2023 KNS 춘계 학술대회 워크샵:
원전적용을 위한 CFD 스케일 해석기술 및 실험

원자력 안전 연구를 위한
GPU 기반 고성능 컴퓨팅 및 무격자 CFD

김 응 수, 서울대학교

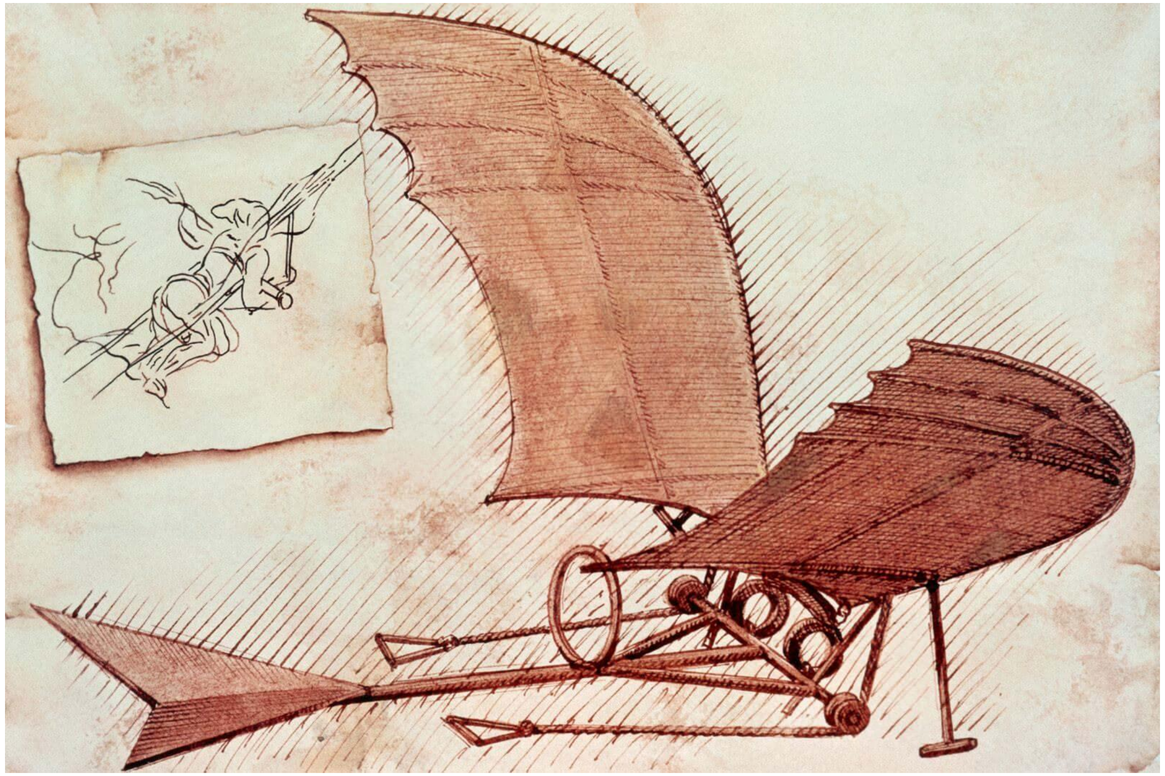
ADVANCED COMPUTING, INNOVATION

ADVANCED MODELING AND SIMULATION: TRANSFORMING THE WAYS WE UNDERSTAND HOW THE WORLD WORKS

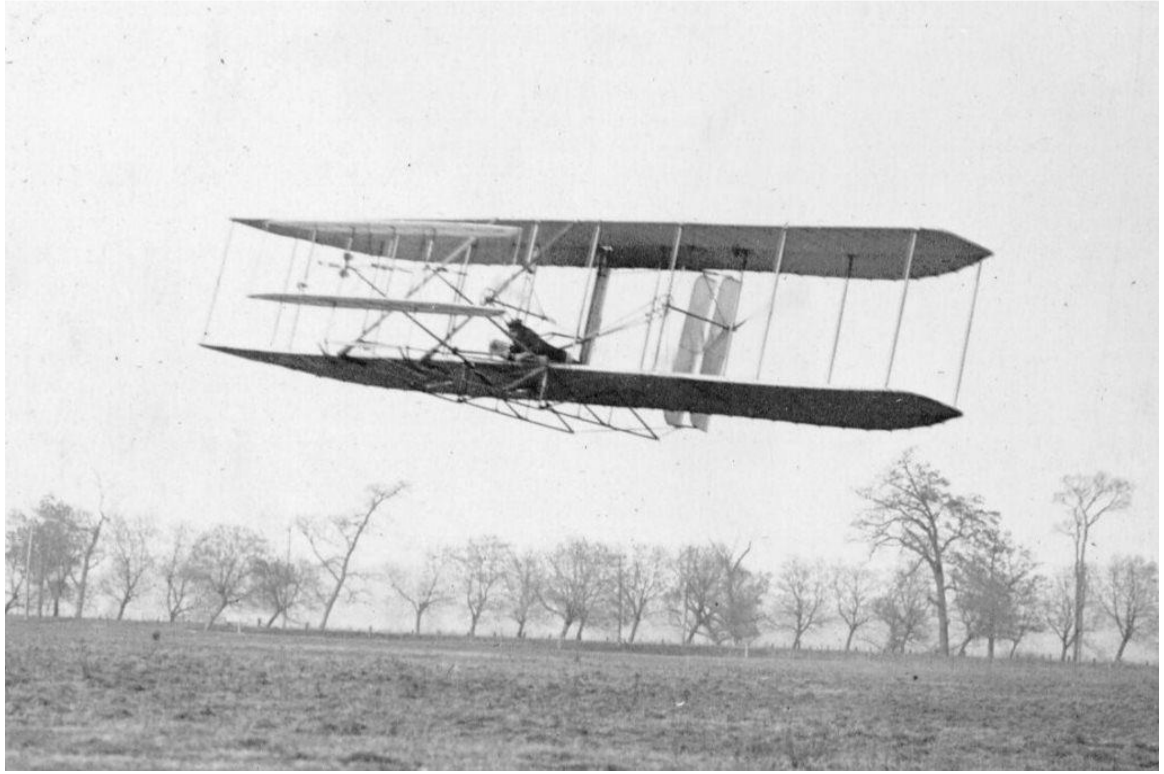
Alex Larzelere

*출처: https://graylinegroup.com/advanced-modeling-simulation/

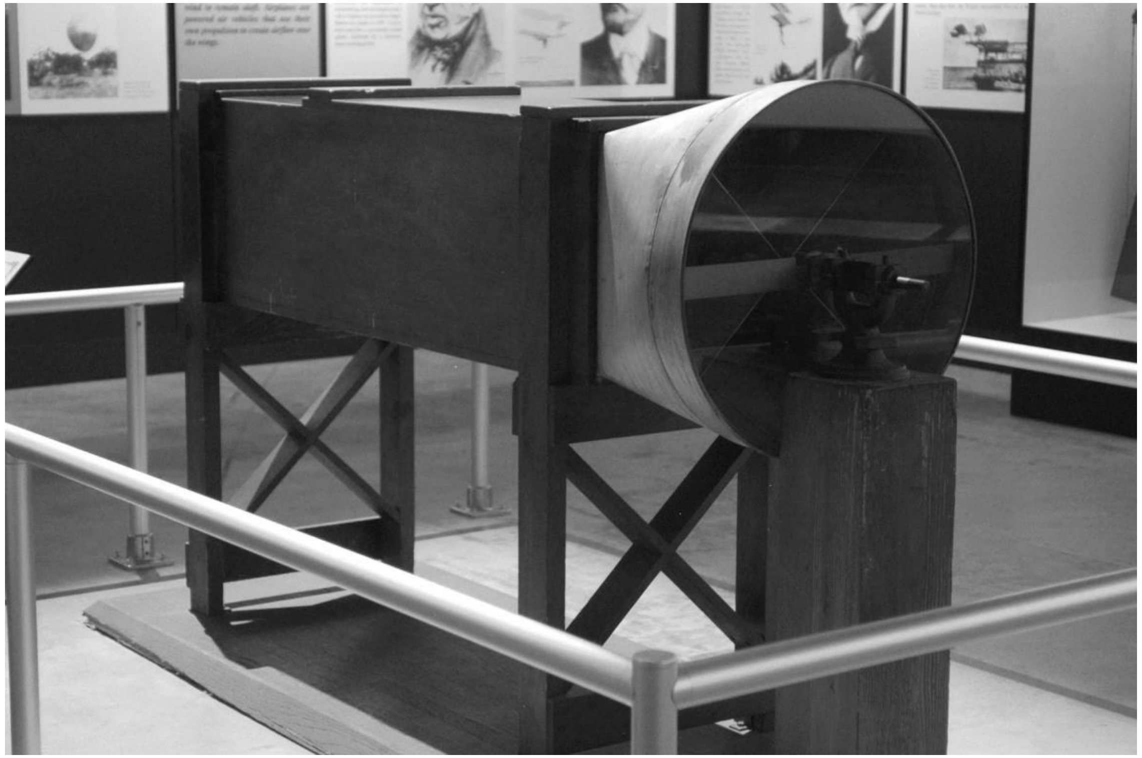
Leonardo Da Vinci

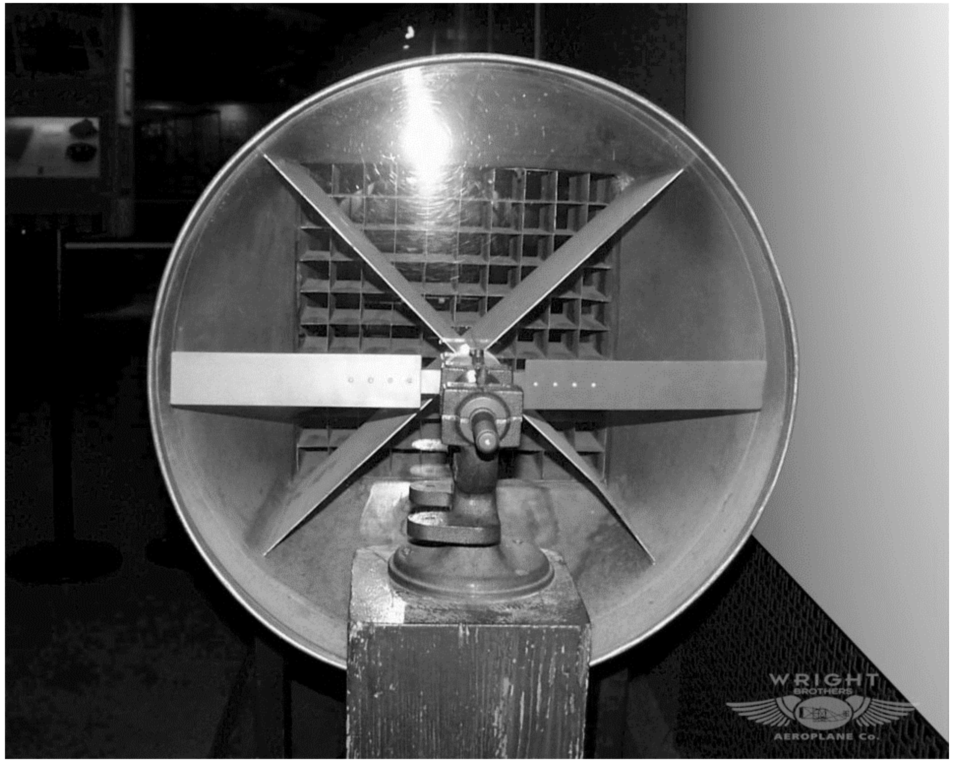


Wright Brothers



1901 Wright Brothers' Wind Tunnel

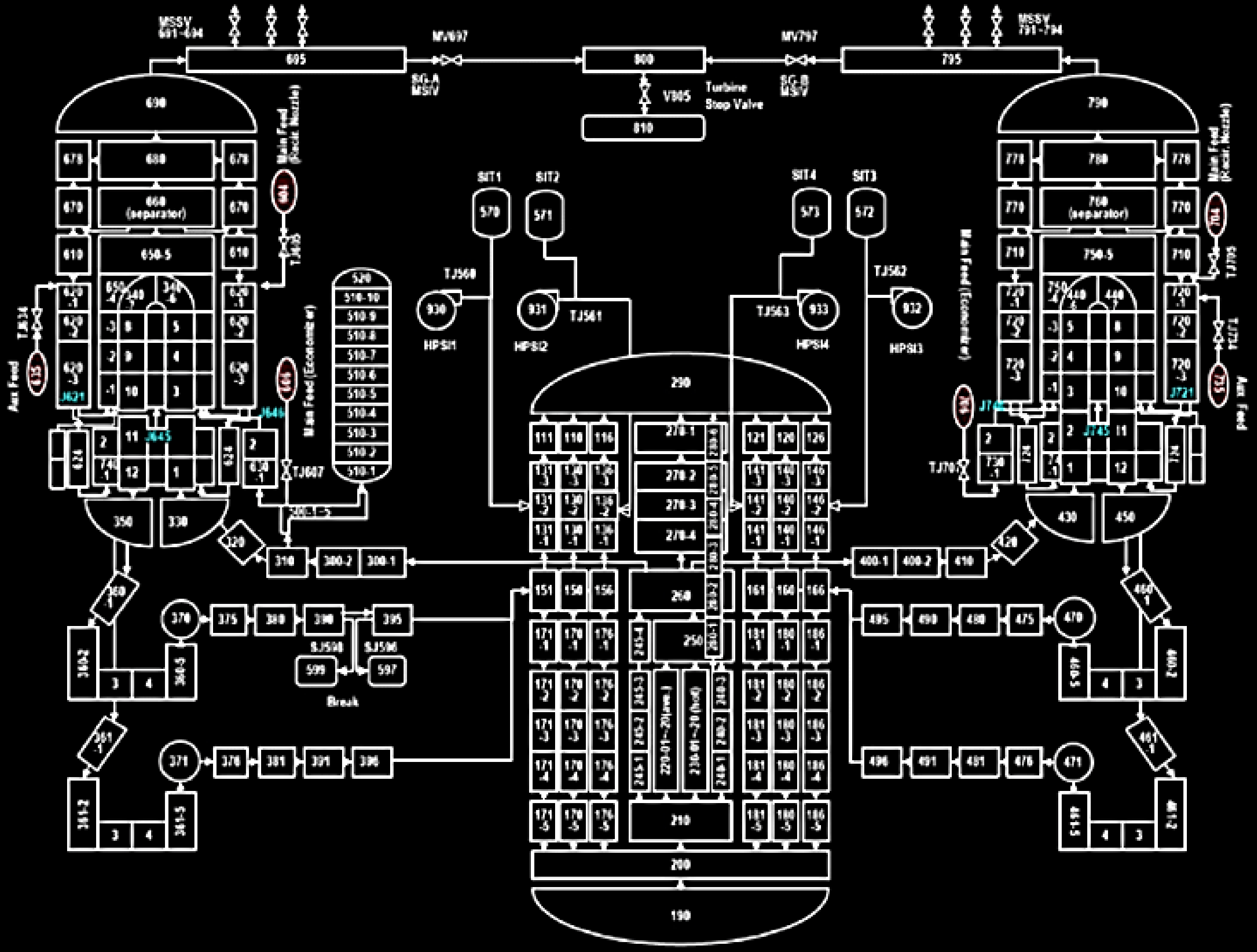


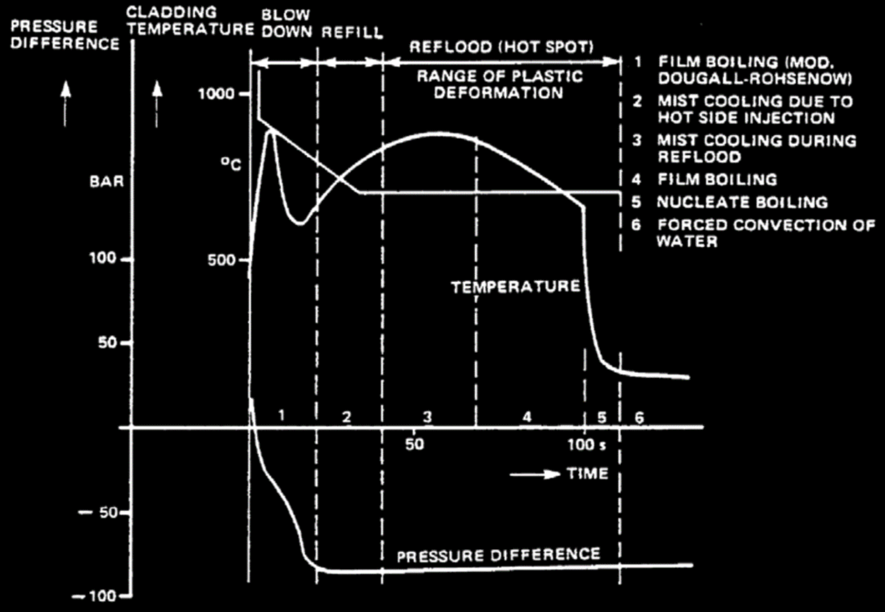


"Traditionally, scientific insights are developed using experiments and developing theories. Experiments are observation of physical processes, sometime done under special circumstances, that allow people to obtain a better understanding of what happens and how it happens."

