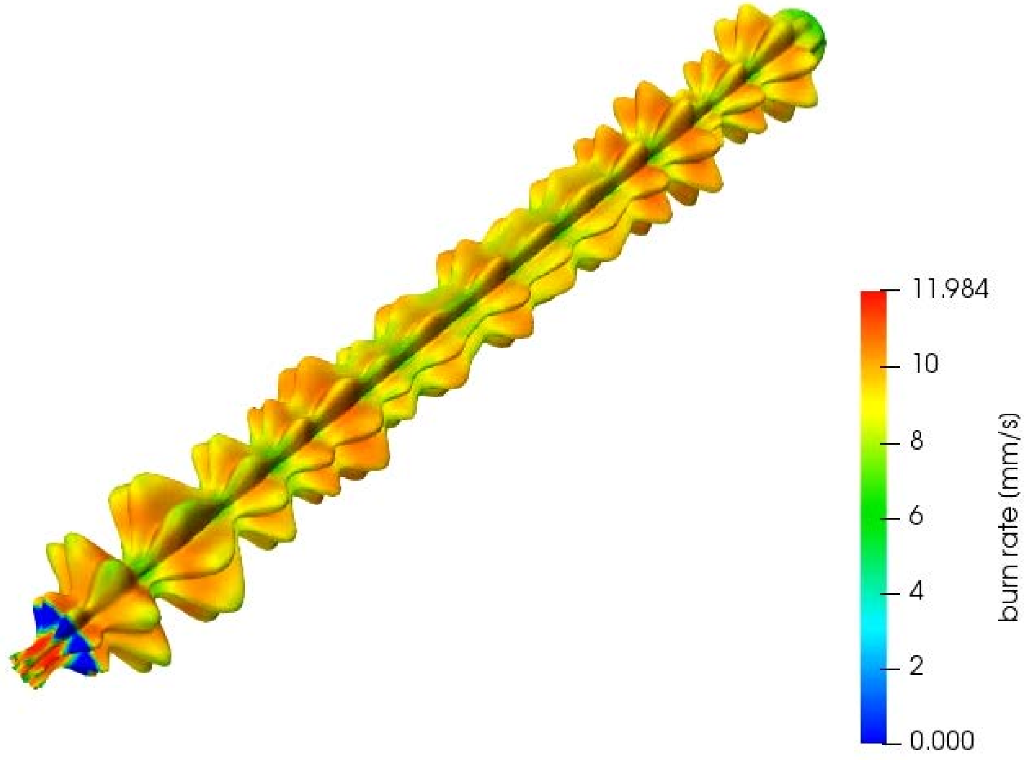
Accomplishment: Synthesize designs for dynamic multi-physics problems



Accomplishment : Time dependent topology optimization for transient problems with dynamically evolving interfaces using level set method.

Impact: Allows complex design optimization for multi-physics problems such as phase-change or fluid-structure interaction





Optimized design: evolution of solid-gas interface in burn process

Problem Objective: Match target thrust profile through controlling shaping and distribution of solid rocket fuel.

Constraints: Fuel must burn out at all at once (no casing insulation), cannot have disconnected islands of fuel during burn process.

Physics: Algebraic thrust model coupled to solid-gas interface evolution (Hamilton-Jacobi)

What's next?

AI: Discover new fundamental laws (of materials, physics)?

Design: Cyber partner in design?
Find unintended interactions?

Math: Rethink physics in terms of computable math?

