P/O/E/T/S

CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

# Optimal 3D **S**patial **P**ackaging of **I**nterconnected **S**ystems with **P**hysics **I**nteractions (**SPI2**)


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Postdoc: Dr. Satya Peddada

Faculty: Prof. Kai James, Prof. James Allison (UIUC)

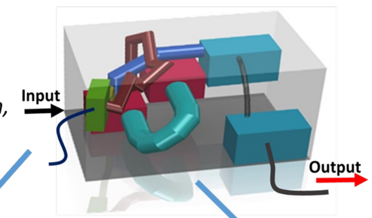
# Optimal 3D Spatial Packaging

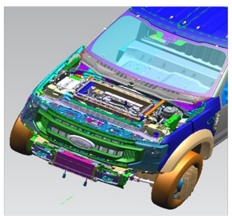
Core project goal: create breakthrough ***computational design methods*** for:

- Optimally distributing system components and interconnect paths (conveying material, energy or information) within a 3D volume,
- Subject to performance objectives that rely on **physics coupling** involving both continuum and lumped-parameter models.

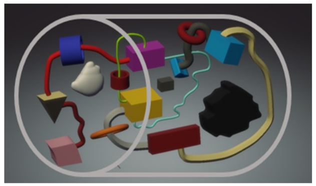
## Project History

**I1.011.19**
**(Jan 2019-Dec 2020)**
*Focused on 2D problem, with 3D foundations*



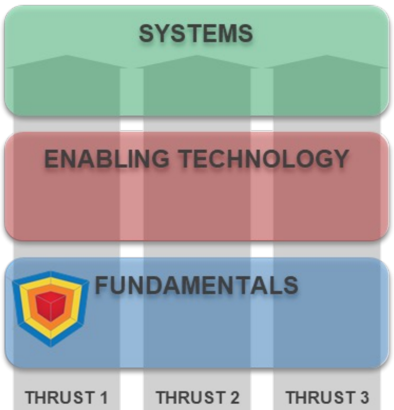



**R1.015.20 (Aug 2020 – present)**
*Ford automotive fuel cell packaging problem*



**I1.018.21 (Jan 2021 – present)**
***3D-SPI2, External Funding Sustainability plan***

**Next Step: SPI2Py**




**O1** *Develop a **systematic design framework to represent, enumerate and identify** unique **3D spatial topologies** of electro-thermal systems.*

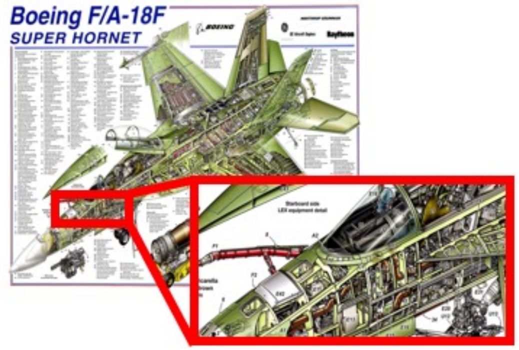
**O2** ***Gradient-based 3D geometric projection method (GPM)** for performing simultaneous multiphysics packing and routing optimization.*

**O3** *Apply the integrated 3D SPI2 two-stage design optimization framework on practical **POETS industry-relevant 3D applications.***

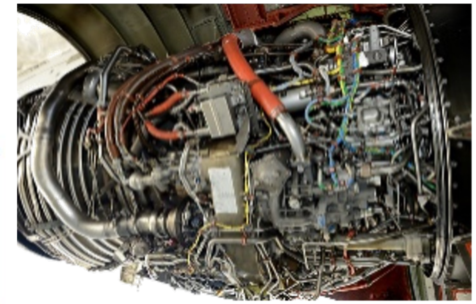
# What is the "Holistic 3D SPI2 Design" Problem?

## SPI2 Design Problem Attributes [1, 2]:

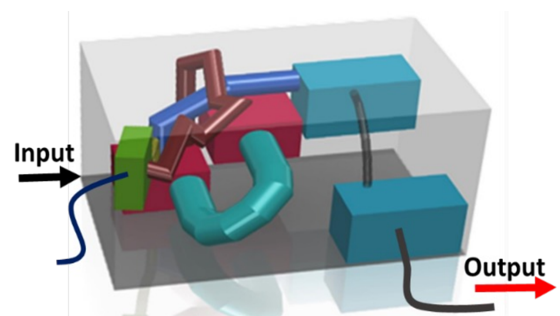
- ***Fundamentally 3-dimensional;*** interconnected components; complex spatial geometries
- ***Interconnects of various types*** (pipes/ducts/wires), sizes, shapes, and requirements (curvature, proximity, thermal, EMI, etc.)
- ***Strongly-coupled physics interactions (thermal, hydraulic pressure, electromagnetic, etc.),*** influence of spatial arrangement on performance
- Must attain ***desired value metrics***: spatial packaging density, volumetric power density, thermal performance, product life-cycle costs, system efficiency, system reliability, etc.
- **Current practice/Bottlenecks:** Manual design supported by CAD. Limited by human cognitive capacity.
- Requires ***a tight interdisciplinary approach*** to tackle this challenging problem.




*Complex packaging under the skin of a fighter jet.*



*External wiring and components of an aero engine*




*A simple 3D representation of a SPI2 system*

[1] S. R. T. Peddada, L. E. Zeidner, K. A. James., J. T. Allison "An Introduction to 3D SPI2 (Spatial Packaging of Interconnected Systems with Physical Interactions) Design Problems: A Review of Related Work, Existing Gaps, Challenges, and Opportunities " ASME IDETC, Aug 2021
[2] S. R. T. Peddada, L. E. Zeidner, H. T. Ilies, K. A. James., J. T. Allison "Towards a Holistic Design of Spatial Packaging of Interconnected Systems with Physical Interactions (SPI2)" ASME Journal of Mechanical Design

# POETS Collaborators

## PI & Co-PI (UIUC)

**Industrial & Systems**

Prof. James Allison

**Aerospace**

Prof. Kai James

## Postdoc

Dr. Satya Peddada

## Graduate students

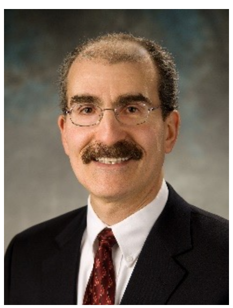
Waheed Bello

Chad Peterson

Corey Parrott

## Industry liaisons

**Raytheon**



Dr. Larry Zeidner

**CU Aerospace**

Dr. Joe Zimmerman

**Ford Motor**

Dr. Man Prakash Gupta

**PCKA**

Dr. Tim Deppen (untill Dec 2021)

# Optimization Problem Formulation for SPI2 Design Automation

**❑ Design automation and method creation goals:**

- Support design of systems with increased complexity, and
- Reduce overall solution expense (including human effort).

### Example SPI2 design optimization

**Objective(s):** System utility (usually based on physical system behavior). For example: overall mission/drive cycle performance, related to elements such as packaging density, thermal distributions, dynamic performance, energy efficiency, etc.

**Constraints:** geometric, functional, failure mode (temp, stress, voltage), assembly/disassembly, accessibility, etc.

**Design Decisions:** Spatial topological decisions, continuous locations/sizing of components/pipes, shape, orientation, control, component tuning parameters, etc.