*출처: National Museum of United States Air Force

ATLAS Experimental Facility (KAERI)

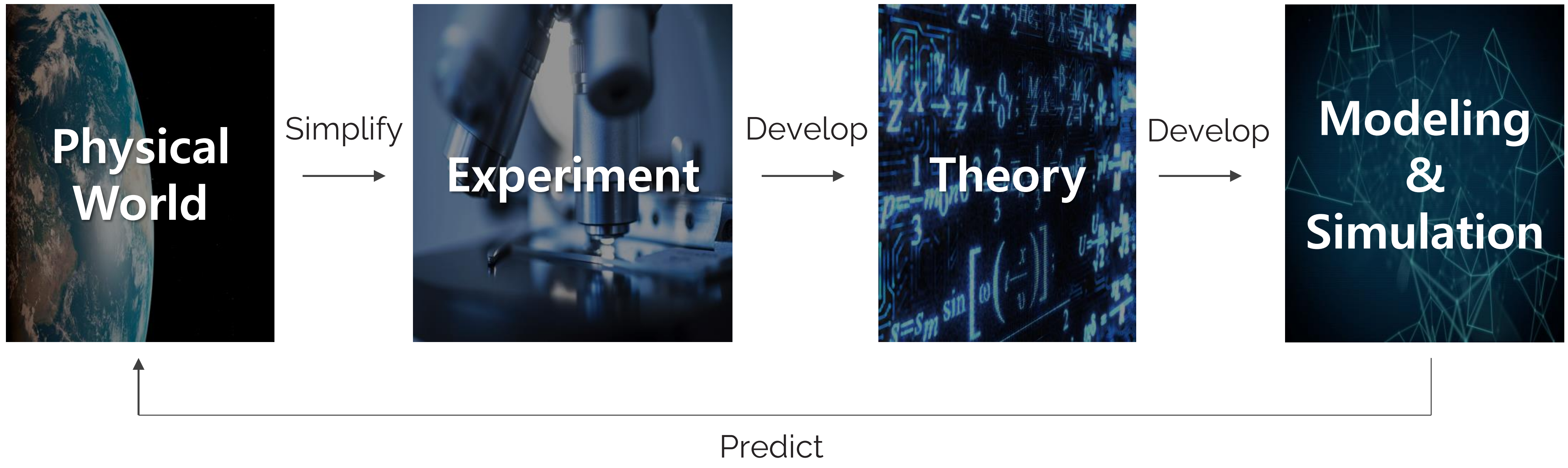




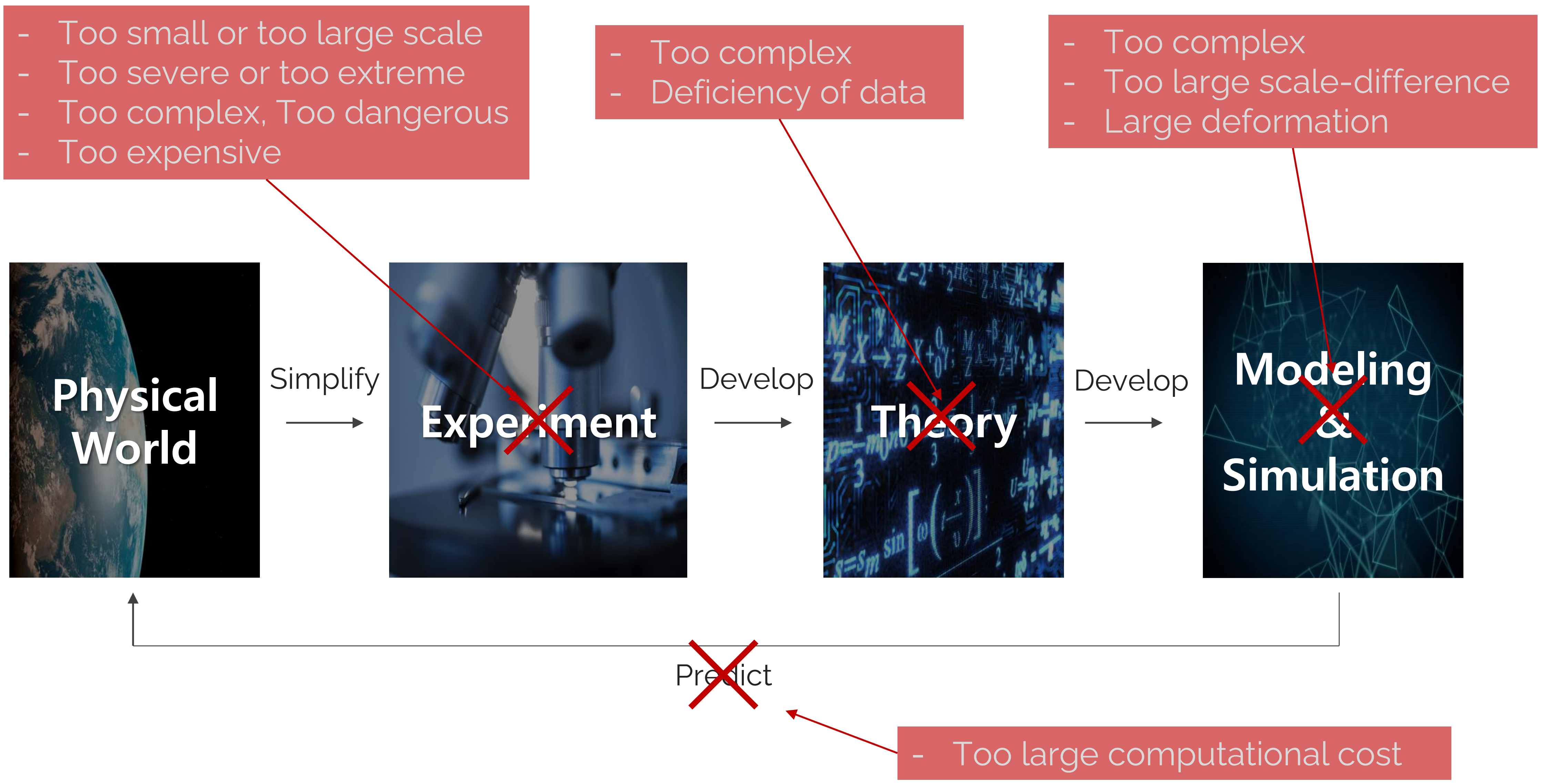
System Code Nodalization (APR-1400)

Systematic Engineering Approach

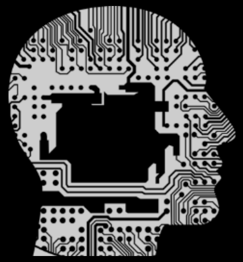
"Successful for 100 years"



What shall we do, if this process fails?


- Too small or too large scale
- Too severe or too extreme
- Too complex, Too dangerous
- Too expensive
- Too complex
- Deficiency of data
- Too complex
- Too large scale-difference
- Large deformation
Physical World
Simplify
Experiment
Develop
Theory
Develop
Modeling & Simulation
Predict
- Too large computational cost

How scientists address these issues.



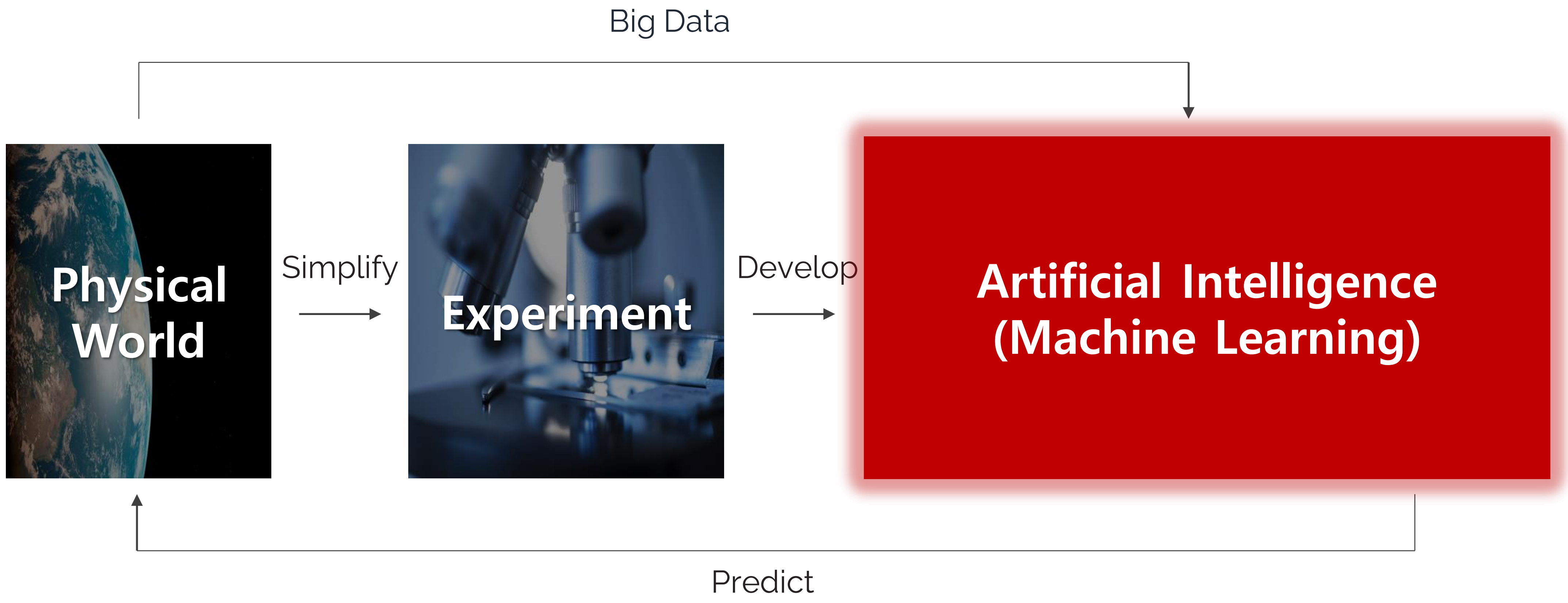
Data-Driven Approach

Maximizing Empiricism

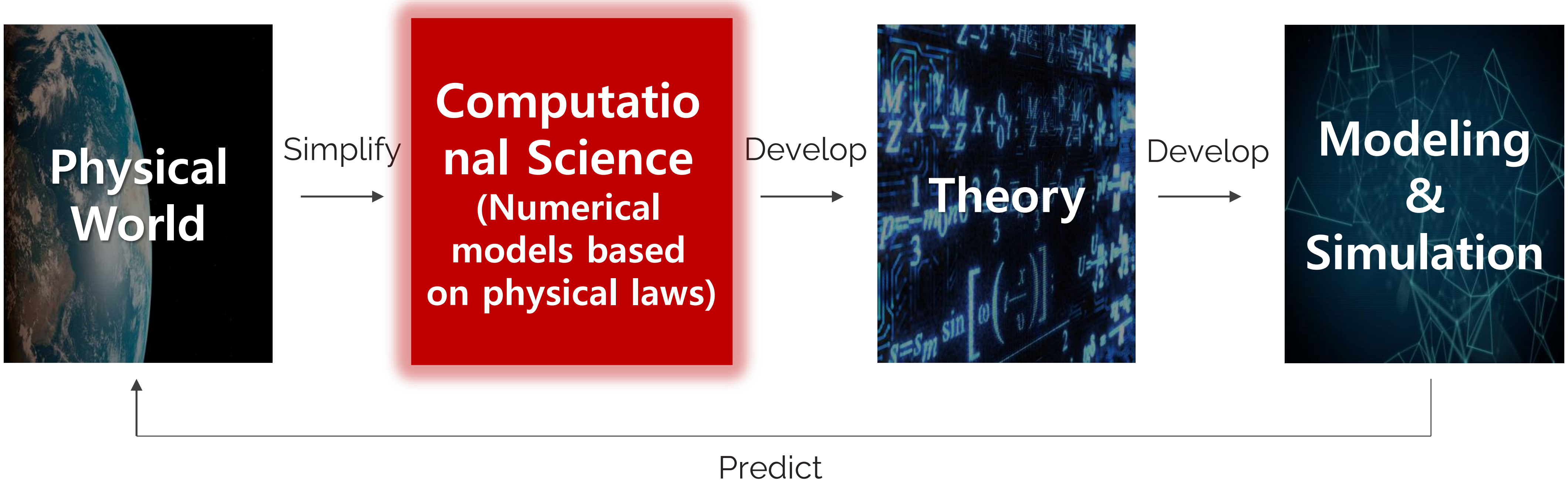
Physics-Based Approach

Maximizing Rationalism

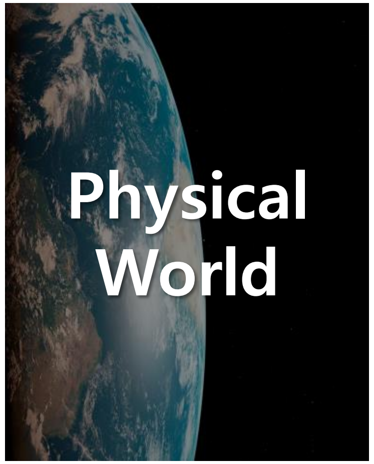
Data-Driven Approach



Physics-Based Approach



Physics-Based Approach

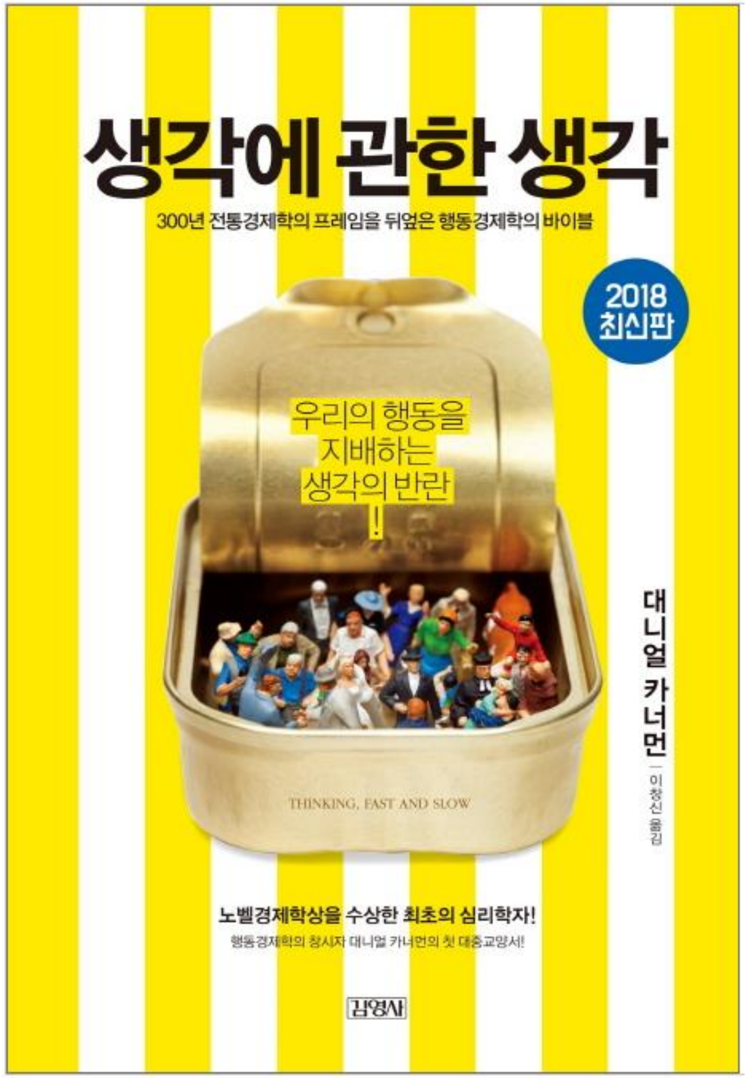


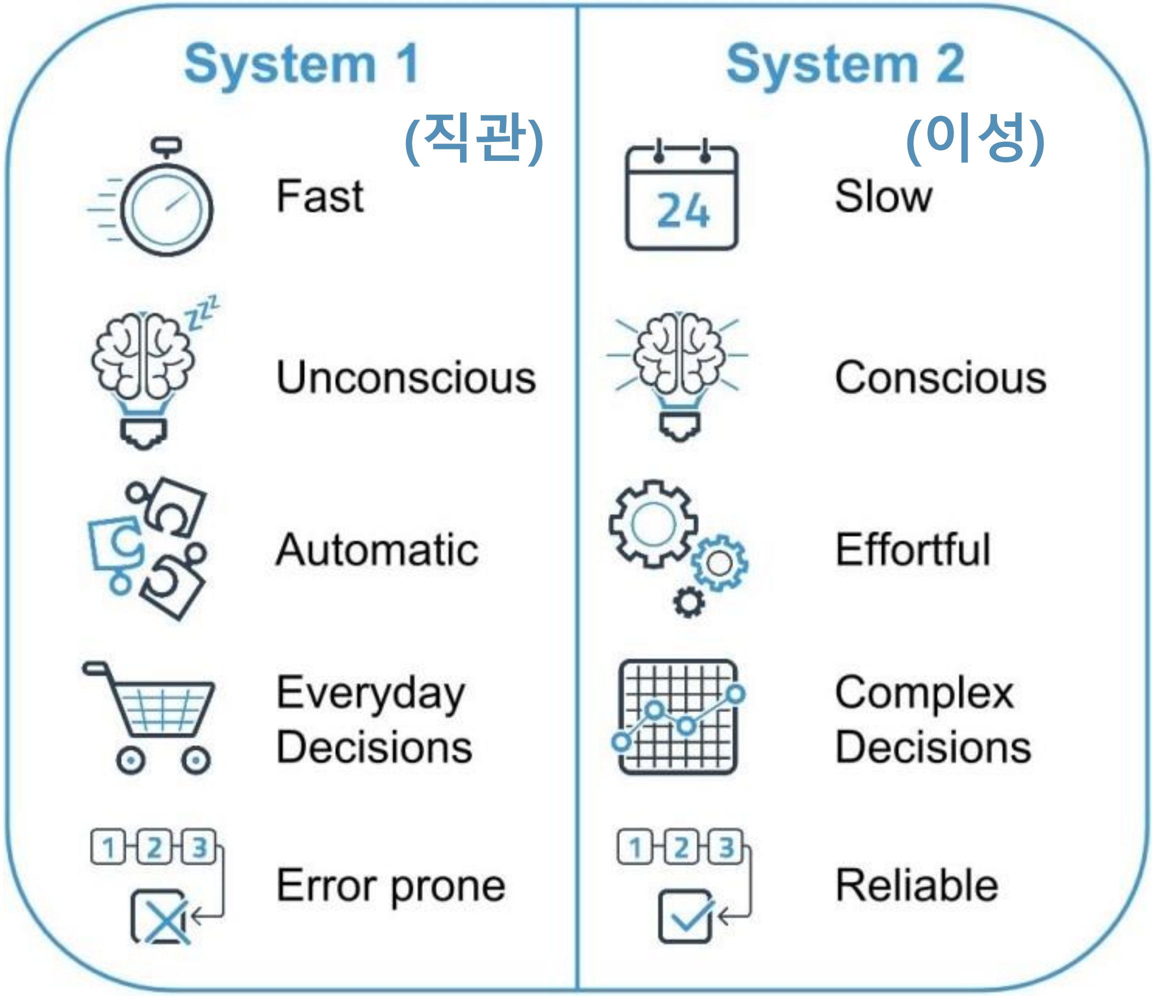
Simplify

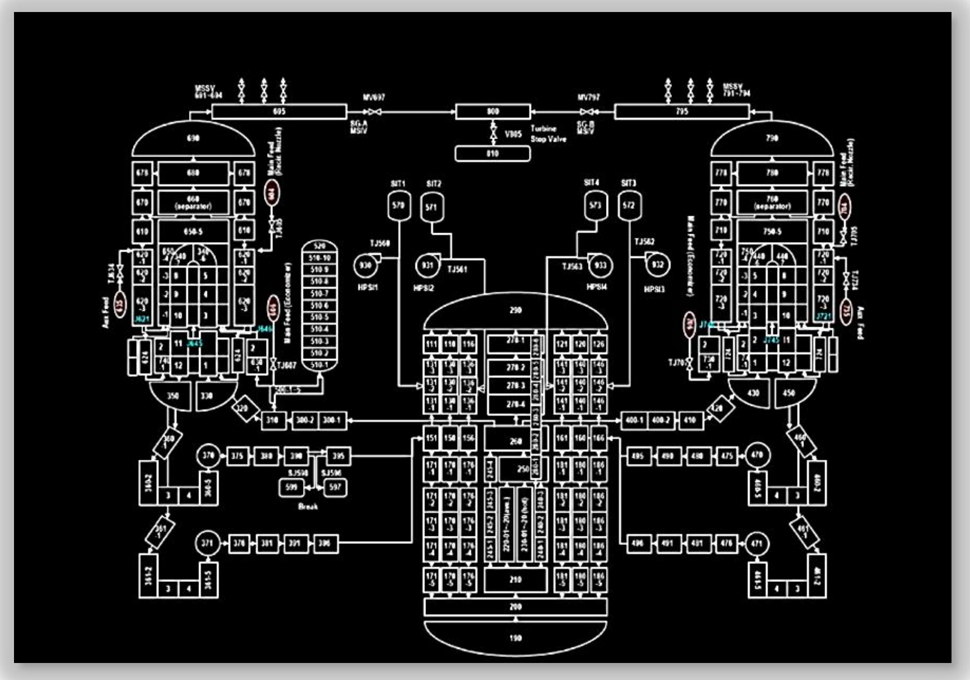
Computational Science
(Numerical models based on physical laws)

Predict

Which one is better?