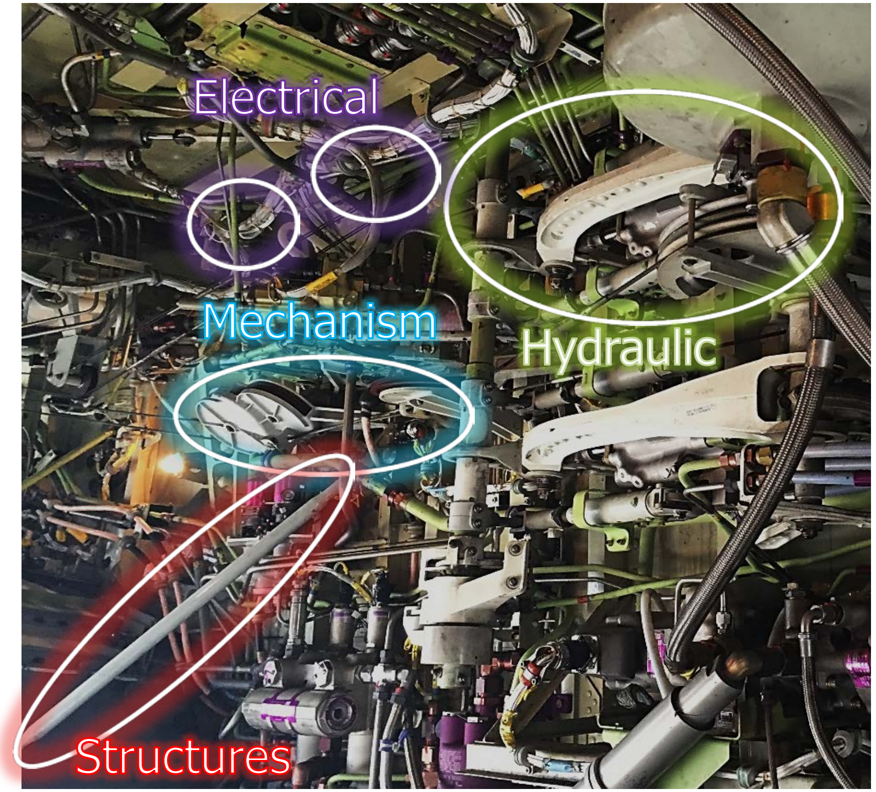
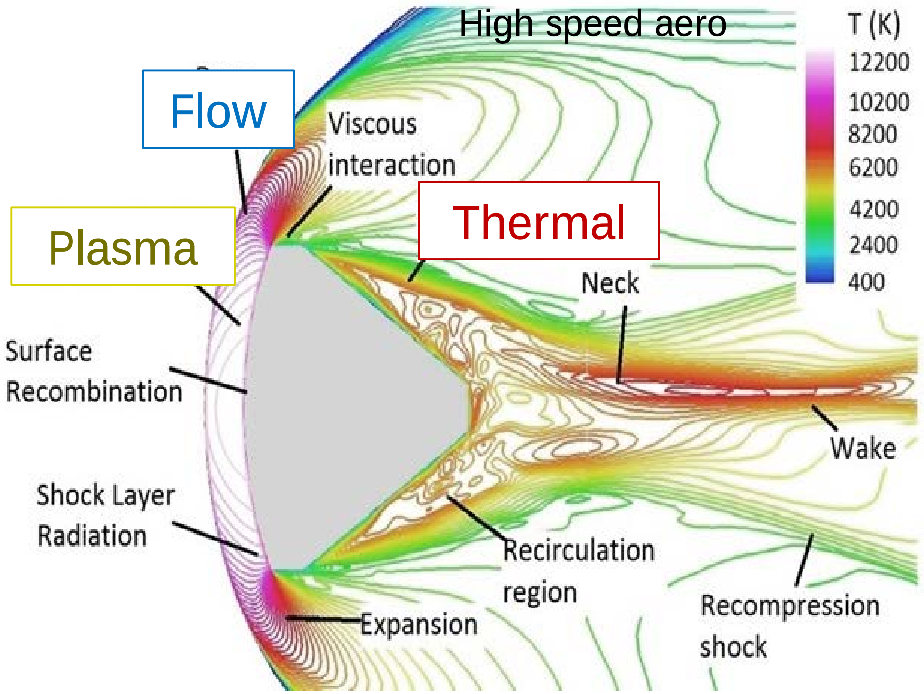


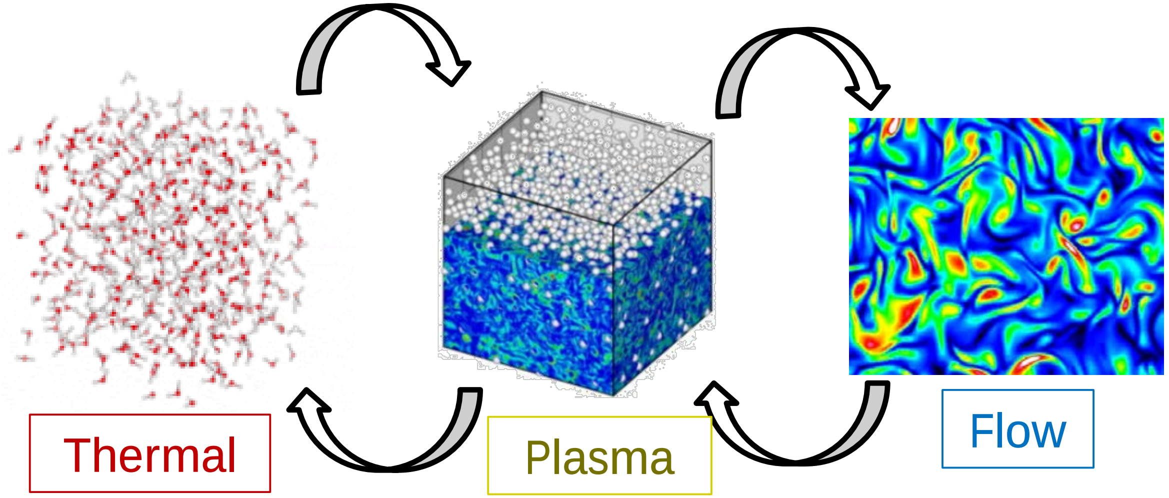
Photo credit: Jan Vandenbrande

Challenge: Lack of efficient ways to generate and compose computations for multiple physics limits our ability to simulate important DoD/DoE platform missions

Many DoD/DoE systems push the limits of physics and are test limited



Can we rethink how we build multi-physics models?



- **Transition to turbulence / shock wave predictions**
  - **Predictions:** Uncertainty = 60% length of body
  - **Impact**: 8x heating rate difference
  - **Testing:** Cannot be reproduced in wind tunnels
  - **Important for**: Thermal protection, materials, ablation
  - **Effort:** Scales unfavorably with the amount of interacting physics

Source: Ivette Leyva, https://physicstoday.scitation.org/doi/10.1063/PT.3.3762

Questions? Ideas? Let’s talk!

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