**SPI2 Design Automation Requires:**

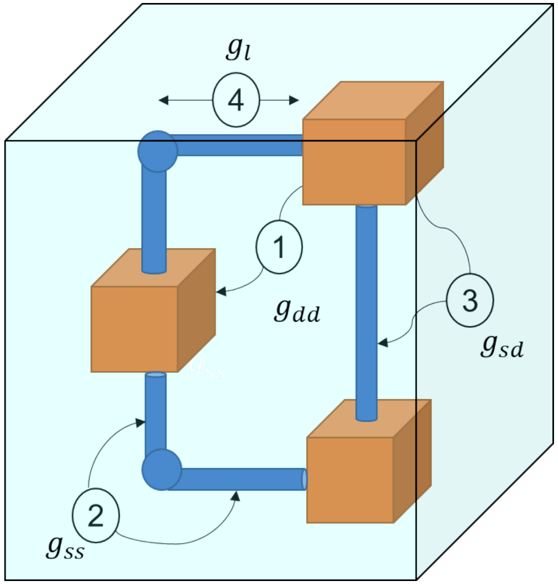
- New theoretical foundation
- Viable mathematical design representations
- Unified geometric representations (UGR)
- MDO extensions
- Tight interdisciplinary teams

## Mathematical Representation:

- $\min_{\boldsymbol{x}} f(\boldsymbol{x}, \boldsymbol{V})$ : Objective function

Subject to:

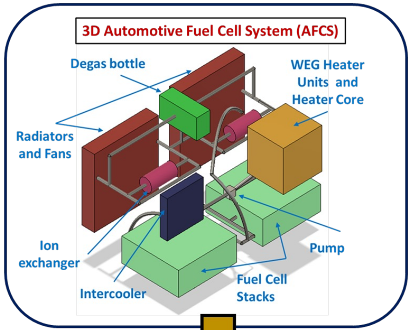
- $g_{phys}$: Physics constraints (device/fluid temp, head loss)
- $g_{dd}$: Device-Device constraints
- $g_{sd}$: Interconnect Segment-Device constraints
- $g_{ss}$: Interconnect Segment-Segment constraints
- $g_l$: Minimum length constraint



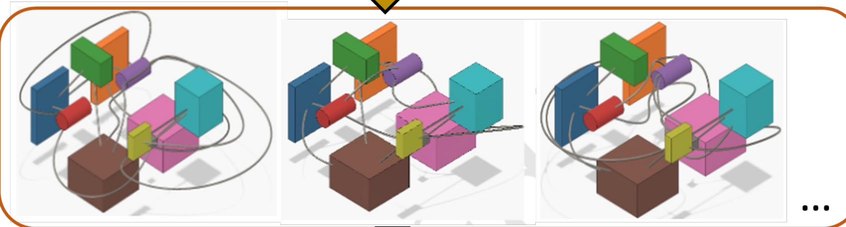

***We developed and demonstrated a successful two-stage design automation approach***

# Two-Stage Design Framework

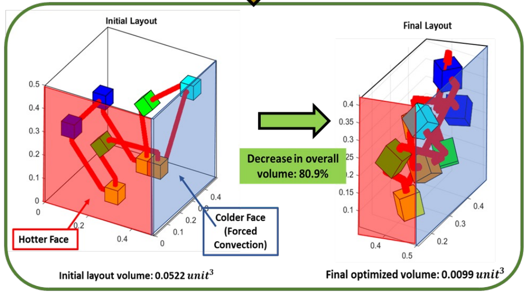
**STAGE 0: User Input (System Specifications)**
- Component geometry, Total bounding volume
- Port connectivity, Routing types
- Physics-based constraints and conditions




**STAGE 1: Feasible 3D Layout Enumeration**
- Explore discrete 3D layout options
- Identify unique topologies
- Spatial graph enumeration algorithms




**STAGE 2: 3D Multiphysics Layout Optimization**
- Gradient-based continuous optimization
- Simultaneous packing and routing
- Geometric projection, Physics FEA models




**Decomposing the problem into two stages is just one way to solve the SPI2 design problem.**

*Figure: Detailed aspects of the sequential two-stage design framework for optimal multiphysics 3D packing and routing*


[3] Satya R T Peddada, Samanta B Rodriguez, Kai A James, James T Allison. *'Automated Layout Generation Methods for 2D Spatial Packing.'* In ASME IDETC 2020, Virtual, Online, USA, Aug 2020.

[4] Alex Jessee, Satya R T Peddada, Danny J Lohan, Kai A James, James T Allison. *'Simultaneous Packing and Routing Optimization Using Geometric Projection.'* ASME Journal of Mechanical Design, 142(11), p. 111702, Nov 2020.

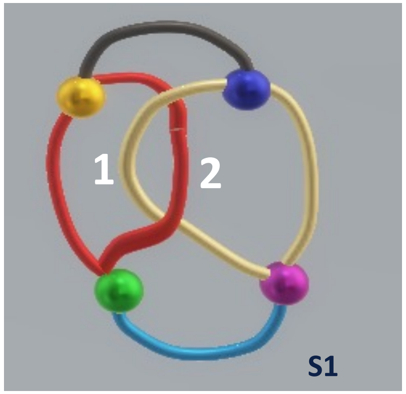
[5] S.R.T. Peddada, K.A. James, J.T. Allison. "A Novel Two-Stage Design Framework for 2d Spatial Packing of Interconnected Components" 2020 **[ 46th DAC- Best Paper Award Nomination & Invited to 2020 Special Issue *of ASME Journal of Mechanical Design*].**

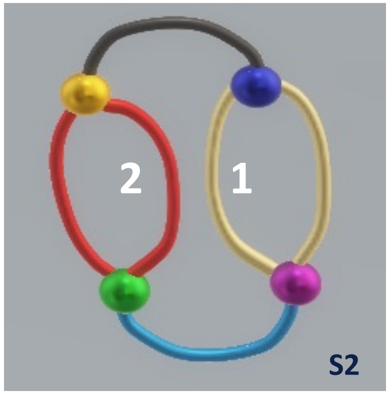
# STAGE 1

## *Spatial Graphs Enumeration for Exploring 3D Topological (Discrete) Design Space*

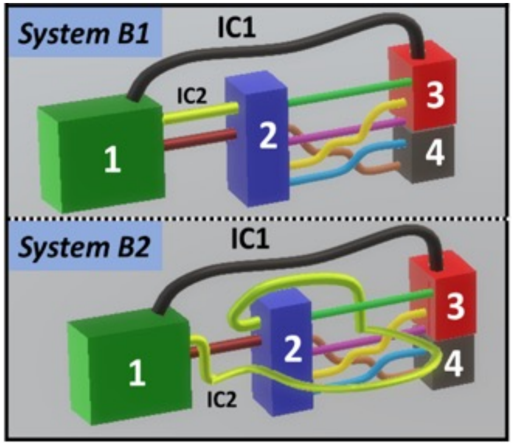
# New Design Representation Needed for Advancing SPI2 Design

- SPI2 design requires making discrete spatial topological decisions. For example, should a duct go under or over a component, etc.
- SPI2 design automation so far has not been possible because no comprehensive topological design representation existed that is compatible with design automation algorithms.
- Design representations must accommodate radically distinct design decision types, while being compatible with design automation




**S1 and S2 are two different spatial topologies of the 3D system ( as system connectivity remains same). Observe that in S1, interconnects 1 and 2 are entangled/linked together while in S2, they are free.**




[6] S. R. T. Peddada, N. M. Dunfield, L. E. Zeidner, K. A. James., J. T. Allison "*Systematic Enumeration and Identification of Unique Spatial Topologies of 3D Systems Using Spatial Graph Representations*" ASME IDETC, Aug 2021

# SPI2 Spatial Graph Representation

- Each SPI2 system can be represented as a spatial graph. Each spatial graph has a corresponding ***Yamada polynomial*** (Yamada 1989)
- ***Topological equivalence*** between spatial graphs is tested here by comparing their corresponding Yamada polynomials.
- Those graphs which have distinct Yamada polynomials are unique spatial topologies
- Efficient and systematic identification of unique spatial graphs from the exhaustively enumerated set using Yamada polynomial invariants.