Safety Analysis Code =

Physical Theory+ Empirical Models

The key is

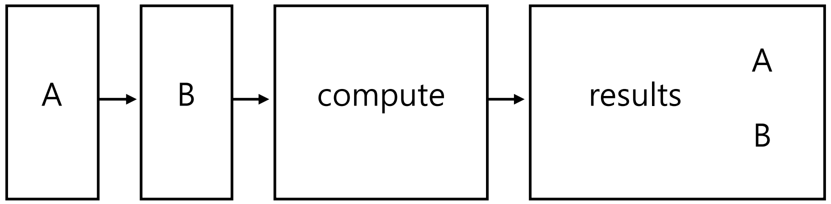
how to **harmonize** them

to maximize $\boxed{\text{performance.}}$

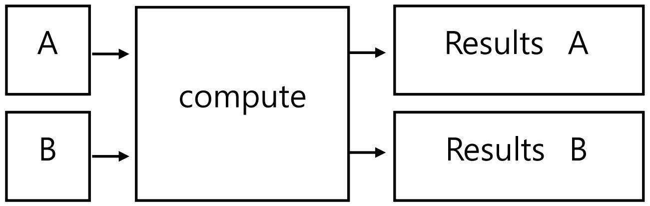
$$= \frac{\text{Product Quality}}{\text{Cost}}$$

High Performance Computing (HPC)

“ **High performance computing** (**HPC**) is the ability to process data and perform complex calculations at high speeds. “ (NetApp)



Serial Processing



Parallel Processing

Types of High-Performance Computing

계산 클러스터

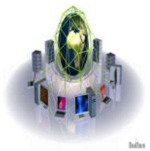
Computer Cluster

분산 컴퓨팅

Distributed Computing

클라우드 컴퓨팅

Cloud Computing



그리드 컴퓨팅

Grid Computing

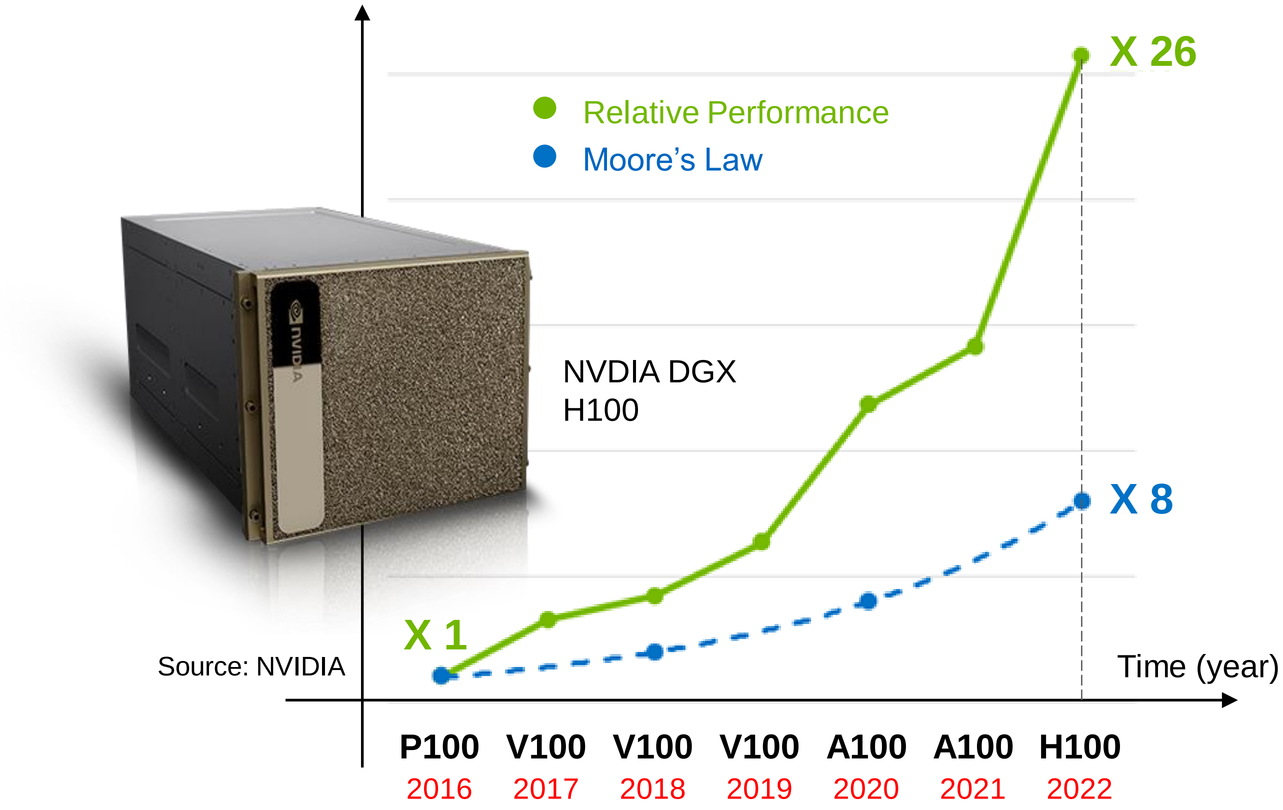
양자 컴퓨팅

Quantum Computing

Graphical Processing Unit (GPU)

“The performance of semiconductors that drive artificial intelligence more than doubles every two years "

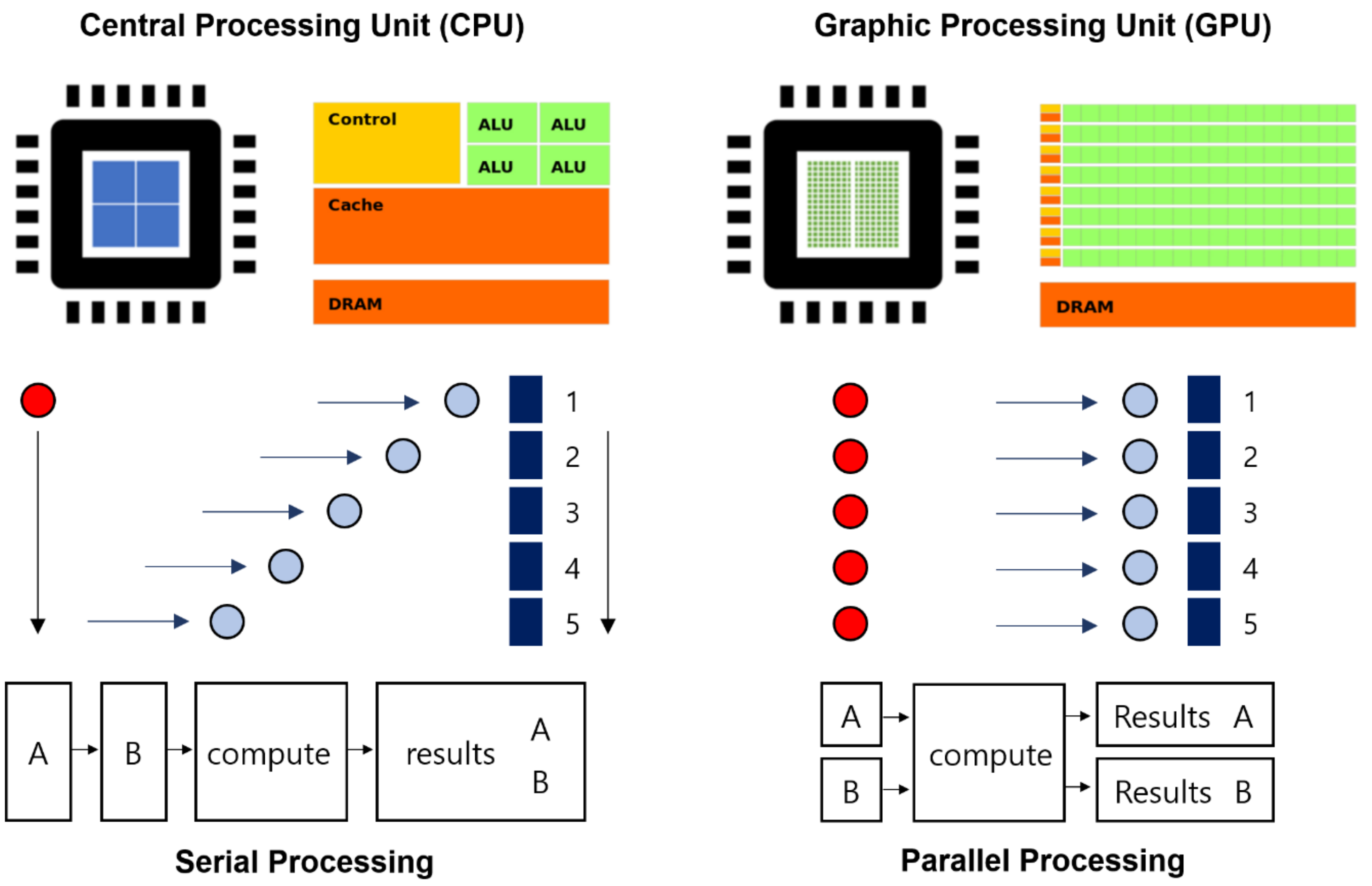
Nvidia Corp. co-founder
Jensen Huang



CPU vs. GPU

Operation

- 논리 연산
- 시프트 연산
- 정수 연산
- 소수점수 연산



CPU vs. GPU (Computing Power)

the FPS review	Core i9 9900K
Code Name	Skylake-X
Process	14nm
Cores/Threads	8 Cores / 16 Threads
Base Clock	3.6GHz
Turbo Boost	4.7GHz
Max Turbo 3.0	5.0GHz
Cache	16MB Intel Smart Cache
Max Memory	128GB
RAM Speed	DDR4 2666MHz
Mem Channels	2
PCIe Lanes	16
TDP	95w
Price	$489

$8 \times 3.6 \times 10^9$

$= 28{,}800{,}000{,}000$ [operations/sec]

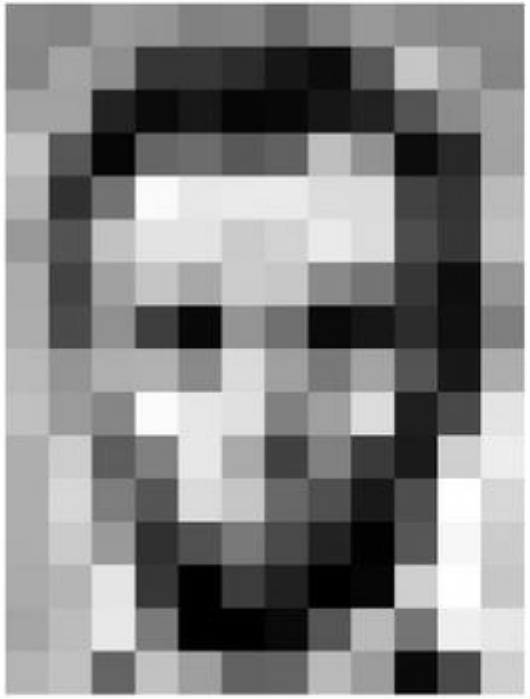
GPU	GeForce RTX 3090 (Founders Edition)
SMs	82
CUDA Cores	10496
Tensor Cores	328 *(3rd Generation)*
RT Cores	82 *(2nd Generation)*
Texture Units	328
ROPs	112
GPU Boost Clock	1695 MHz
Memory Clock	9750 MHz
Total Video Memory	24576 MB GDDR6X
Memory Interface	384-bit
Memory Bandwidth	936 GB/s
TGP	350W

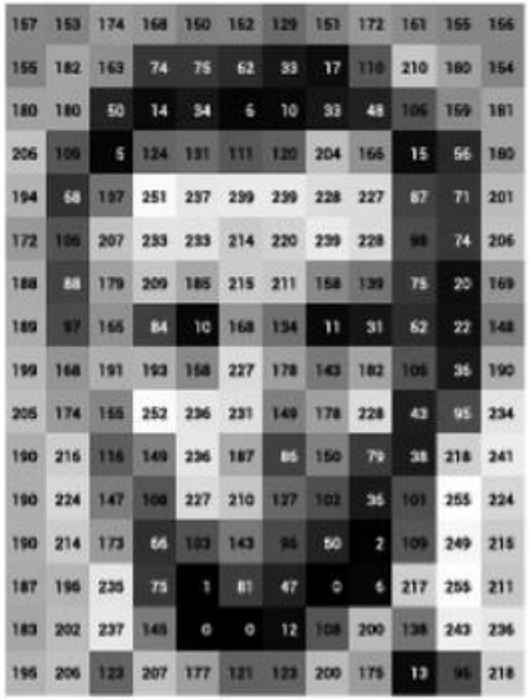
$10{,}496 \times 1.7 \times 10^9$

$= 17{,}843{,}200{,}000{,}000$ [operations/sec]

Pixel

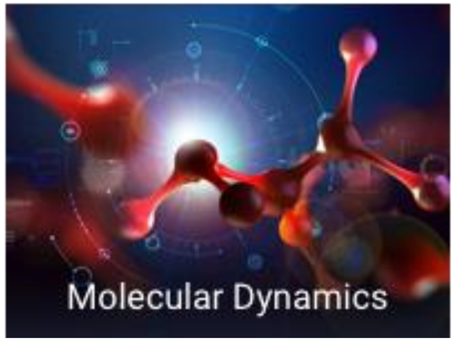
Matrix

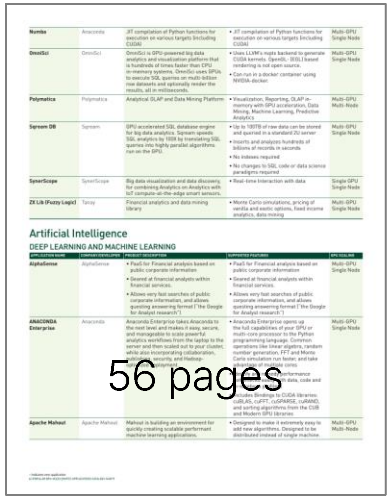




157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

A General-Purpose Graphics Processing Unit (**GPGPU**) is a graphics processing unit (GPU) that is programmed for purposes beyond graphics processing.





Applications of GPU

Graphics Processing Units (GPUs) have become increasingly important in engineering and science due to their ability to perform complex parallel computations at high speed. They are used extensively in simulation and modeling, artificial intelligence and machine learning, image and video processing, and high-performance computing. The use of GPUs is expected to continue to grow in these fields as researchers and engineers seek faster and more efficient ways to process data and perform complex computations.

Anyone Can Do.
Everyone Must Do.

Versatile Computational Solutions

For Nuclear Systems and Safety

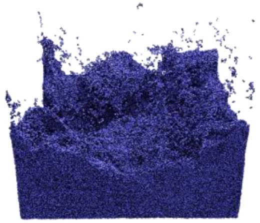
1 professor
1 research professor
15 PhD students
9 MS students
5 undergraduate students

ESLAB
Nuclear Energy System Lab

About Us

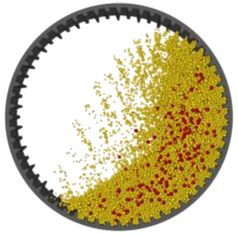
Our laboratory develops innovative & versatile computational solutions for developing nuclear systems and enhancing nuclear safety empowered by state-of-the-art technologies.

