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Defense Nuclear Nonproliferation Research & Development
Nonproliferation Enabling Capabilities
Remote Detection

DAM 2021 Meeting

Persistent DyNAMICS: Remote Sensing Based on Domain-Informed Analytics

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Persistent-DyNAMICS: Persistent Dynamic Nuclear Activity Monitoring via Intelligent, Coordinated Sensing

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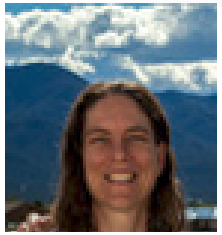
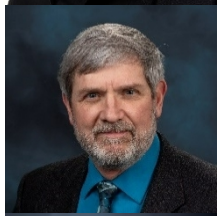
6 Labs: LANL, LLNL, ORNL, PNNL, SNL, STL
Sponsor: Office of Proliferation Detection





Venture Management Team:
Venture Manager: Norma Pawley, LANL
Science Integration Lead: Tom Kulp, SNL
Experimental Integration Lead: Bob Priest, LLNL
Mission Assurance Lead: Paul Pope, LANL

Data Management Team:
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SNL – Rose Borden, Craig Ulmer
ORNL – Janice Greenwod

Testbed Team: Jeff Johnson, ORNL (Lead)
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PNNL – Romarie Morales Rosado, Jereme Haack, Lee Burke, James Bradford, Paul Keller, Dave Engel, Jackson Chin

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SNL – Sam Eaton, Randy Brost, Benjamin Cipiti, Philip Honnold, Tom Reichardt, Jason Reinhardt, David Farley

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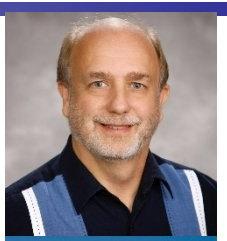
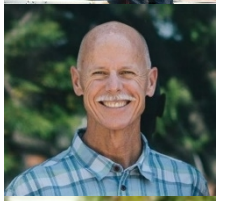
Collections: Bob Priest, LLNL (Lead)
SNL – Mark Smith, Stephen McConnell, James Ramsey, Jon Slater, John VanderLaan, David Yocky, Holly Eagleston
LLNL – Aaron Wegner, Randy Sanchez, Josh Dunn, Garth Pratt, Steve Shiromizu, Jim Curry
STL – Chris Burt, Kevin Lee, Carmelo Gonzalez, Ljuboslav Boskic, Ian Bortins, John DiBenedetto

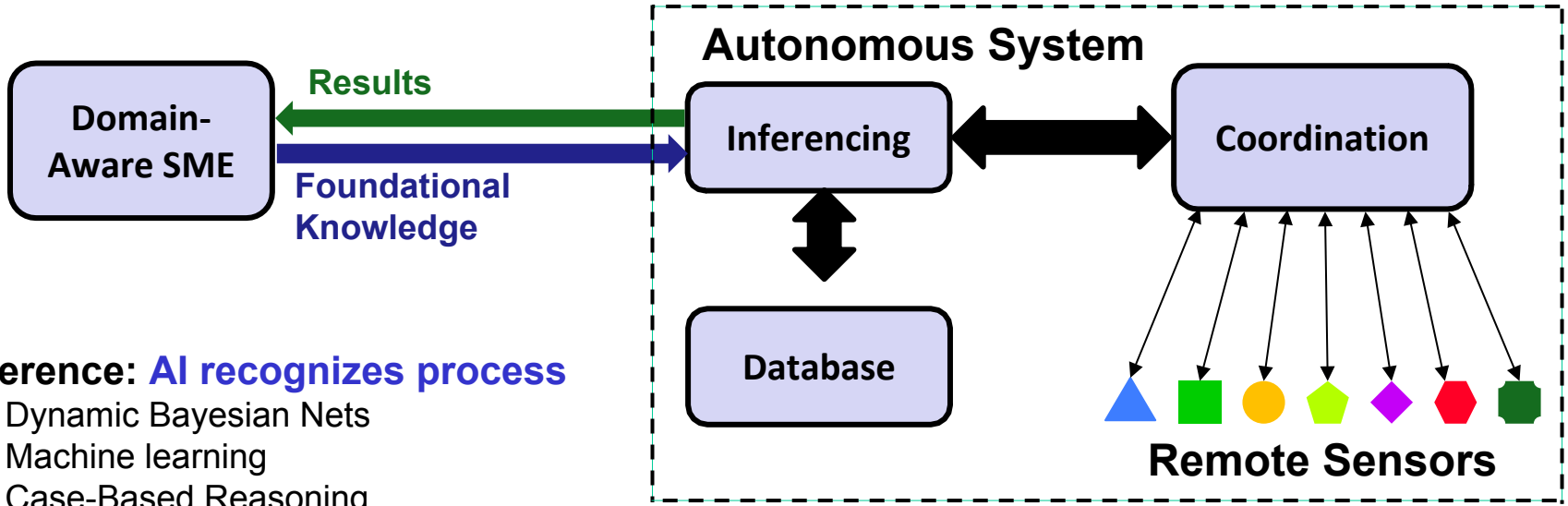
Integration: Michele Decroix, LANL (Lead)
Kriste Henson, PNNL