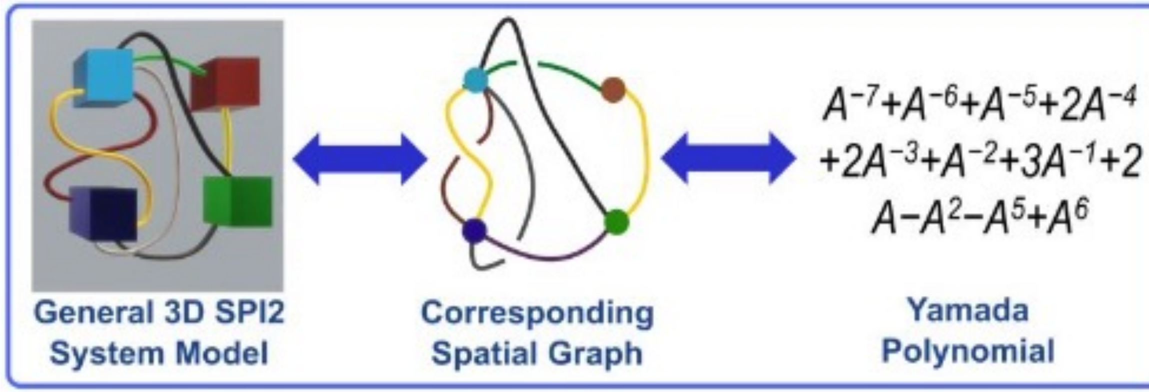



**Figure:** A 3D SPI2 engineering system is represented using a *spatial graph (SG)*. SG supports description of components as nodes, interconnects as edges (strings), multiple-crossings (under/over), and variable component valency. Each graph can be represented as a *Yamada polynomial* to help enumerate and identify unique spatial topologies.

**Advantages of spatial graphs:**

1) Simplicity;
2) Easy to visualize/conceptualize;
3) Design flexibility;
4) Scalable/Decomposable;
5) Support 3D model generation; and
6) Design parameterization


[6] S. R. T. Peddada, N. M. Dunfield, L. E. Zeidner, K. A. James., J. T. Allison "*Systematic Enumeration and Identification of Unique Spatial Topologies of 3D Systems Using Spatial Graph Representations*" ASME IDETC, Aug 2021

# Simple Enumeration Demonstration

- **Assume:** A four component SPI2 system architecture with each component having three ports (trivalent).
- We have enumerated all spatial graphs from zero to a maximum of 3 interconnect crossings.
- Spatial graphs in each class belong to the same spatial topology
- We group the graphs having the same Yamada polynomial (YP) under the same topological class based on YP properties.

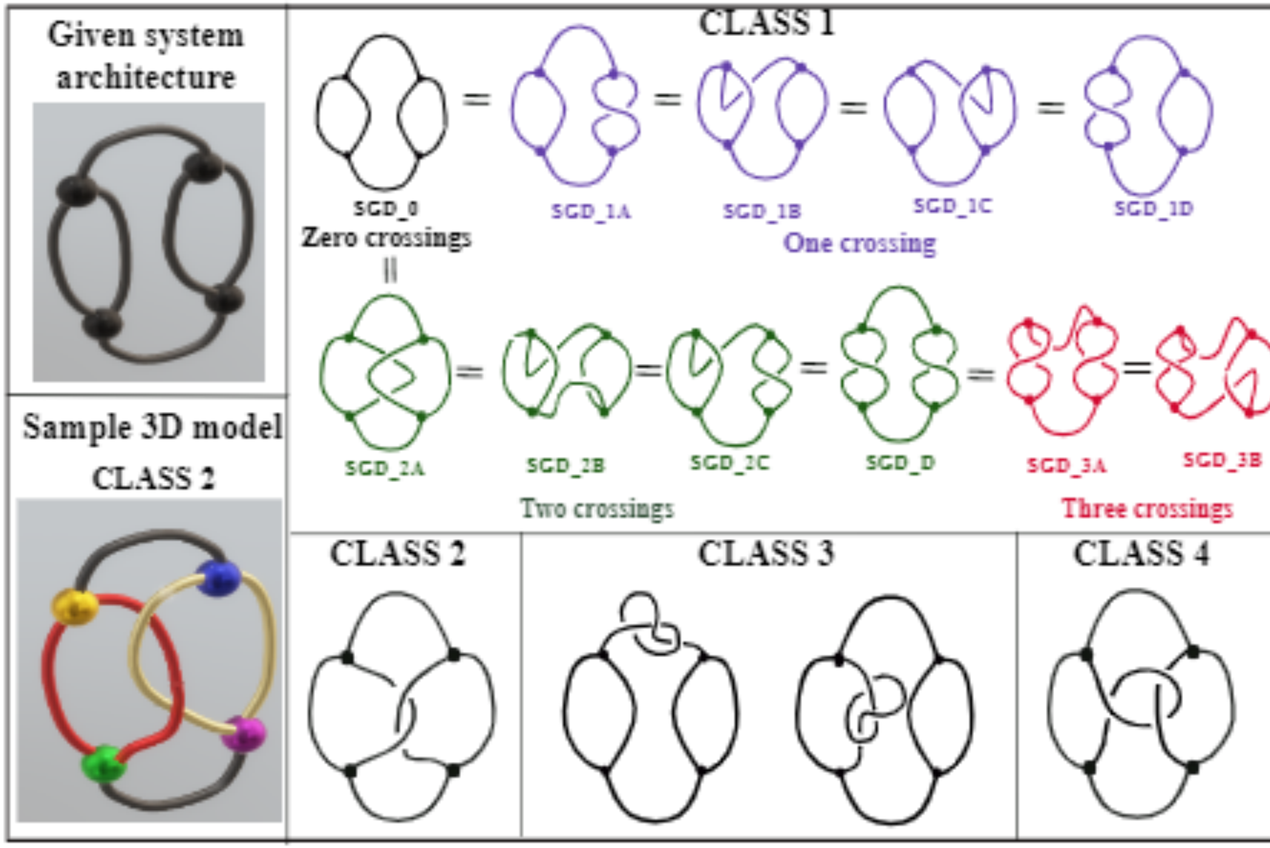



***Figure: Results from case study for a given SPI2 system containing four tri-valent components for maximum interconnect crossing numbers between 0 through 3.***


[6] S. R. T. Peddada, N. M. Dunfield, L. E. Zeidner, K. A. James., J. T. Allison "Systematic Enumeration and Identification of Unique Spatial Topologies of 3D Systems Using Spatial Graph Representations" IDETC 2021

- We enumerated a comprehensive set of 3D spatial configurations of the Automotive Fuel Cell System (AFCS shown below) based on a given system architecture
- **Collaboration:** Ford Motor Company; **Example:** Automotive Fuel Cell System (AFCS)