Meshless Method



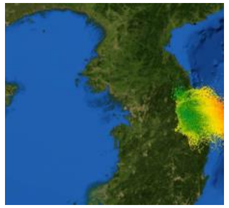
Solving Continuum Mechanics

Smoothed Particle Hydrodynamics (SPH)



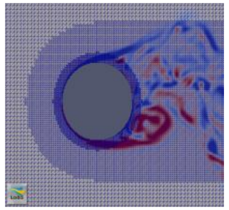
Solving Discrete Solid Elements

Discrete Element Method (DEM)



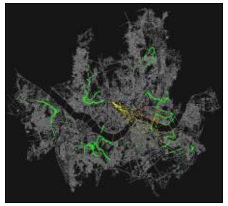
Solving Particle Stochastic Dispersion

Lagrangian Dispersion Method (LDM)



Solving Meso-scale Physics

Lattice Boltzmann Method (LBM)



Solving Human Behaviors

Agent Based Model (ABM)

On-going Researches

[코드개발 / 수치해법 개발 / 고성능컴퓨팅]

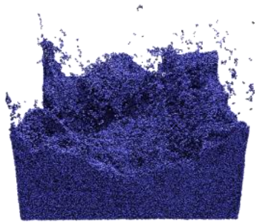
WCSPH, ISPH, EISPH, ALE, IBM 등의 다양한 SPH 수치해법을 단일 솔버로 통합
ALE-SPH 기반의 Adaptive Meshless CFD 기술 개발
대규모 다중 GPU SPH 해석을 위한 동적부하균등 알고리즘 개발 및 고도화
SPH 기반의 대규모 도시 내 유동 시뮬레이션 기술 개발
LBM 기반의 실시간 대규모 도시 내 유동 시뮬레이션 기술 개발
Lumped Parameter Model 기반의 MCCI 해석코드 개발 및 검증

[물리모델 개발 / 모델링 / 역함수 모델]

열유동 및 구조해석을 연계한 IVR-ERVC 통합 해석기술을 개발
SPH를 이용한 FFRD 모델링 기술 개발
SPH를 이용한 파이로 공정 중 Electrolytic Oxidation Reduction 해석 및 최적화
SPH 기반 충격파-구조 상호작용 모델링 기술 개발 및 검증
SPH를 이용하여 Bubbly Flow 모델 구현 및 Boiling 모델 구현
LES 기반의 SPH 난류모델 고도화
SPH-DEM 연계를 통한 MCCI 시 Debris 거동 모델 개발 및 고도화
SPH-DEM-MC 연계를 통한 Pebble Bed Reactor 열유동 상세해석기술 개발
X-Pinch Plasma 현상을 모의할 수 있는 물리모델 및 수치해법 개발
SPH를 이용하한 3-D Printing 모델링 기술 구현
SPH를 이용한 Microfluidics 모델링 기술 개발
LDM 기반의 고성능 오염물 대기확산모델링 기술 개발 및 고도화
메타휴리스틱 및 인공지능 기반의 최적화 알고리즘을 활용한 방사능물질 선원항 평가기술 개발

[창의설계 / 최적화]

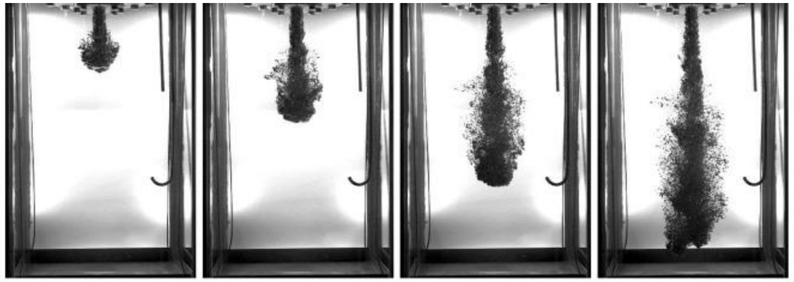
무격자 기반 위상 최적화 및 진화 디자인 기술 개발
인공지능을 이용한 진화 디자인 기술 개발



Solving Continuum Mechanics

Fluid Flow Modeling with Large Deformation & Multiple Phases (SPH)

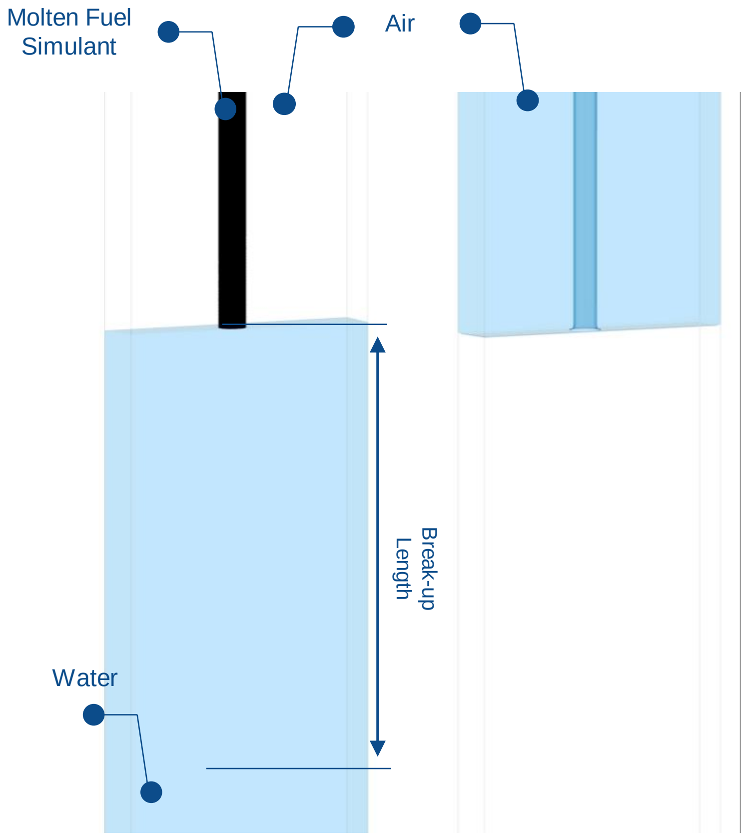
Fuel Coolant Interaction (FCI): Jet Break-up

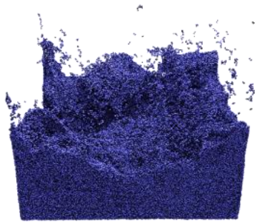


(a) Time interval = 0.1 s (D_j = 50 mm, $V_{j,in}$ = ~1.0 m/s, T_l=40°C)

(b) Time interval = 0.05 s (D_j = 50 mm, $V_{j,in}$ = ~4.0 m/s, T_l=40°C)

(Bang et al., 2018)

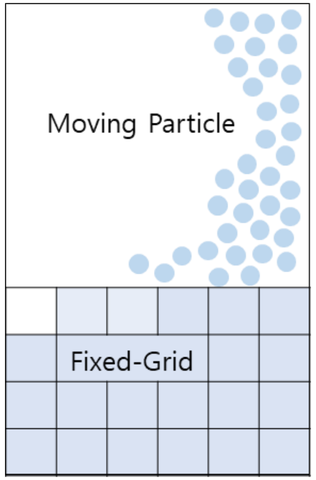


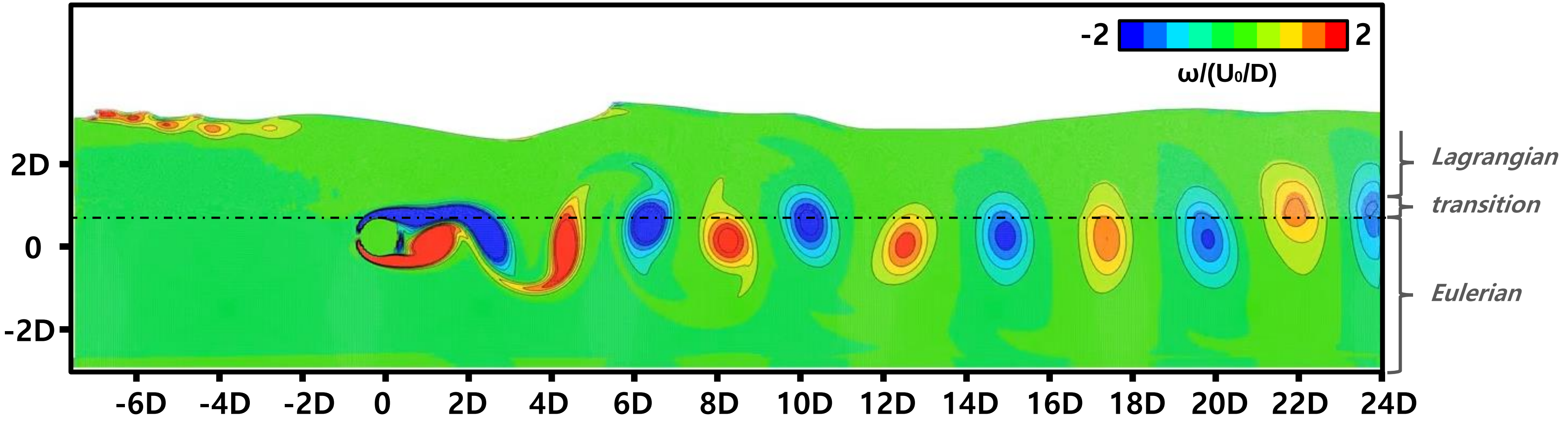


Solving Continuum Mechanics

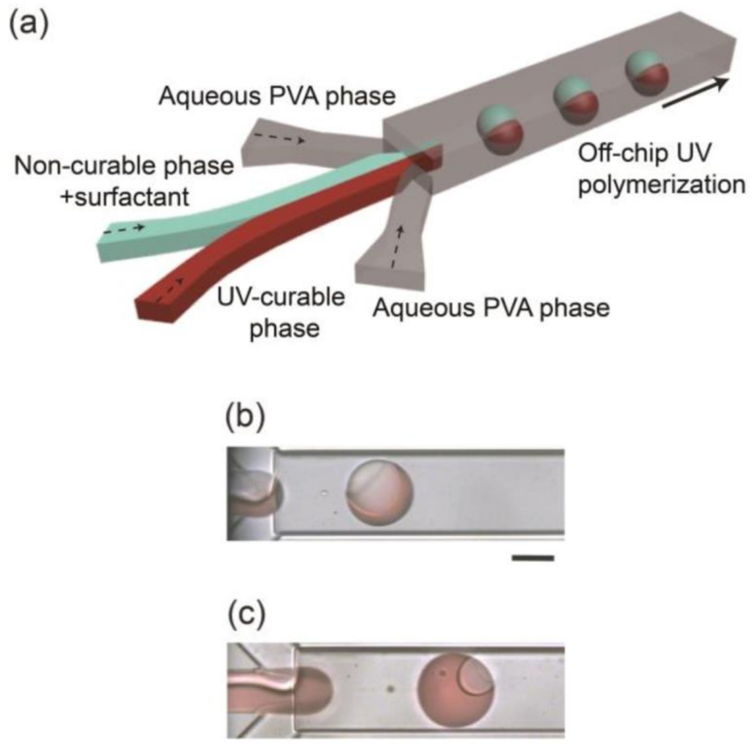
Free Surface Flow Modeling using Mixed Eulerian-Lagrangian Scheme (SPH)

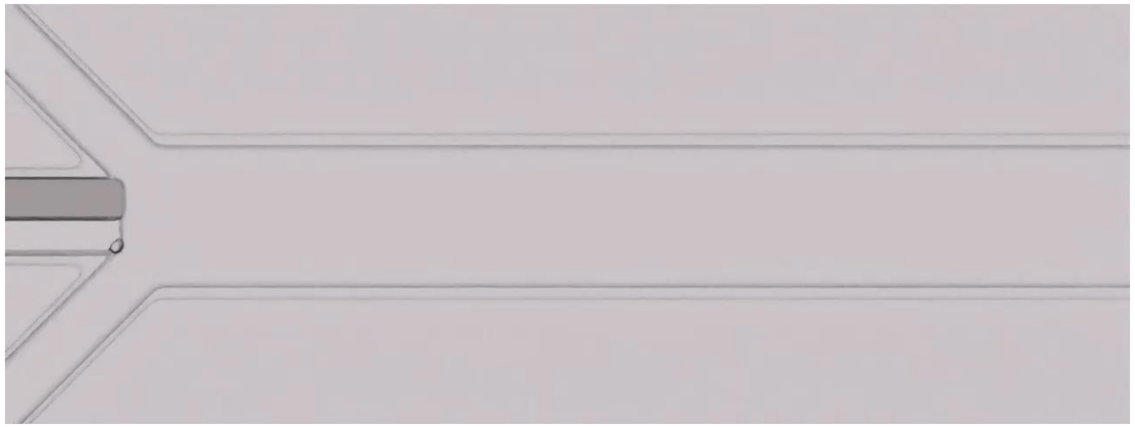
ALE

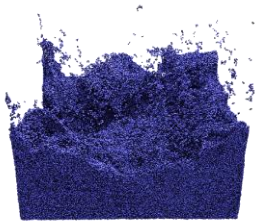




Synthesis of Janus Droplet



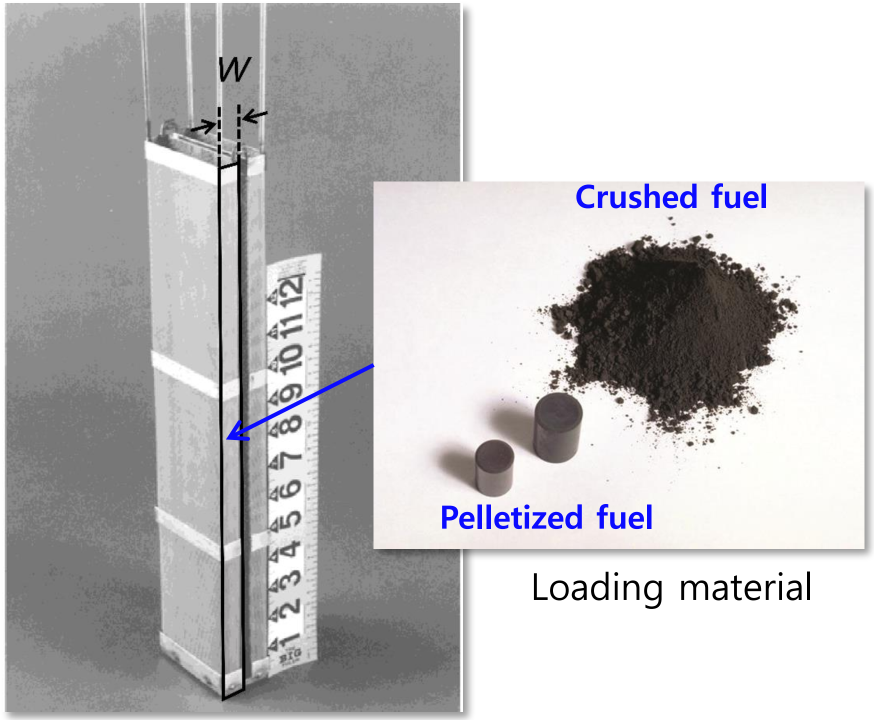




Solving Continuum Mechanics

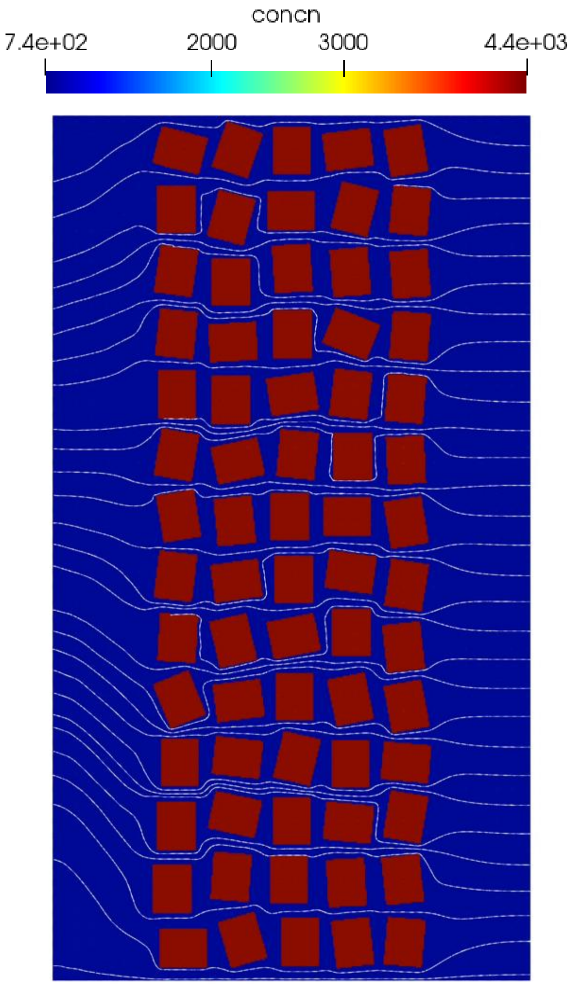
Convective Diffusion Modeling with Moving Boundaries (SPH)

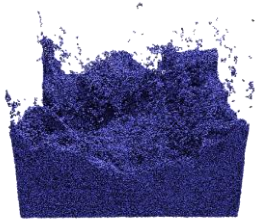
Electrolytic Reduction Basket for Pyro-processing



Loading material

Reduction basket
(Karell et al., 2002)

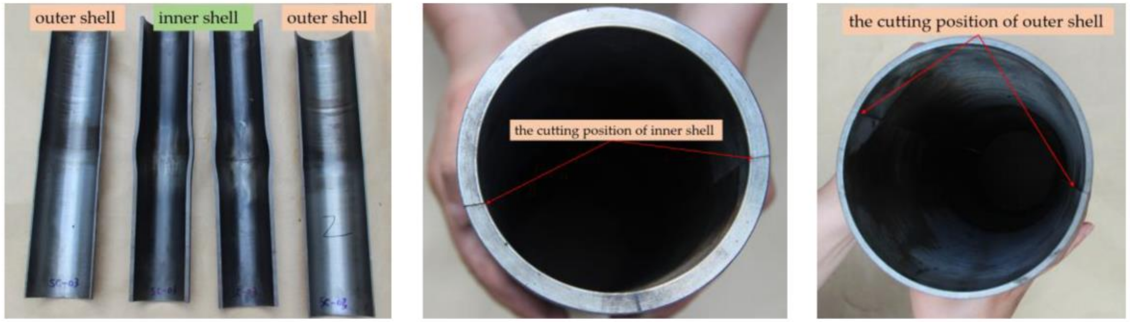




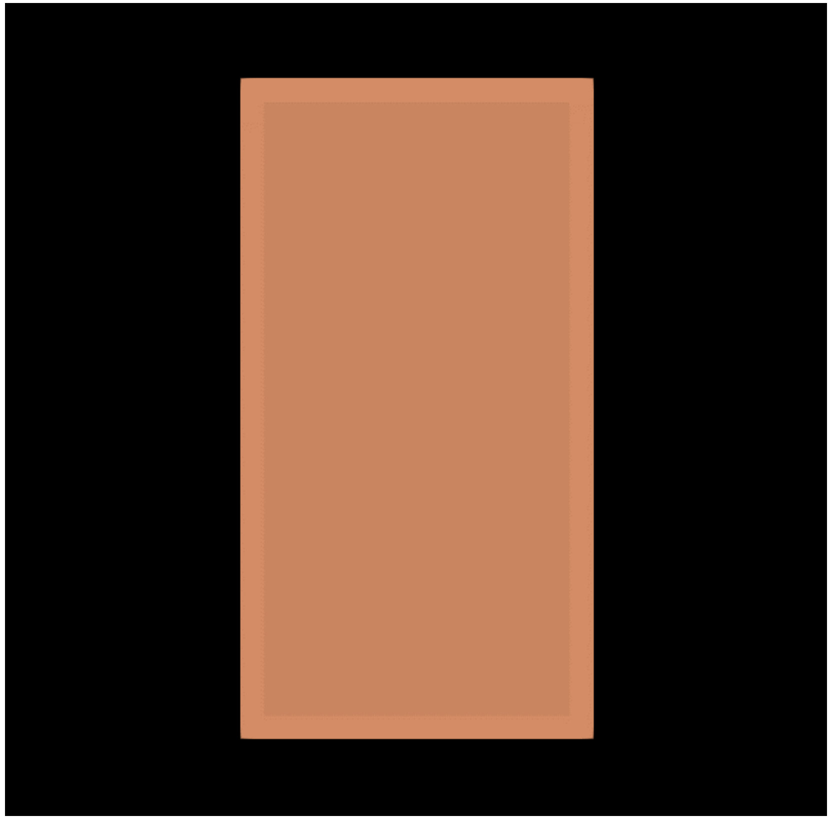
Solving Continuum Mechanics

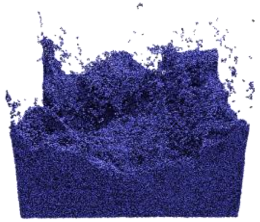
Unified Shockwave-Elastoplastic Structure Interaction Modeling (SPH)