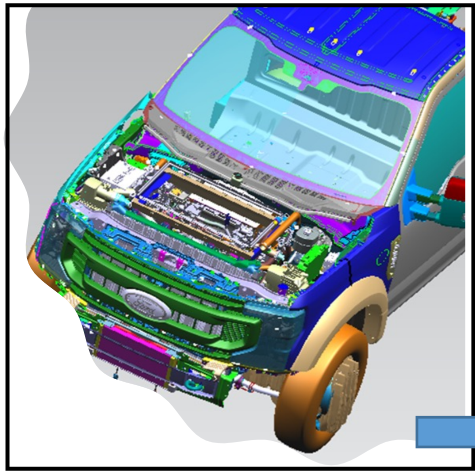


*Figure 1: Underhood of a vehicle containing the fuel cell system.*

Ford Motor Company

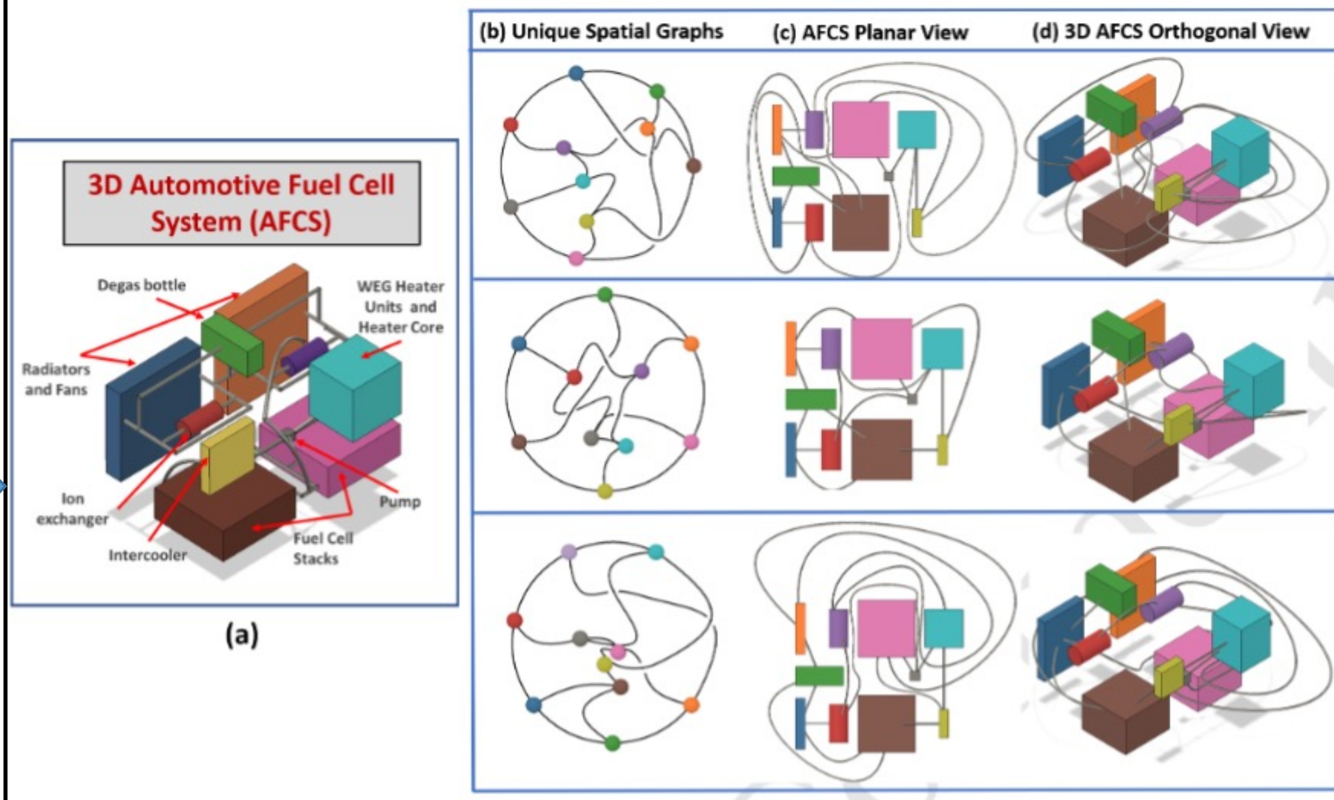
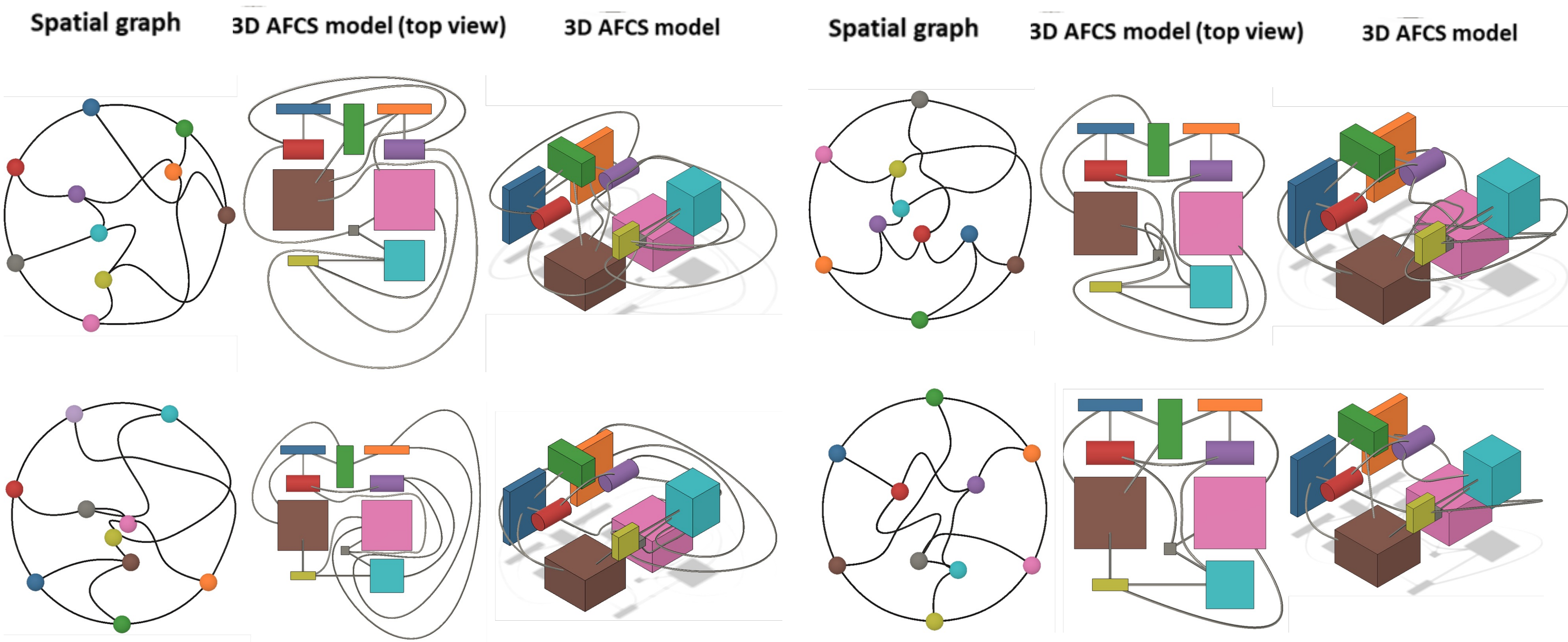



*Figure 2: (a) shows 3D AFC system; (b) shows a sampling of three of the several unique spatial graphs enumerated for the given AFCS; (c) and (d) are the planar and orthogonal views, respectively, of the 3D models generated from their corresponding spatial graphs shown in (b).*

# More unique configurations




- The results show that this method is **efficient, scalable, applicable to all general 3D interconnected system networks,** and
- Each of these configurations can be used as initial designs for continuous 3D multiphysics component placement and routing optimization; i.e., Stage 2 of the 2-stage approach.

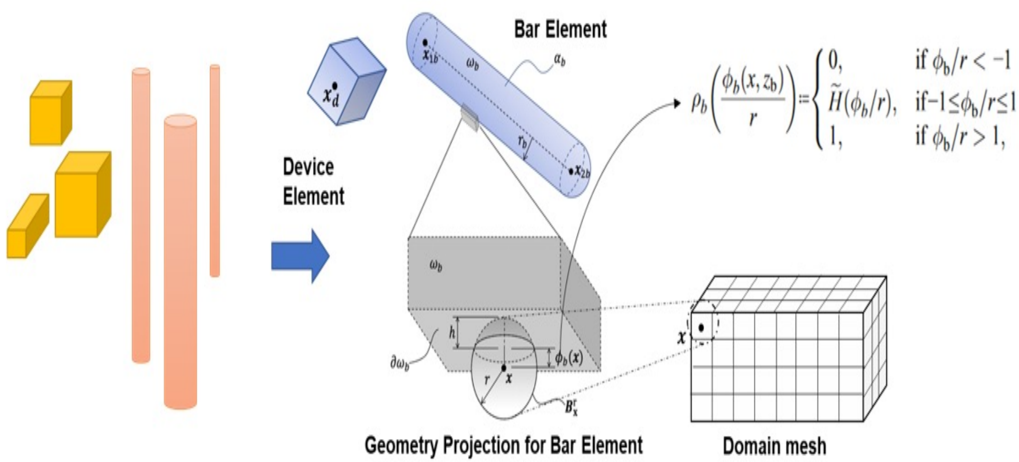
# STAGE 2

## *3D Multiphysics packing and routing optimization*

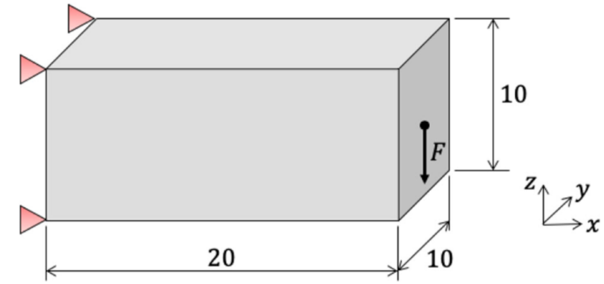
## *(One Possible Strategy)*

# Stage 2: 3D Multiphysics Optimization using Geometric Projection (GP)

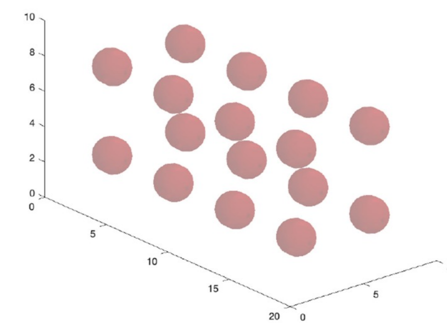
- Conventional topology optimization methods result in organic structures modify component geometry/structure and may not always be manufacturable.
- Topology optimization using geometric primitives supports both layout design and manufacturing.
- 3D Geometric Projection allows design of structures made of stock materials (flat or curved plates/primitive solid shapes), in cuboid or irregular design regions. [Norato 2020 *et* al.]



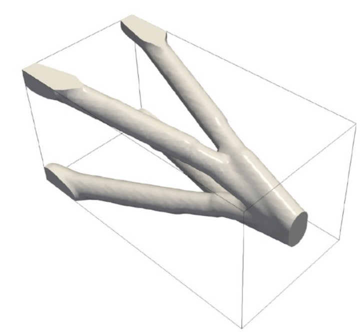

**Initial 3D domain**




**Initial 3D domain seeded with bar elements**



**Optimized domain**



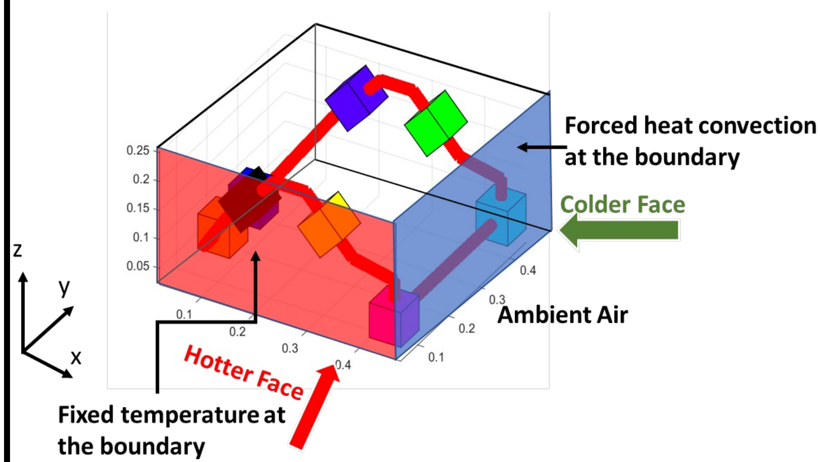
# Continuous Multiphysics Packaging Optimization: A Sample Result

*A sample case study (an interconnected 8-component multiphysics system):*

- **Objective:** Minimize packaging volume
- **Constraints:** Max. device temperatures, device heat dissipation rates, boundary conditions, non-interference between elements, bounding box, fluid flow, fluid temperature, obstacles, etc.
- **Design variables:** Component (locations, orientation), and interconnect (lengths, diameters, bend radius, etc.)
- **Future work:** Arbitrary complex component shapes, moving components, life cycle considerations, and other physics aspects (electrical, structural, vibrational, etc.)

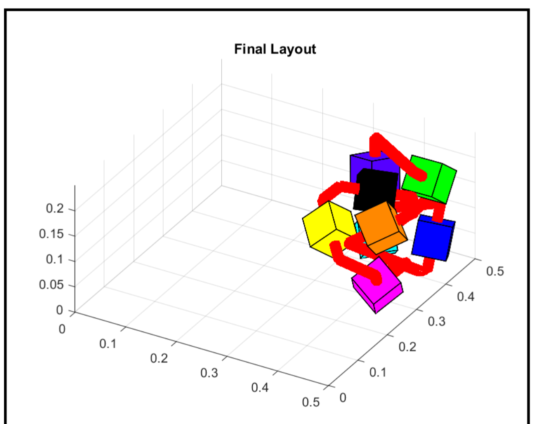
## Initial Layout

### Normal view

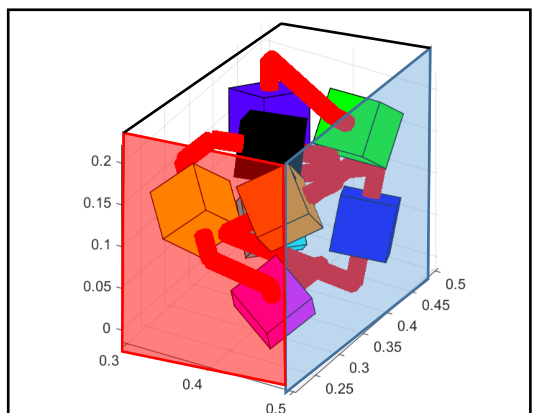



## Final Layouts

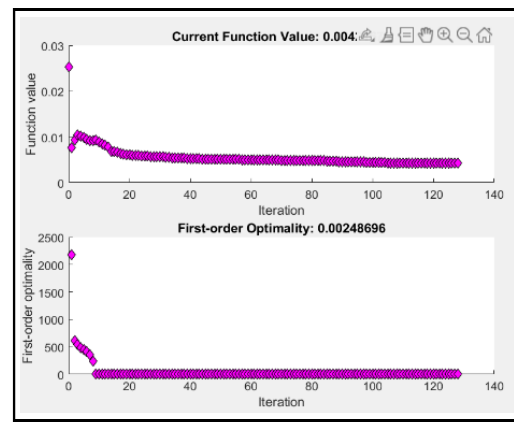
### Normal view




### Closer view



### Optimization Process




**We see ~73% reduction in the overall system volume**

# TRL 4-5: Working toward an Open-Source Software Tool

## ❑ Current state of development

- We developed a **2-stage design framework** to support packing & routing of 3D thermo-fluid systems.
- Efficient 3D spatial topology enumeration and identification methods
- Gradient based packing & routing in 3D FEA framework