Underwater Explosion in Metal Container



(a) (b) (c)

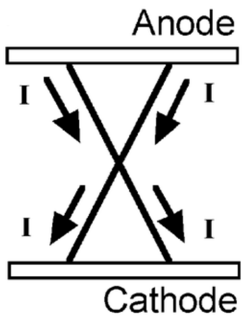


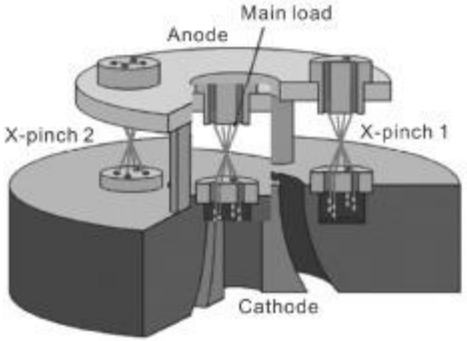


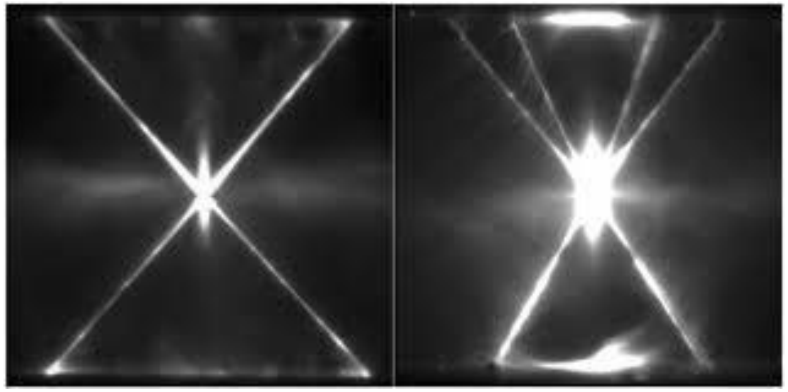
Solving Continuum Mechanics

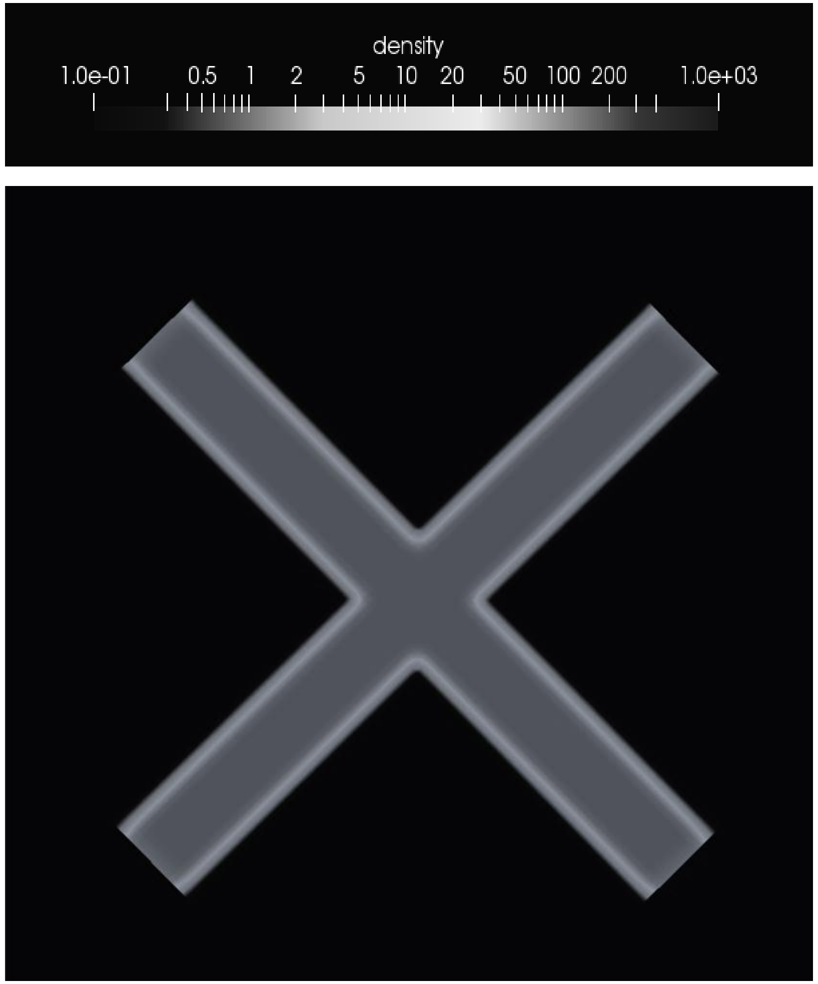
Fluid Flow Modeling Interacting with Electromagnetic Forces (SPH)

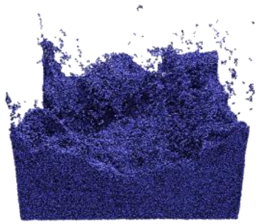
X-Pinch: High Density Plasma







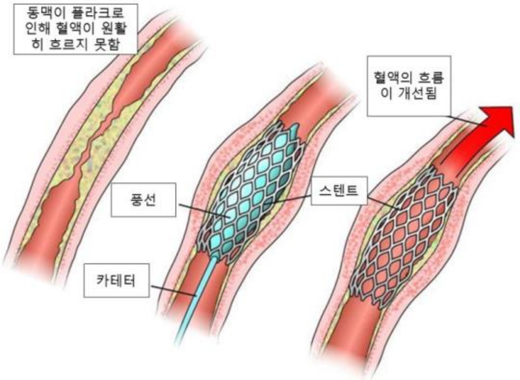


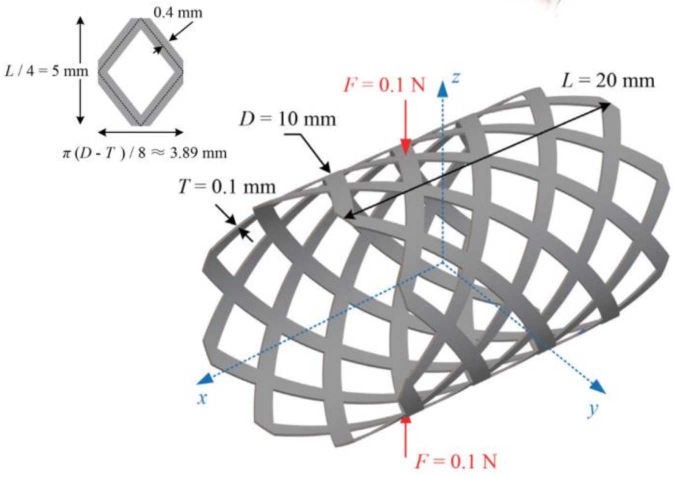


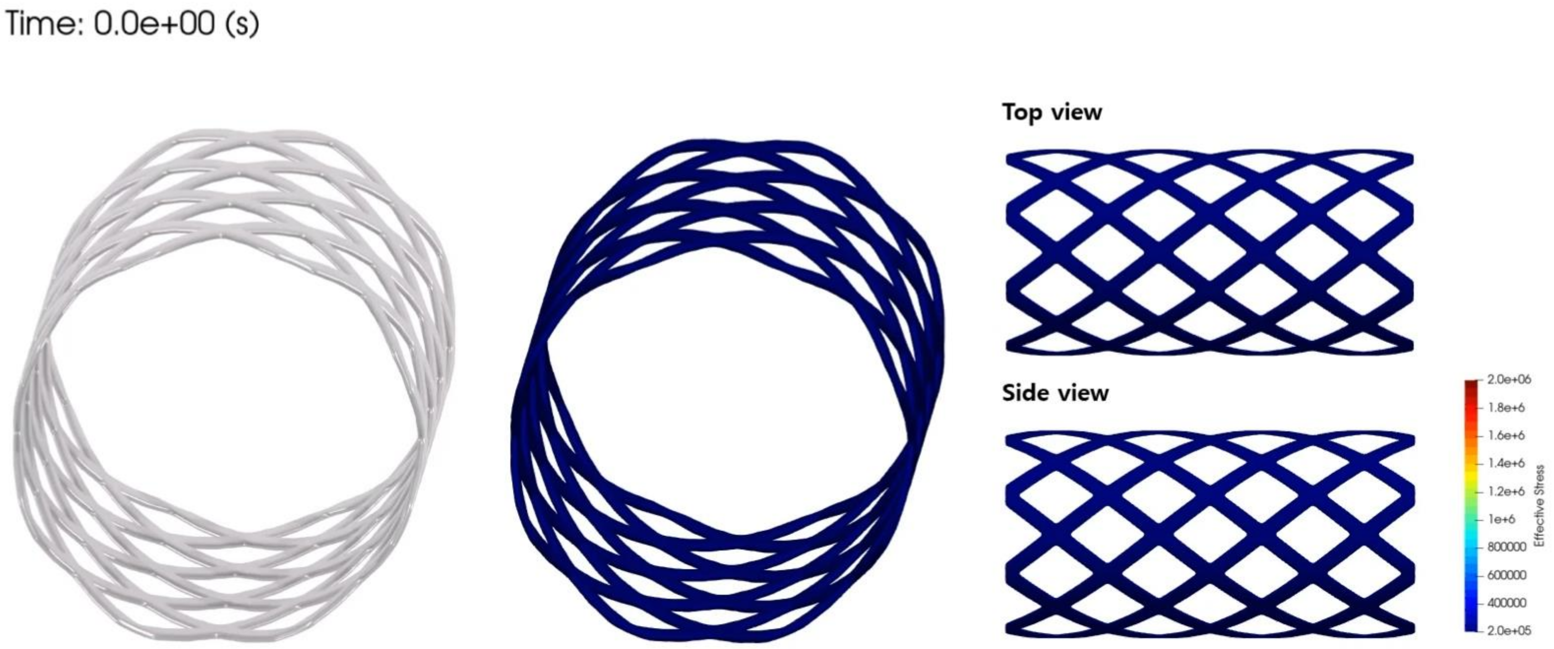
Solving Continuum Mechanics

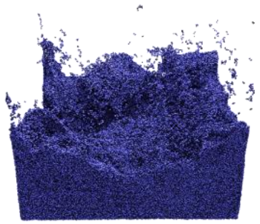
Total Lagrangian Solid Structure Modeling with Large Deformation (SPH)

Biomechanical Stent



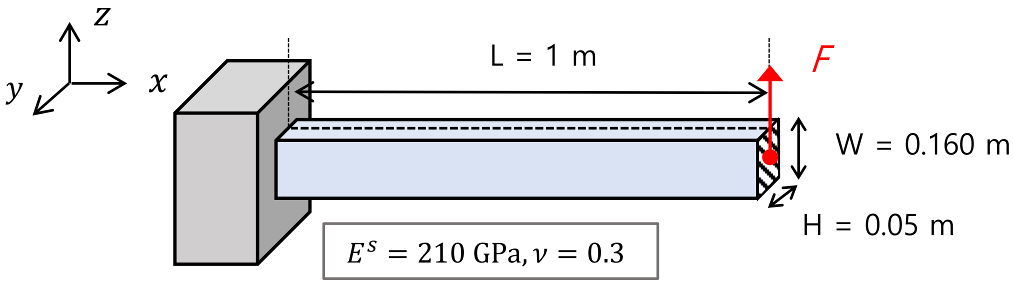


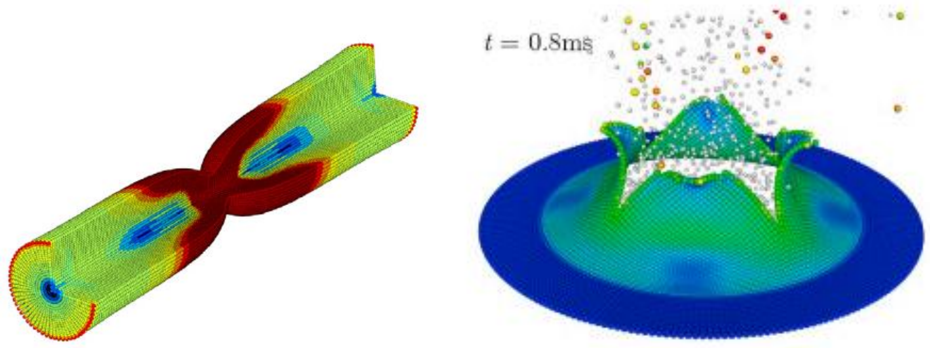


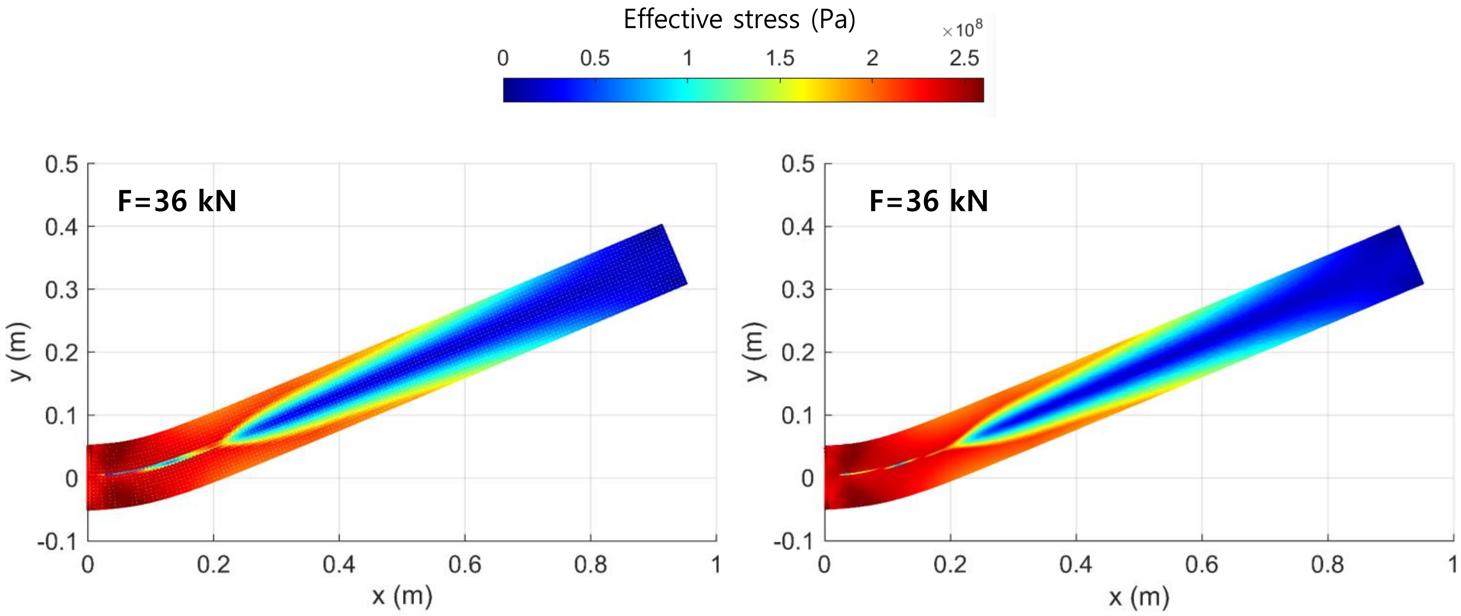


Solving Continuum Mechanics

Large Strain Elastoplastic Deformation Modeling with Hyperelastic Model (SPH)

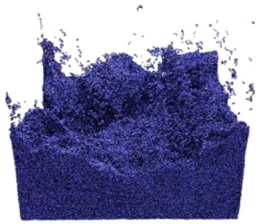






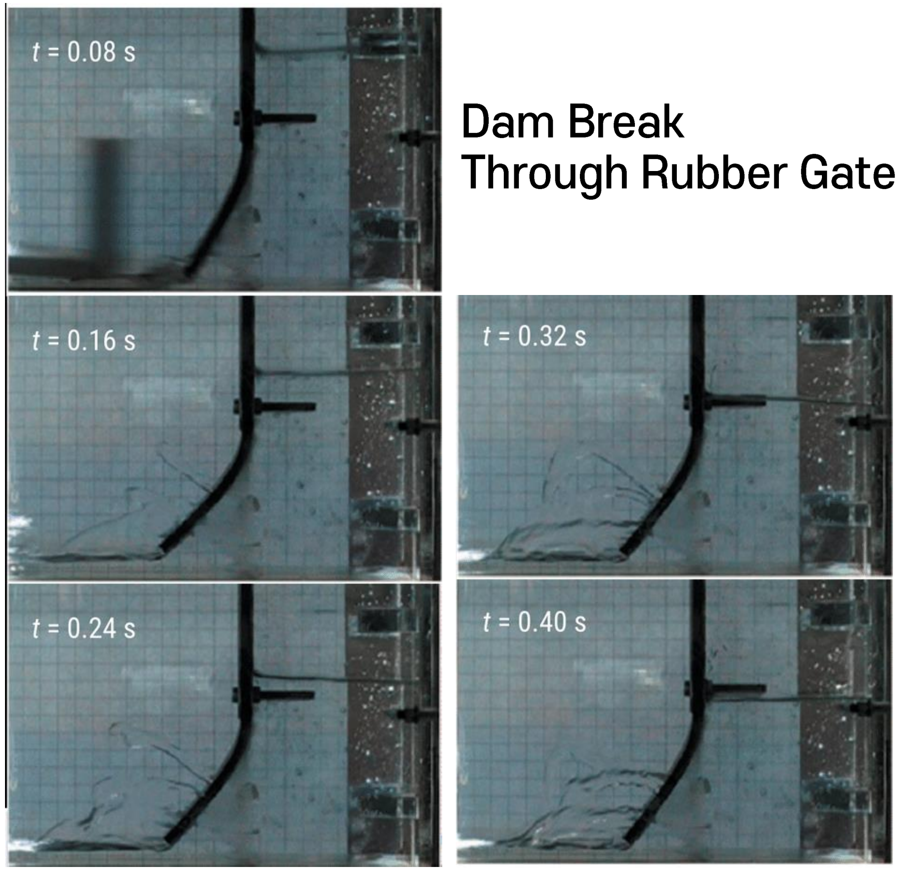
Ansys/Mechanical

This study (SPH)