## ❑ Selected work in progress…

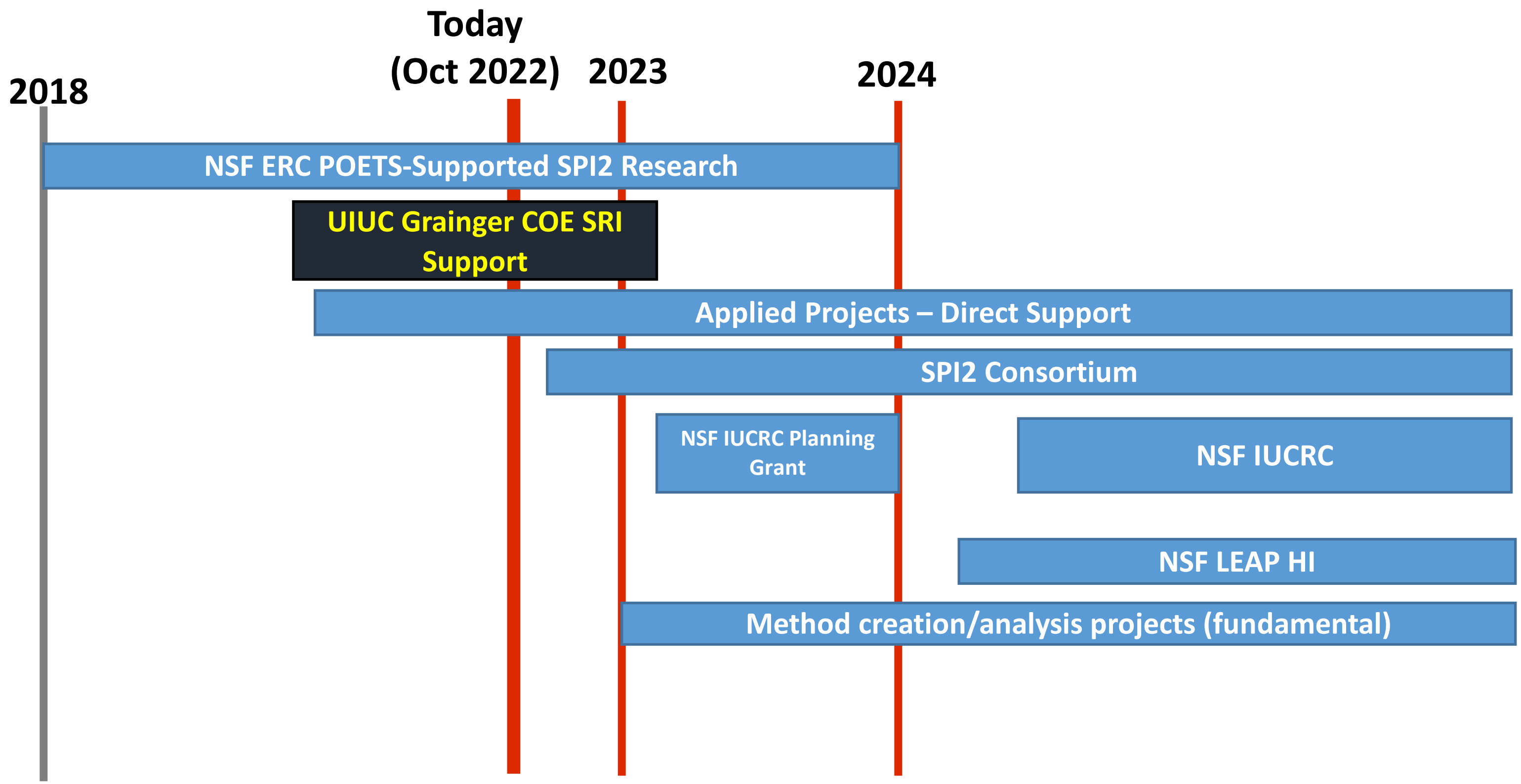
- Machine learning and AI-based methods
- Spatial Graphs – multi-valent components – Prof. N. Dunfield (UIUC)
- 3D Routing – both rigid and soft piping – Prof. Nancy Amato (UIUC)
- DFX - Design for Manufacturability, Assembly, Maintenance and Repair – Texas A&M Univ.
- Robotic cable manipulation for assembly – Purdue
- Unified Geometric Representation (UGR) – UConn & Georgia Tech

## ❑ Proof of concept is established

- **The current TRL of our software tool – 4-5**
- **We are continuing to refine this software**
- **IAB Proposal: Higher TRL open source SPI2 design automation tool (SPI2Py)**
- **Collaboration with engineering software companies**

TRL 9
TRL 8
TRL 7
TRL 6
TRL 5
TRL 4
TRL 3
TRL 2
TRL 1

# SPI2 Research Timeline/Project Portfolio




- Nov. 16-17 2022: Inaugural SPI2 research workshop held in-person at UIUC
- Joint effort to define a SPI2 research consortium and future NSF IUCRC

# SPI2Py Open-Source Software Tool

- The **first version of an open-source SPI2 design software tool**
- Codebase: Python
- GitHub Repository
- Submitting a POETS IAB project proposal for the next funding cycle: Transition from research code to practical open-source code
- Supporting companies in efforts to learn and use this software tool will be a focal point of the SPI2 consortium
- POETS and associated projects impact: Translating revolutionary new SPI2 design methods into practice

SPI2Py

## Welcome to SPI2Py

SPI2 stands for the Spatial Packaging of Interconnected Systems with Physical Interactions.

The SPI2 framework packages components, routes interconnects, and performs multiphysics simulations simultaneously.

At this point in time, we are working on the initial release so many features are missing/untested. We plan to demonstrate an early working version in mid-November of 2022.

For more information regarding the SPI2 Strategic Research Initiative see the following.

Website:

https://spi2.illinois.edu/

# Conclusion: Project Summary

## Progress Summary

**O1** *Developed a **systematic design framework to represent, enumerate and identify** unique **3D spatial topologies** of electro-thermal systems.*

**O2** *Developed a simultaneous **multiphysics 3D packing and routing optimization** method utilizing **3D geometric projection (GPM)***

**O3** *Applied the 3D SPI2 two-stage design optimization framework on practical **industry-relevant 3D applications**. For example, the Ford **automotive fuel cell packaging** problem.*

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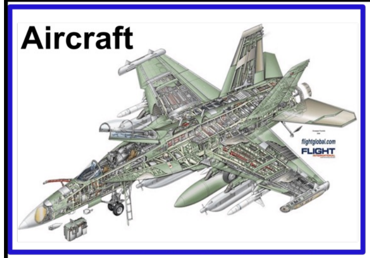
## Significant Upcoming Activities:

- ***Creating and demonstrating an initial version of open-source SPI2 software tool*** **(by Dec. 2022)**
- ***Working toward SPI2 research sustainability: Associated projects and funding beyond POETS***
  - ***Continue SPI2 activities that connect directly to POETS priorities, expand SPI2 capabilities and impact through associated projects***
  - ***Nov. 16-17 in-person workshop @UIUC***
  - ***Launch SPI2 consortium (2023)***
  - ***Larger scale proposals: NSF IUCRC, NSF LEAP HI, NSF RCN, DARPA, etc.***
  - ***Directly funded (IP) and fundamental (method creation and anlaysis) SPI2 research projects***