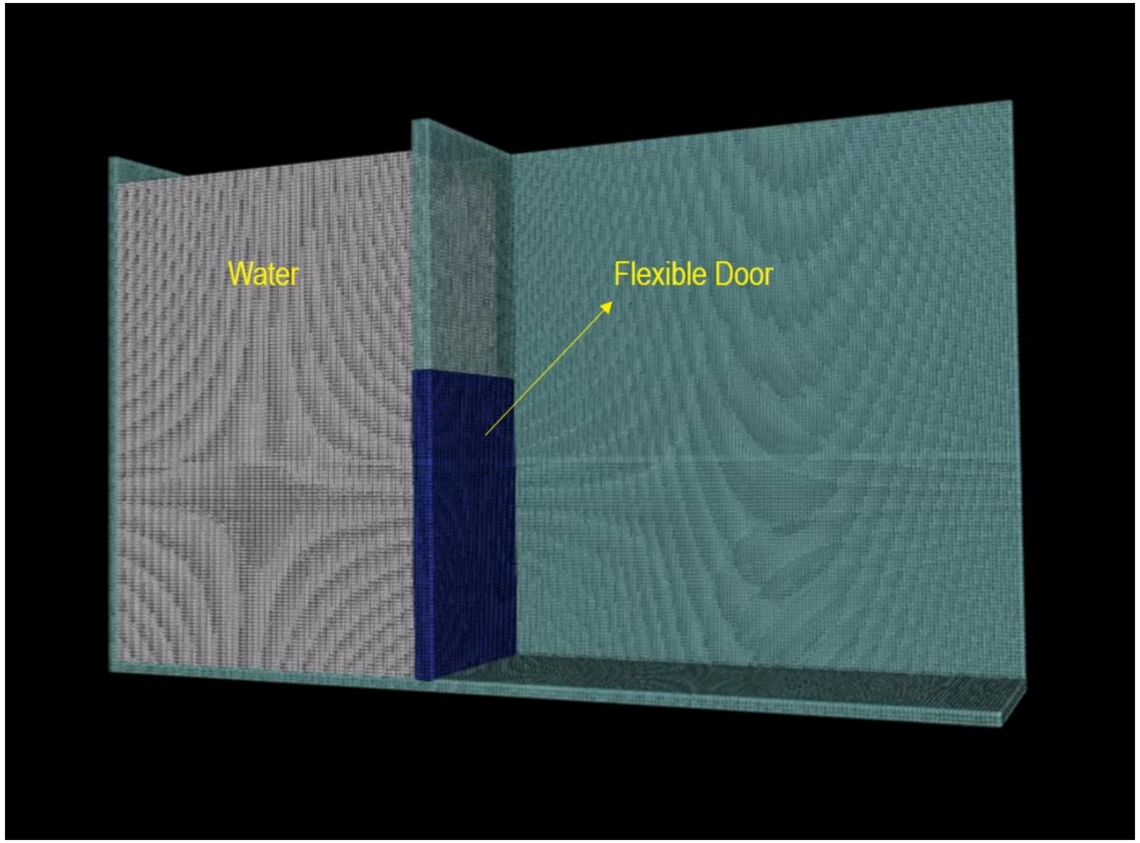


Solving Continuum Mechanics

Unified Fluid-Structure Interaction Modeling (SPH)

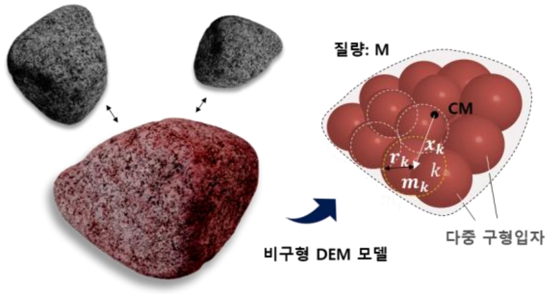


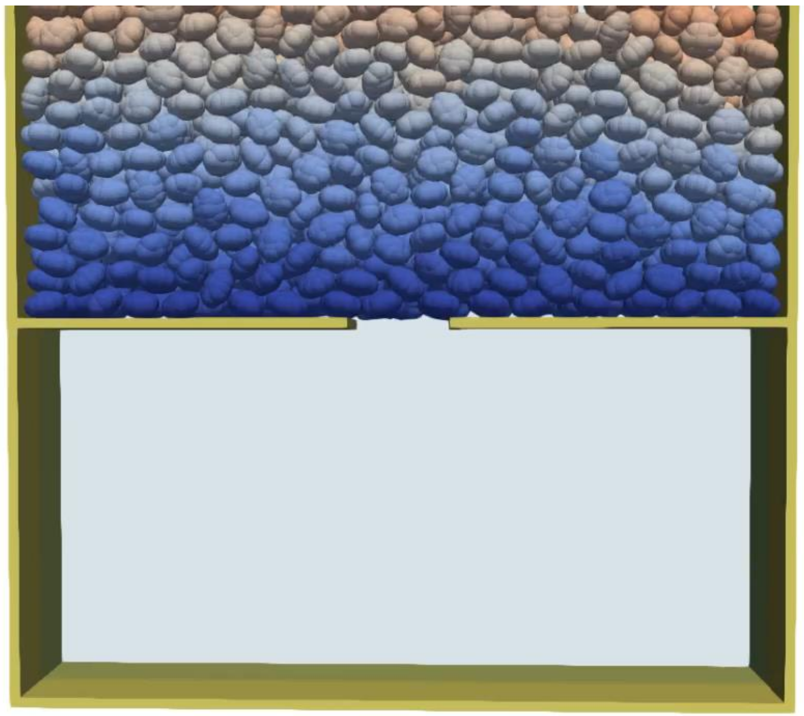
Dam Break
Through Rubber Gate

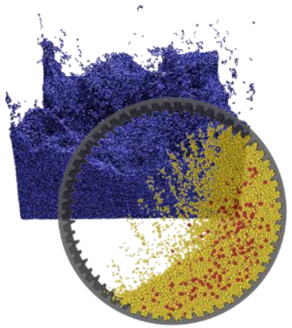


Solid Particulates Modeling with Arbitrary Geometries (DEM)

Non-spherical DEM model



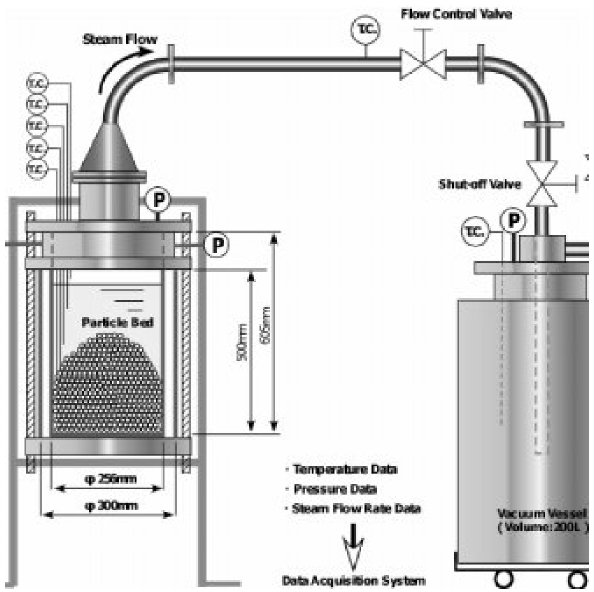


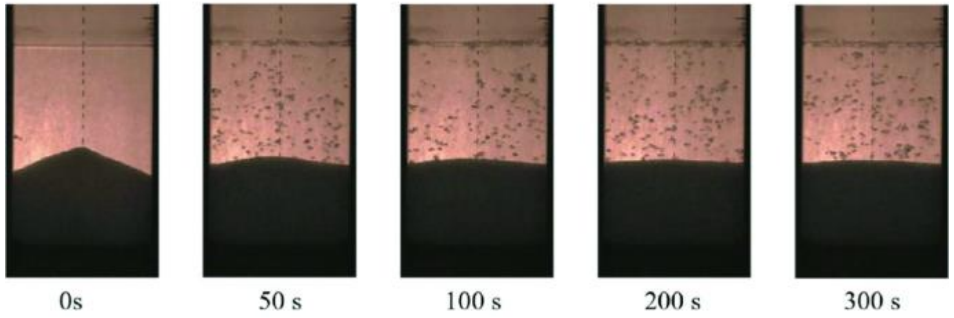


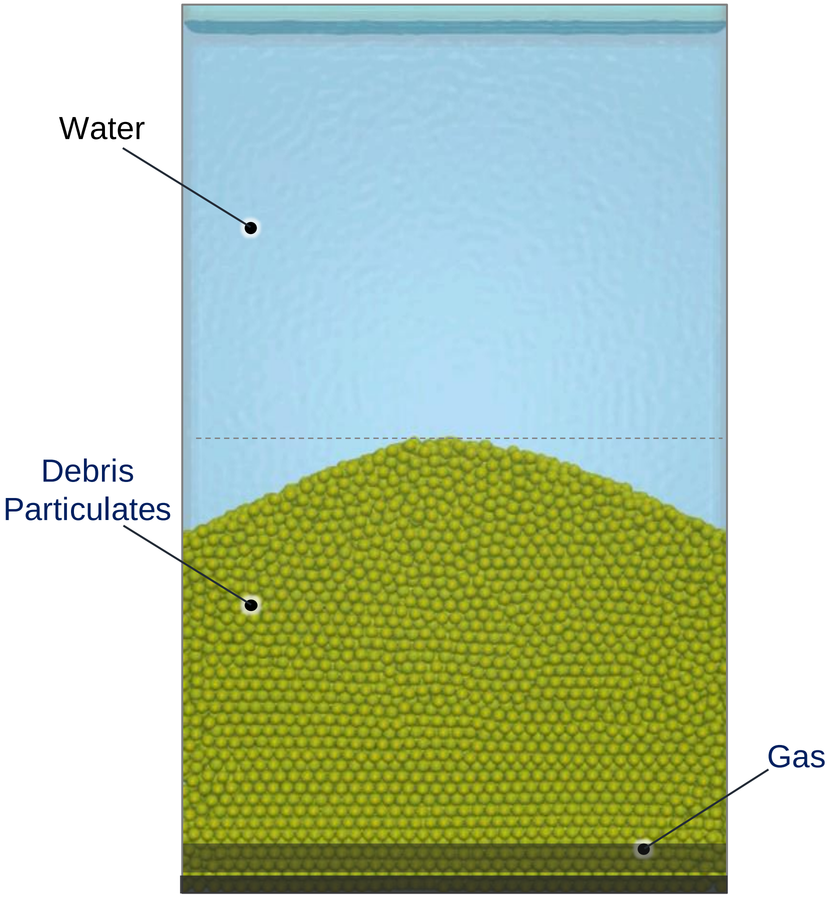
Solving Continuum Mechanics

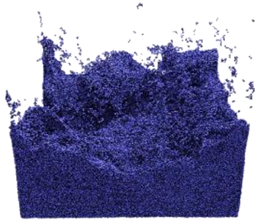
Fluid-Particulate Interaction Modeling with Gas-Liquid-Sold Phases (SPH/DEM)

Debris Self-leveling



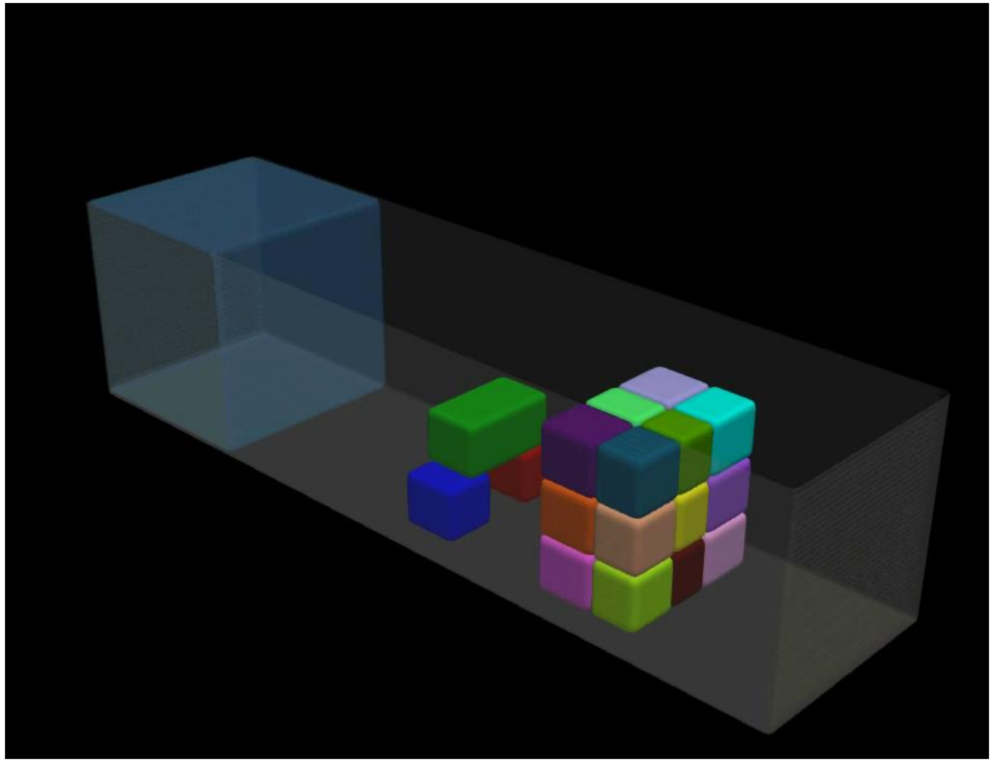






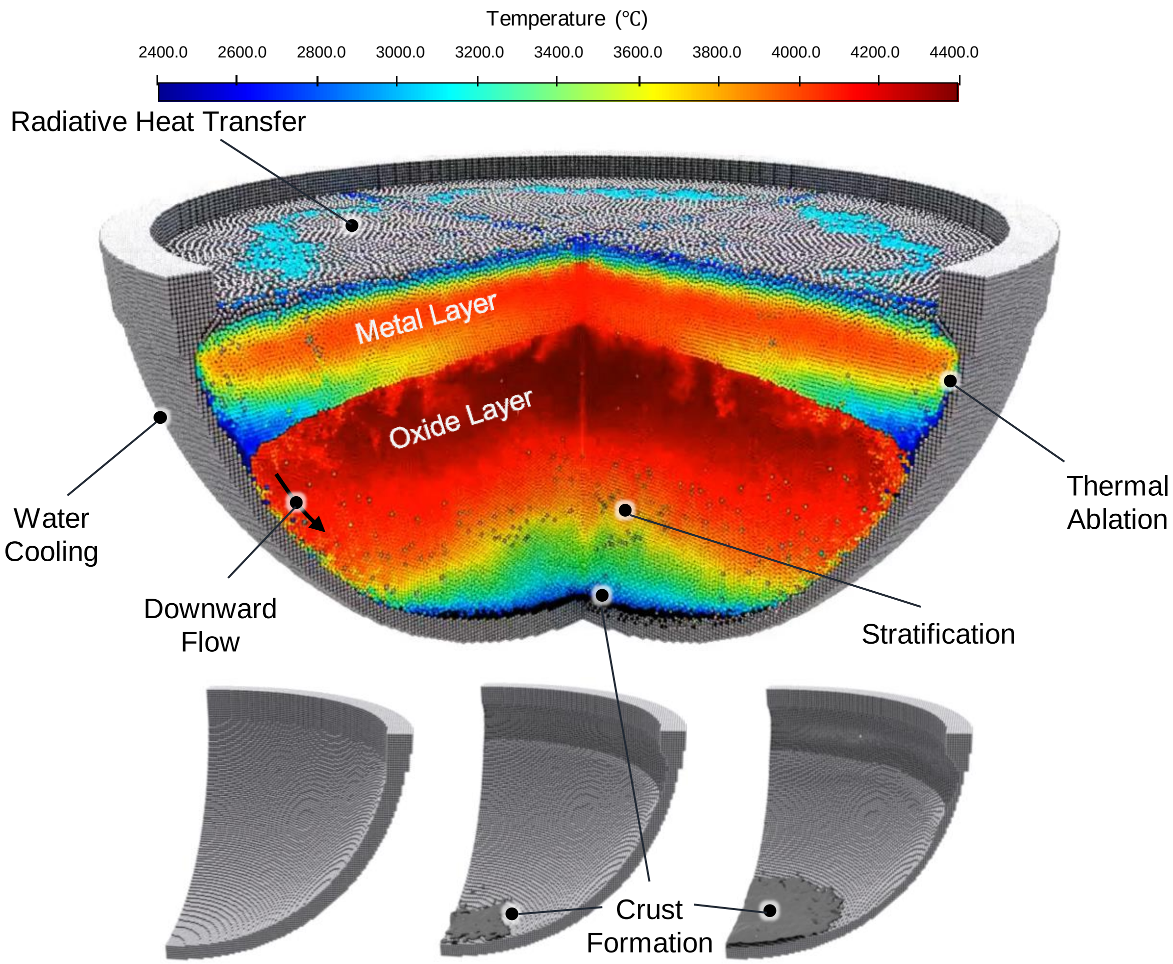
Solving Continuum Mechanics

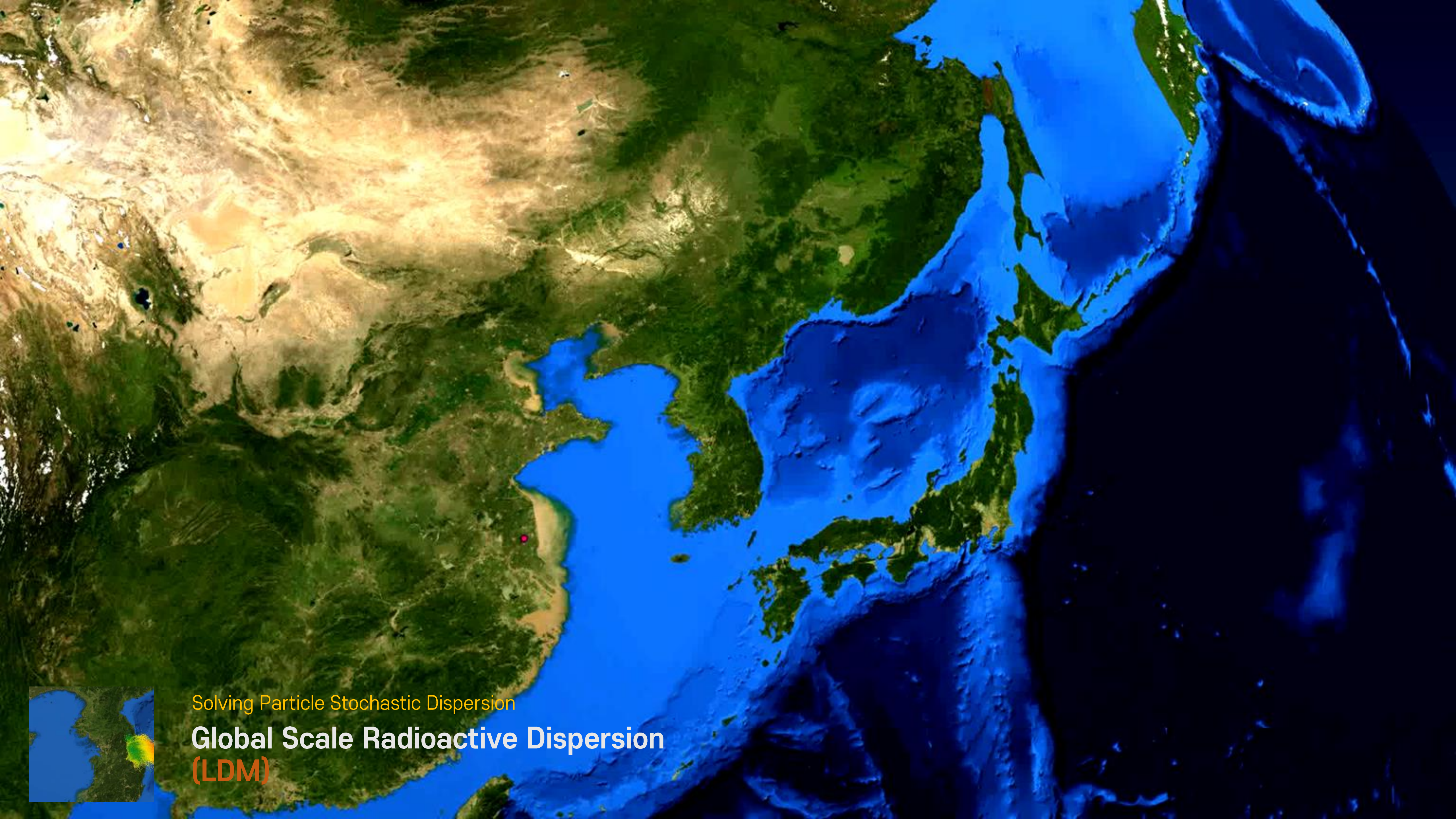
Unified Fluid-Rigid Body Interaction Modeling (SPH)



Solving Continuum Mechanics

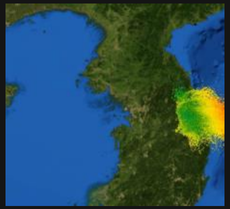
Multi-physics Simulation for Nuclear Safety (SPH)





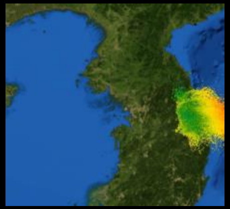
Solving Particle Stochastic Dispersion

Global Scale Radioactive Dispersion (LDM)



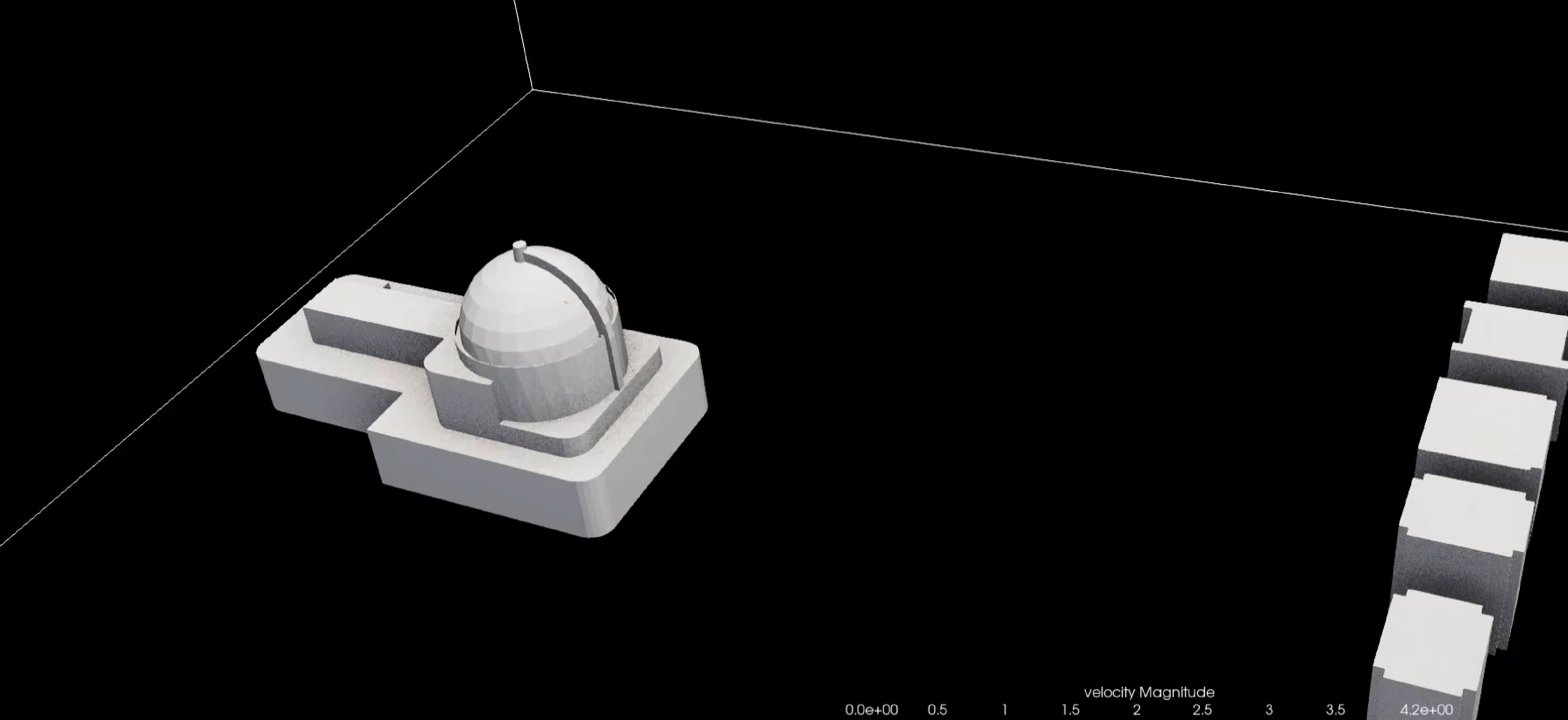
Solving Particle Stochastic Dispersion

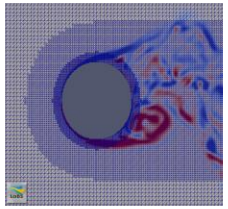
Local Scale Radioactive Dispersion with Evacuation (LDM)



Solving Particle Stochastic Dispersion

Local Scale Lagrangian Stochastic Modeling Coupled with CFD & LBM (LDM)

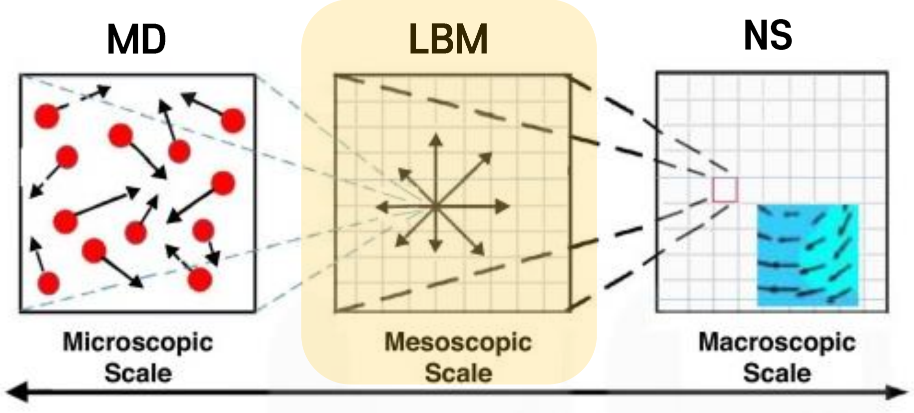


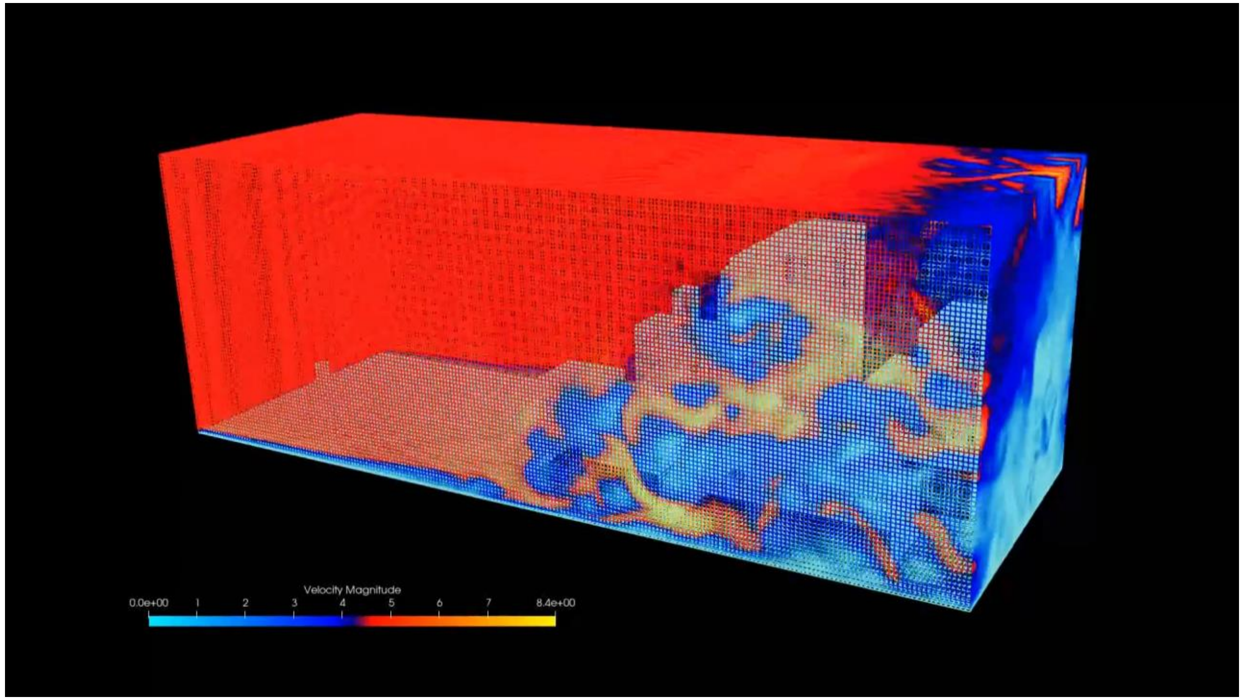


Solving Meso-scale Physics

Real-time Urban Wind Simulation using GPU-based Lattice Boltzmann Model (LBM)

$$\frac{\partial f}{\partial t} + \vec{\xi} \cdot \nabla f = Q(f, f).$$





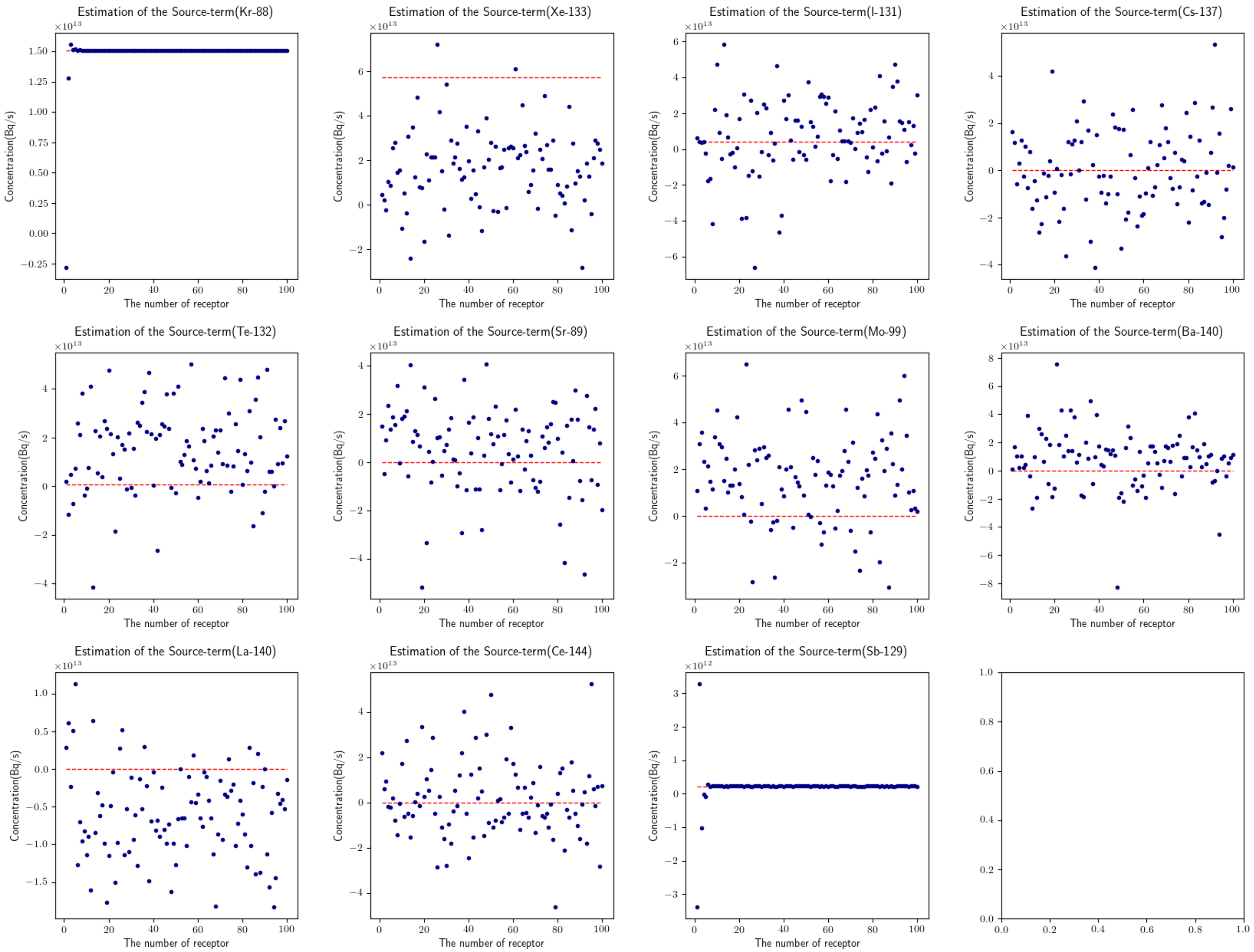
Gradient-Free Inverse Modeling

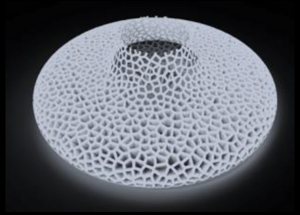
Source Term Estimation from Radiation Dose Measurement (EKI/GA/PSO/ML)

Back Trajectory – CWT

Back trajectory method is a numerical modeling technique used to determine the path that an air parcel has traveled from its source to its current location.