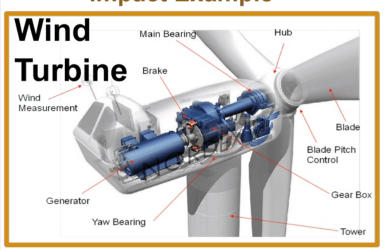
# APPENDIX

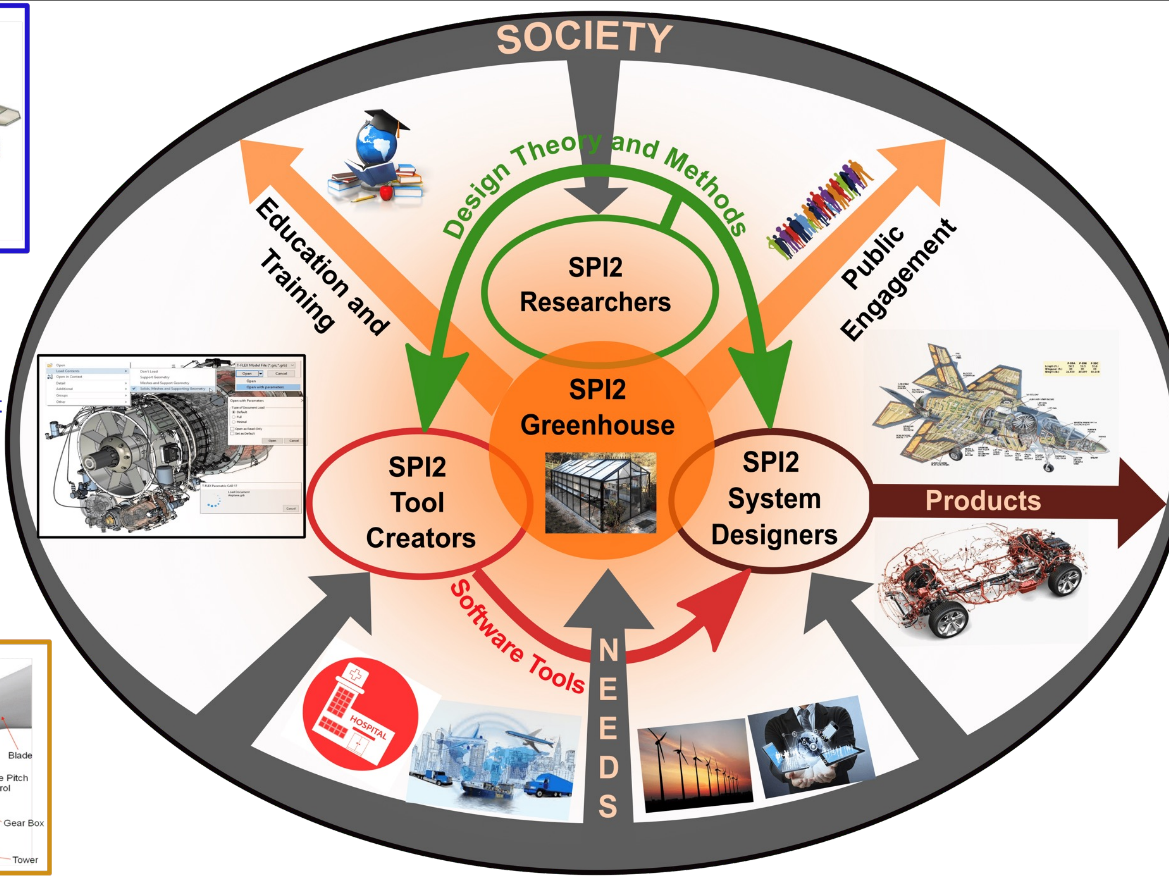
# SPI2 Research and Practice Ecosystem

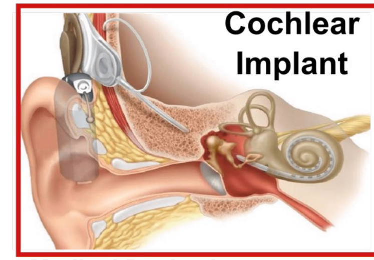



**Aerospace Industry Impact Example:** Enable (for the first time) rapid redesign of SPI2 system elements in an aircraft when considering system configuration changes that could disrupt geometry. Current practice resists large changes due, in part, to profound redesign time and cost.

**Renewable Energy Impact Example**

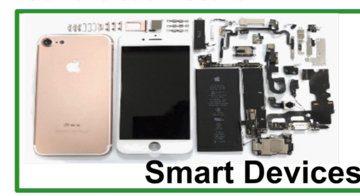



**Medical Device Impact Example:** Medical implants are highly constrained spatially. Advanced SPI2 design will open the door to successfully expanding the set of features/ functions that can fit and operate within an implant.

**Digital Device Impact Example:** Current levels of packing density, thermal management, and performance required decades to achieve. SPI2 design automation will collapse the time required to achieve such results.



# SPI2 Consortium – SPI$^2$C

- Modest annual membership to support deeper engagement with SPI2 researchers (not direct support of research projects)
- Learn cutting-edge SPI2 methods from consortium researchers
- Additional engagement opportunities beyond public seminars
- Early access to research outcomes
- Long-term engagement with consortium faculty, students, and postdocs
- Secure your ability to influence the trajectory of SPI2 research at the early stages
- November 2022 workshop (@UIUC in person):
  - Work out SPI2 consortium details (intend to launch in 2023)
  - **Workshop date: Nov 16-17, 2022 @UIUC**
  - **Event information is available at: https://spi2.illinois.edu/2022/09/25/uiuc-spi2-in-person-workshop-nov2022/**
- Consortium members may help shape plans for large proposals (NSF IUCRC, LEAP HI, etc.)

# Fall 2022 SPI2 Workshop at UIUC – Nov. 16-17

**Primary Nov 2022 SPI2 workshop goals**:

- Initial definition of the structure of an applied SPI2 design research consortium, which may lead to the creation of an NSF IUCRC.
- Provide an opportunity for individuals from a diversity of industries to engage and share ideas related to the common thread of complex SPI2 design decisions.
- Develop an understanding of the most pressing industry needs and challenges connected with SPI2 design.
- Refine roadmapping for the SPI2 research and practice ecosystem, focusing on long-term success in the translation of fundamental research into practice

**Draft agenda for Nov 2022 SPI2 workshop:**

Nov 16$^{th}$ (Wednesday) evening:

- Welcome and Overview
- Dinner/Networking reception

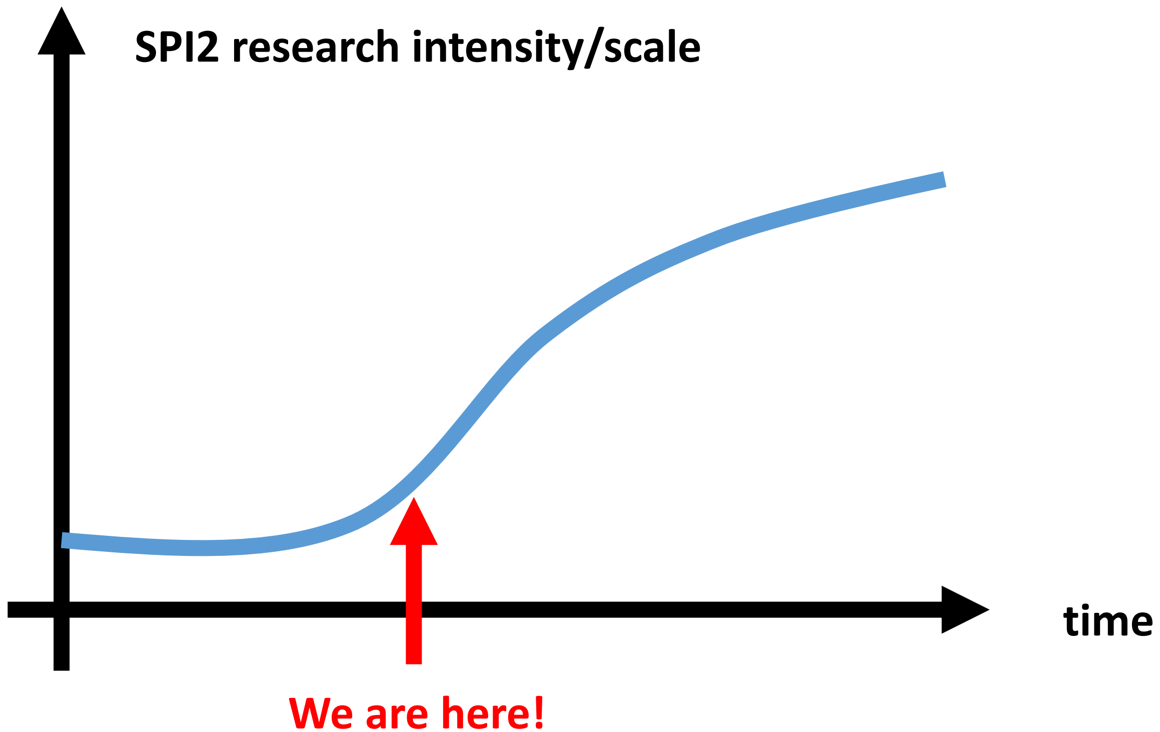
Nov 17$^{th}$ (Thursday - whole day, ~ until late afternoon):