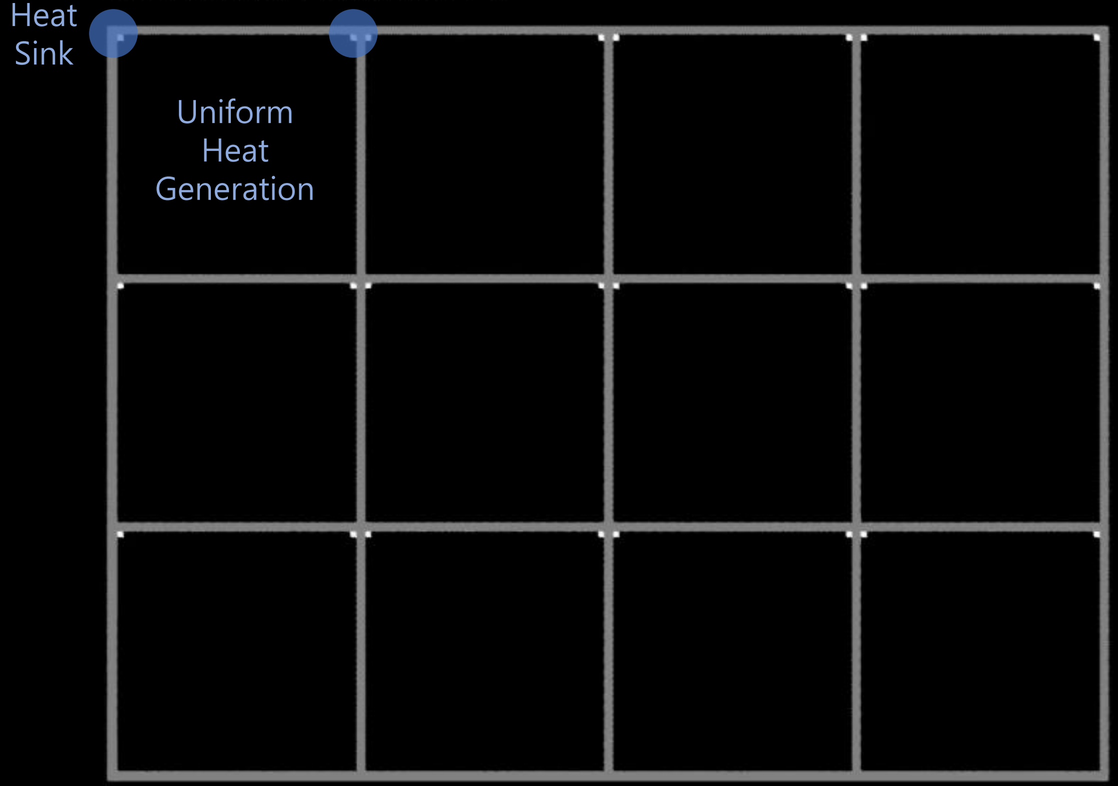
Ensemble Kalman Inversion (EKI) / Genetic Algorithm (GA) / Particle Swarm Optimization (PSO) / Machine Learning (ML)





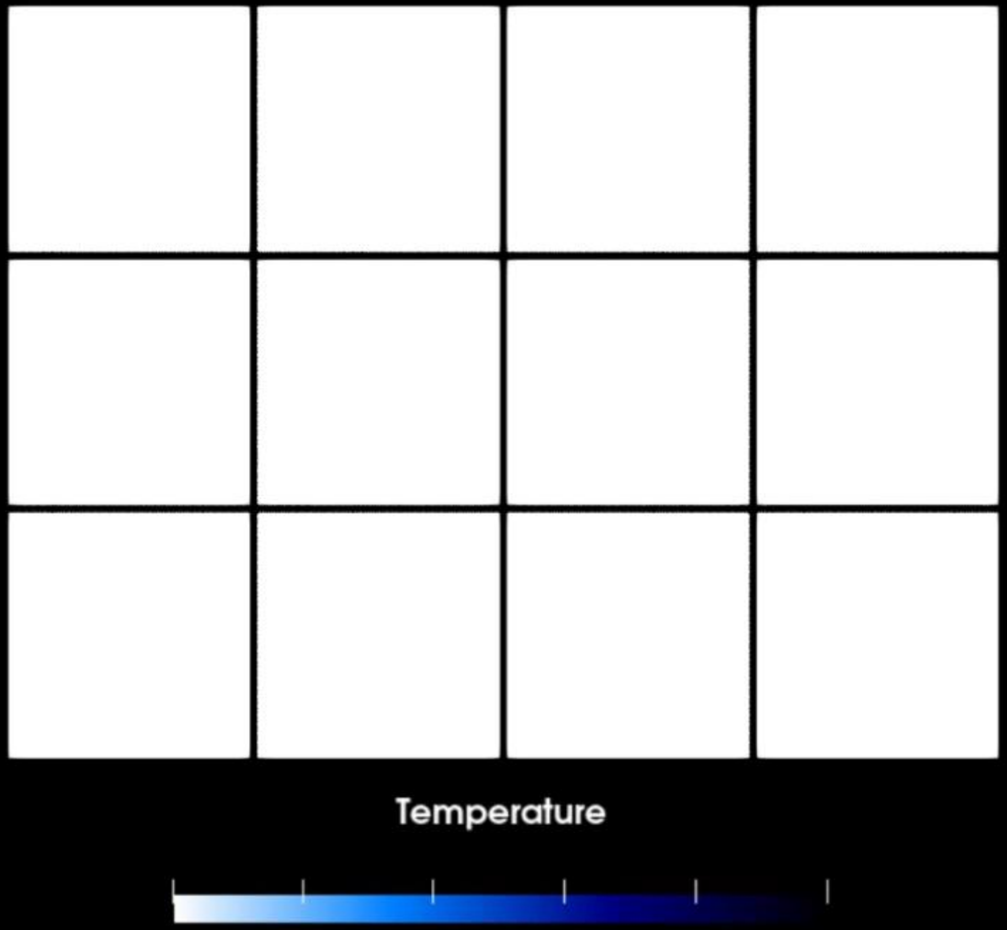
Design Topology Optimization

GPU-based Generative Design based on Meshless CFD (GD)



Number of populations = 50

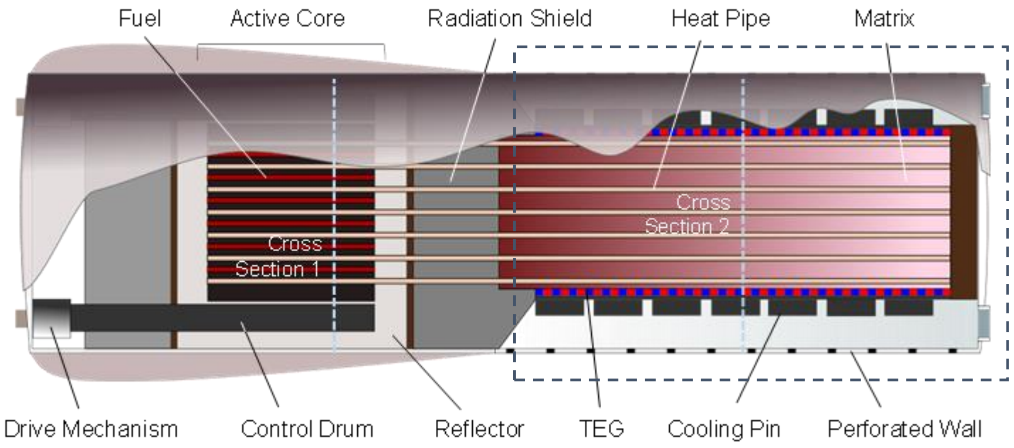
Fining Optimal Distribution of Materials for Minimizing Average Temperature

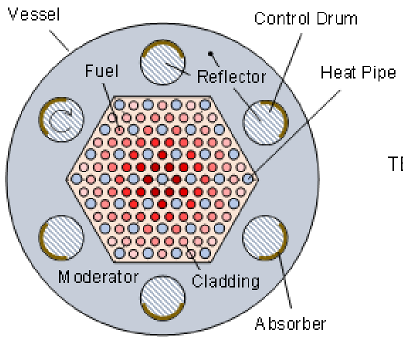


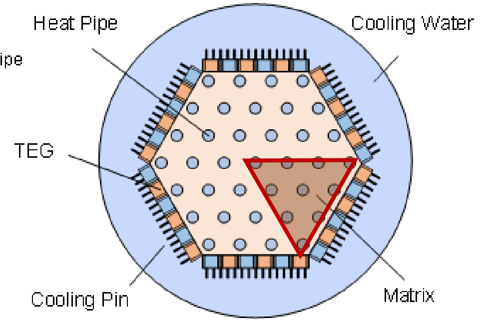
Design Topology Optimization

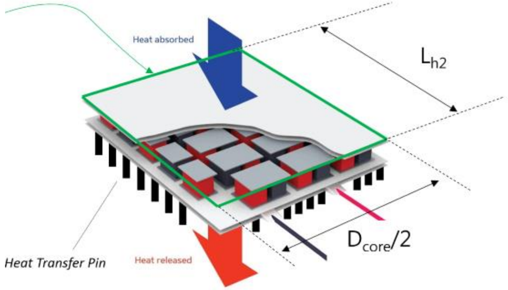
Generative Design & Additive Manufacturing (GD)

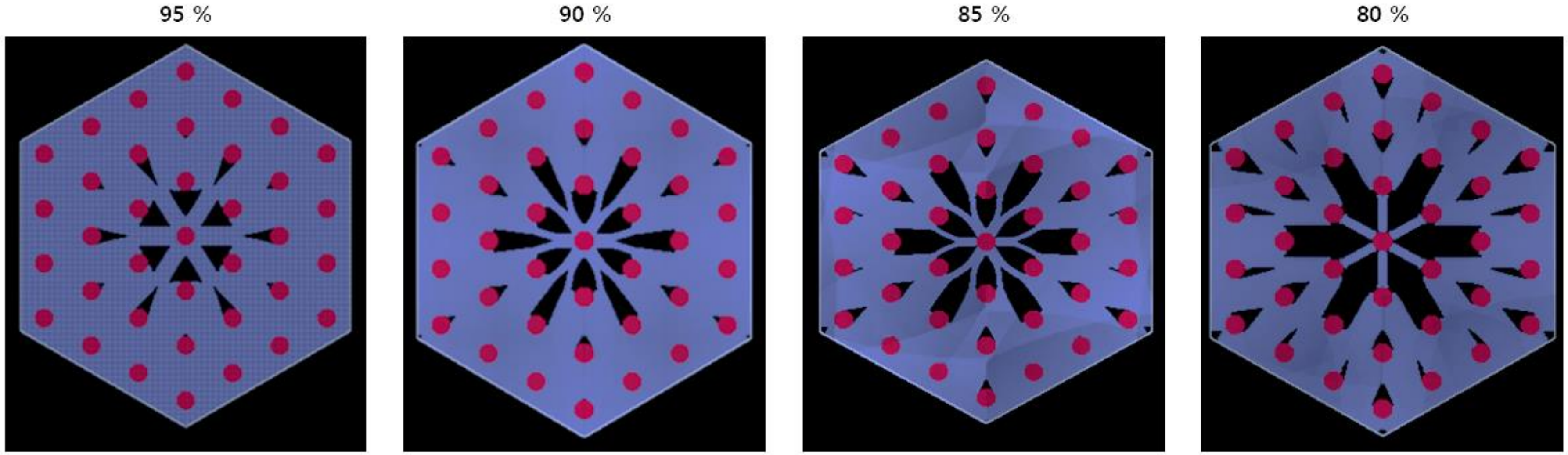
Heat Pipe Micro-Reactor







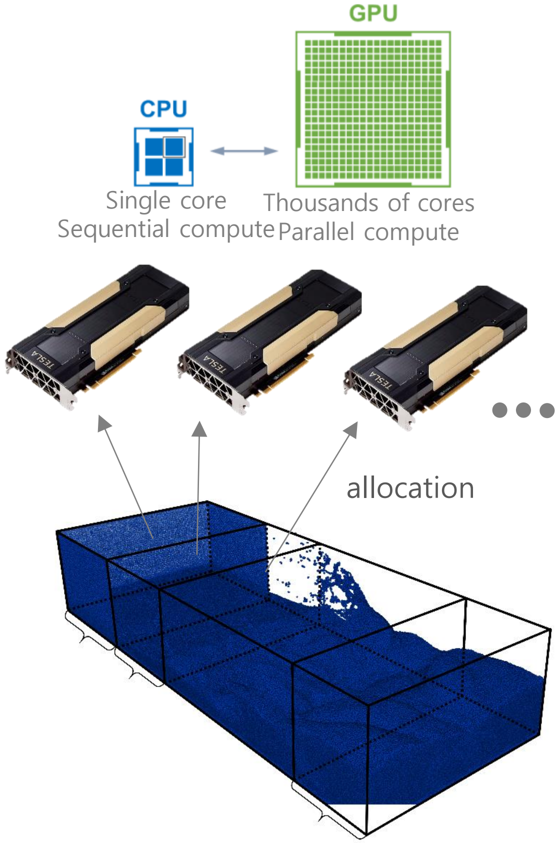




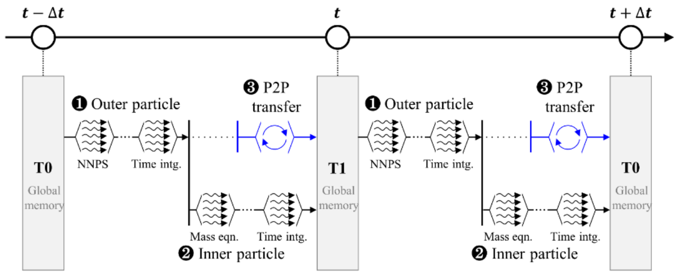
High Performance Computing

Dynamic Load Balancing of Multi-GPUs for Meshless CFD (HPC)

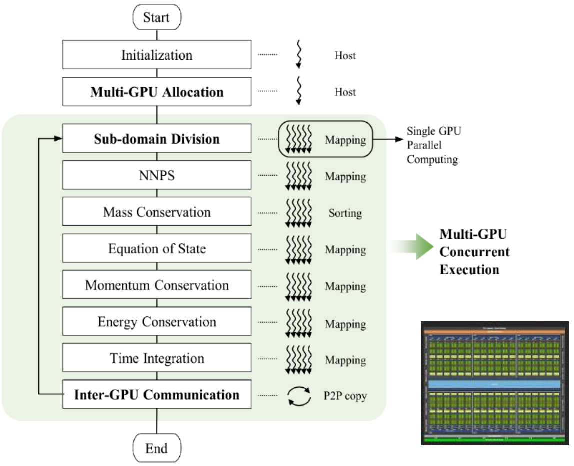
Multi-GPU Parallelization with Domain Decomposition



1. Domain Decomposition



2. Multi-streaming & Multi-threading

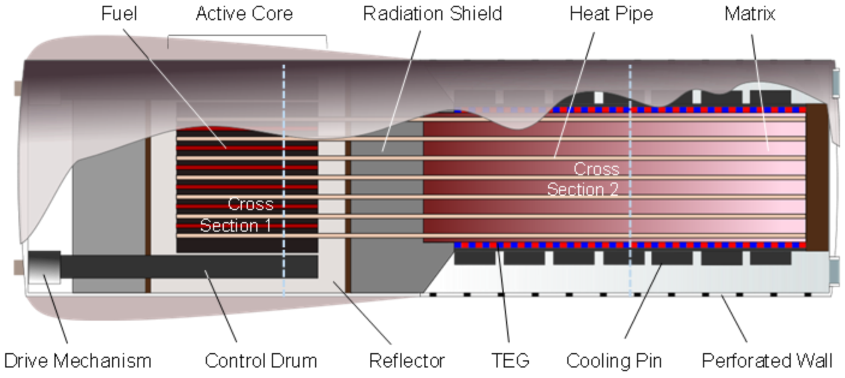


3. Particle-wise Parallelization

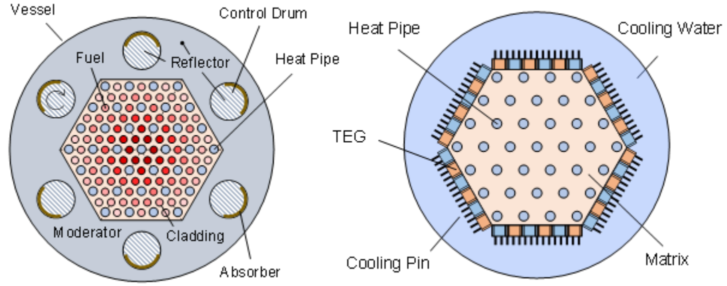
2-D Dynamic Load Balancing

System Dynamics Modeling

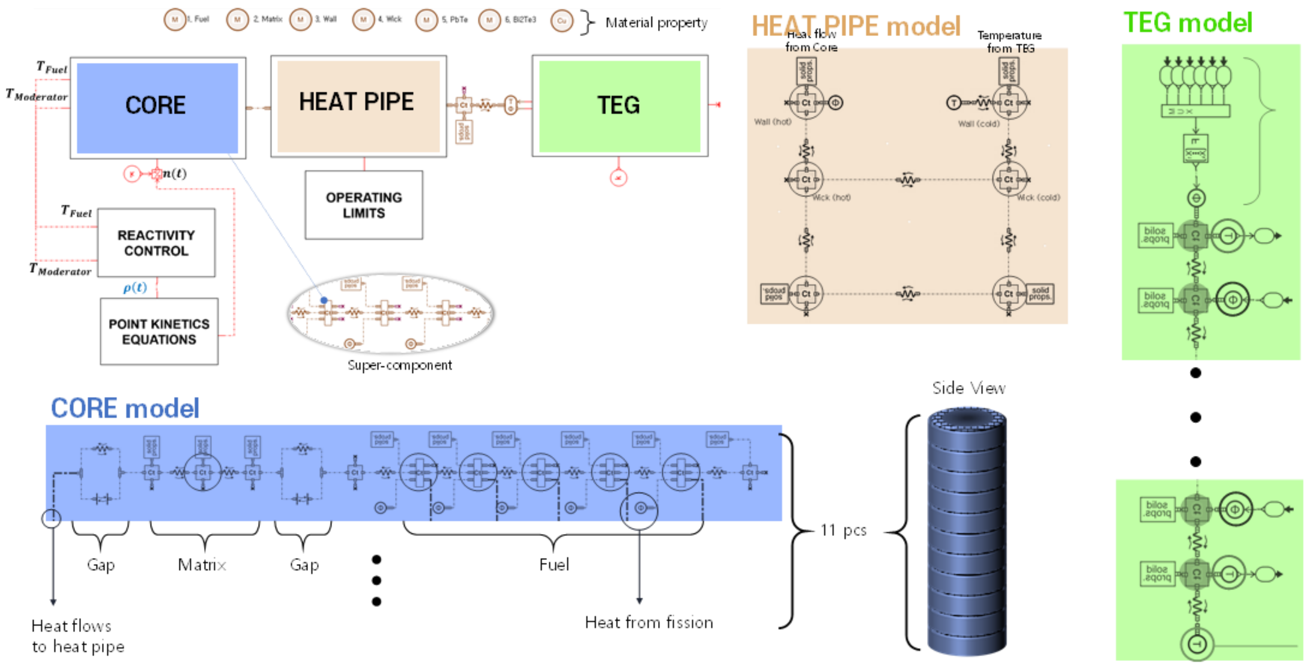
System Dynamic Modeling for Heat Pipe Micro-reactor (AMESIM)

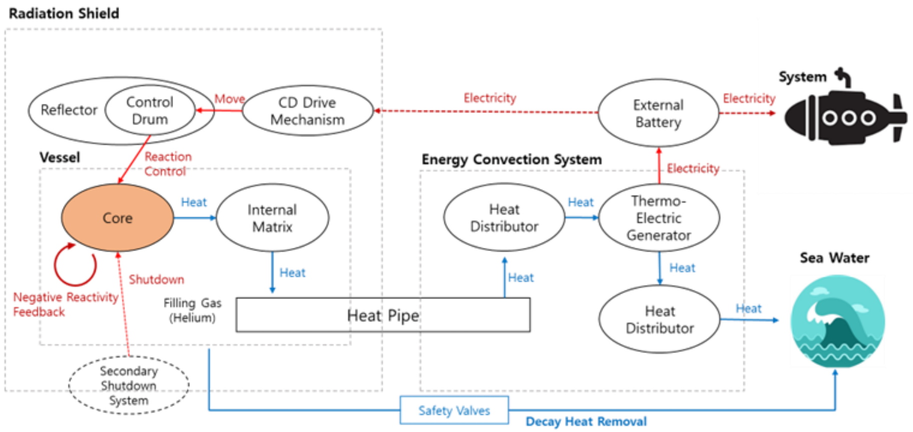


10 kWe Heat Pipe Nuclear Fission Battery



Variables	Value	Unit
Thermal Power	74	kW_t
Electric Power	11.3	kW_e
Maximum Temperature of Fuel Rod	1047	K
Matrix Temperature	1021	K
Matrix Temperature	988.8	K
Heat Pipe Evaporator Temperature	964.5	K
TEG Average Temperature	626.5	K
Heat Sink Temperature	298.0	K





Summary & Conclusion

Thank you!

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ESLAB
Nuclear Energy System Lab