- Multiple working sessions with specific goals related to the formation of the SPI2 consortium
- Some of the working sessions will be available as hybrid opportunities, but the main networking opportunities will only be available in person.

# Engagement Options

- Free Smells: SPI2 listserv, SPI2 Slack Channel
- Direct research projects: Currently working with several companies
- SPI2 Consortium: Organizing soon (Nov 2022 workshop)
- Collaboration on government-funded research projects (e.g., GOALI)
- Engagement on larger proposals (EAB for NSF LEAP HI)
- NSF IUCRC Membership: Phased proposals/workshop in 2023, earliest start date summer 2024

# SPI2 Consortium – SPICon



**Example: NSF GOALI**

- Industry partner can be a Co-PI
- Standard projects: 3 years
- All NSF funds support university researchers
- Industry partner does not receive NSF funding, but benefits from direct collaboration on a project supported by NSF
- Should have a fundamental research component, but must have a clear rationale for industry engagement

# SPI2 listserv, SPI2 Slack Channel

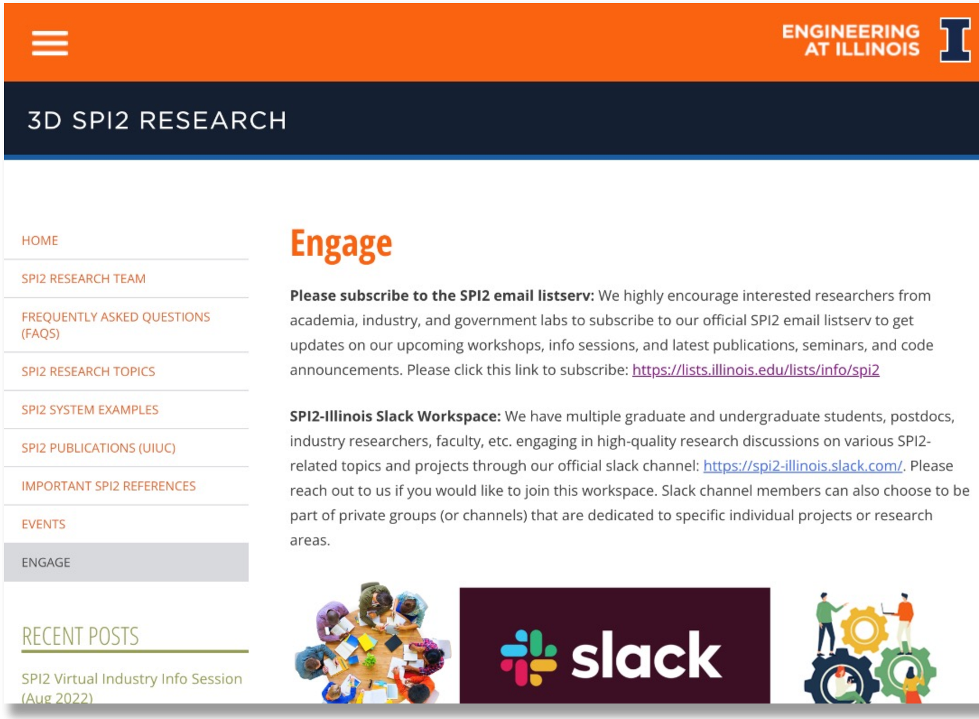
https://spi2.illinois.edu/engage/

**SPI2 listserv:**

- Go to https://lists.illinois.edu/lists/info/spi2, click subscribe, enter your name and email address.
- Stay abreast of SPI2 developments, public events, publications, code releases, etc.

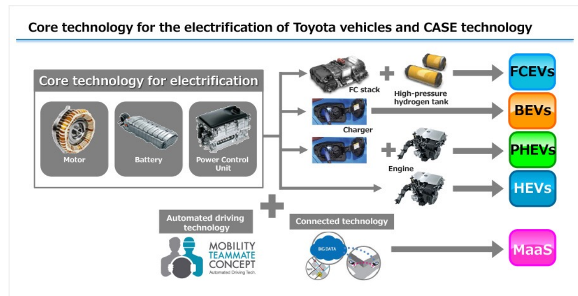
**SPI2 Slack Workspace:**

- https://spi2-illinois.slack.com/
- Engage with SPI2 research discussions

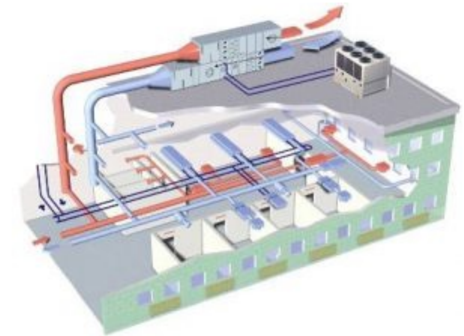


# Sample SPI2 Research Activities/Interests

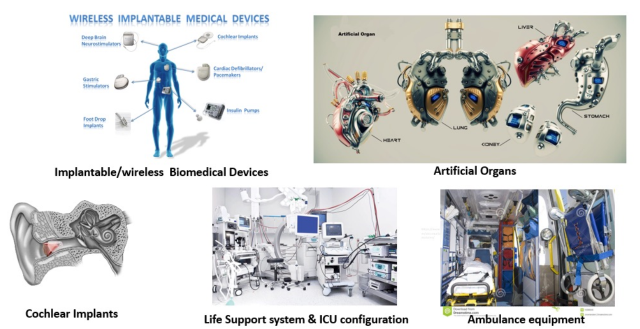
*Multi-robots for Packaging, Assembly/Disassembly, Maintenance, and Repair*




*Hybrid and Full-electric Vehicle Design and Packaging with Dynamic System Control*

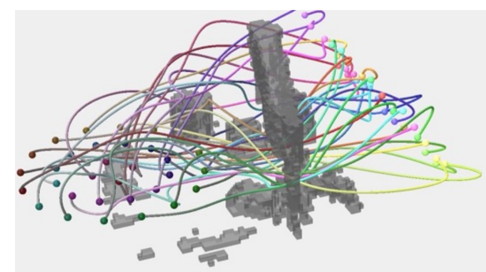


*HVAC System Design for Buildings*




*Healthcare: Biomedical Devices Design and Manufacturing*


*3D Microelectronic Systems Design and Fabrication*



*3D and 2D Pipe Routing using Multi-robot Path Planning Algorithms*