We are developing a *system* to characterize processes

Here, we will discuss how this system uses domain-informed analytics



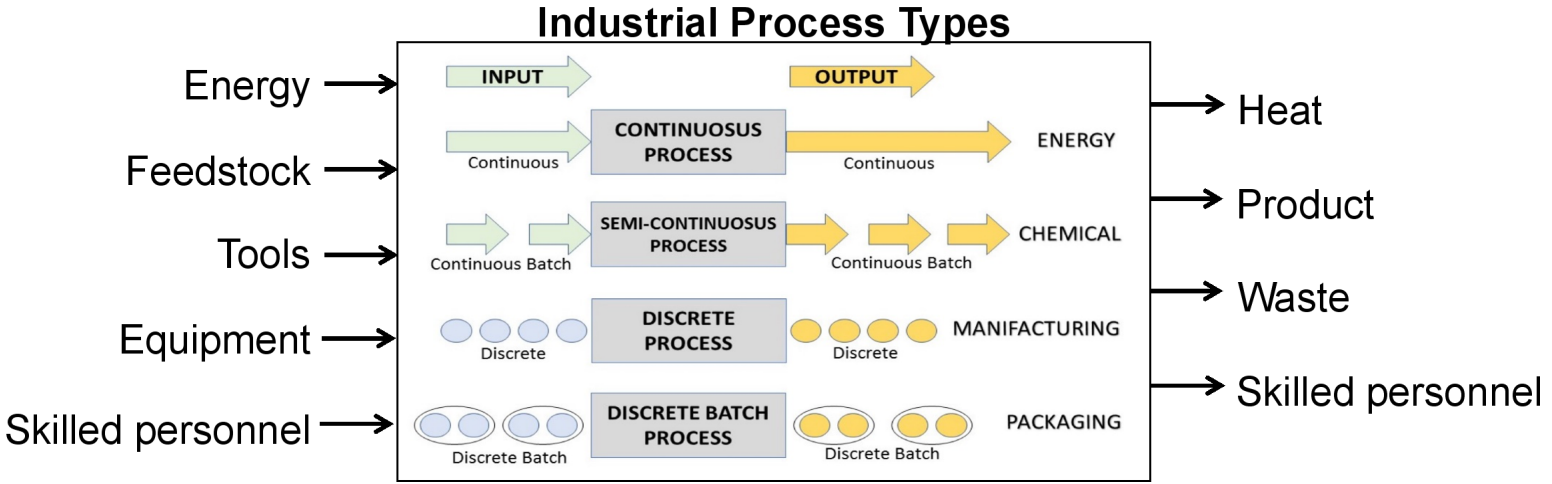
Inference: AI recognizes process

- Dynamic Bayesian Nets
- Machine learning
- Case-Based Reasoning

Foundational Knowledge: Domain Knowledge codified for AI

Coordination: Measurements scheduled using domain "script"

Industrial processes follow a domain-informed "script"



- Activities are both technical and "pattern of life"
- Each is driven/influenced by science and "engineering best practice"

With domain knowledge:

↓ Need for data **↑ Explainability** **↑ Transferability**

From: https://www.oreilly.com/

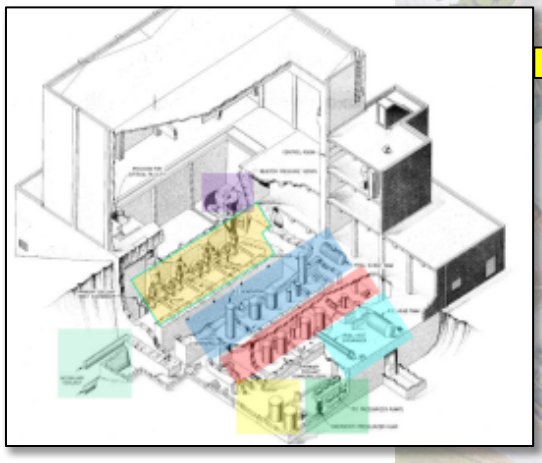
HFIR is the current Persistent DyNAMICS Testbed

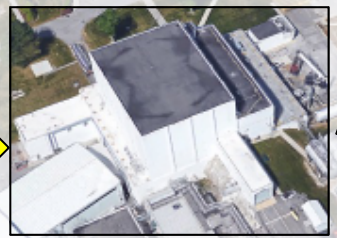
ORNL High Flux Isotope Reactor (HFIR) Complex

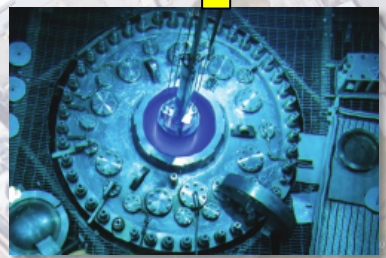
There are two connected facilities at the Complex

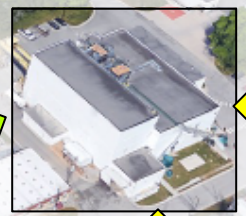
HFIR
Irradiate material targets to create new isotopes

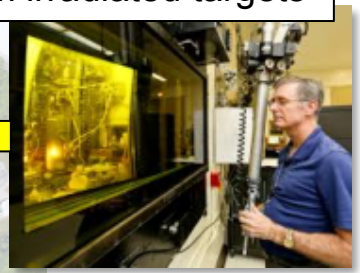
REDC*
- Prepare targets for irradiation
- Extract products from irradiated targets

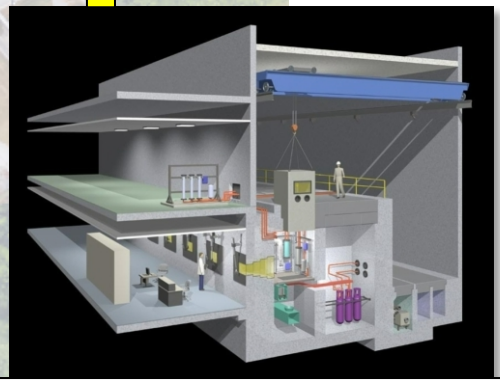












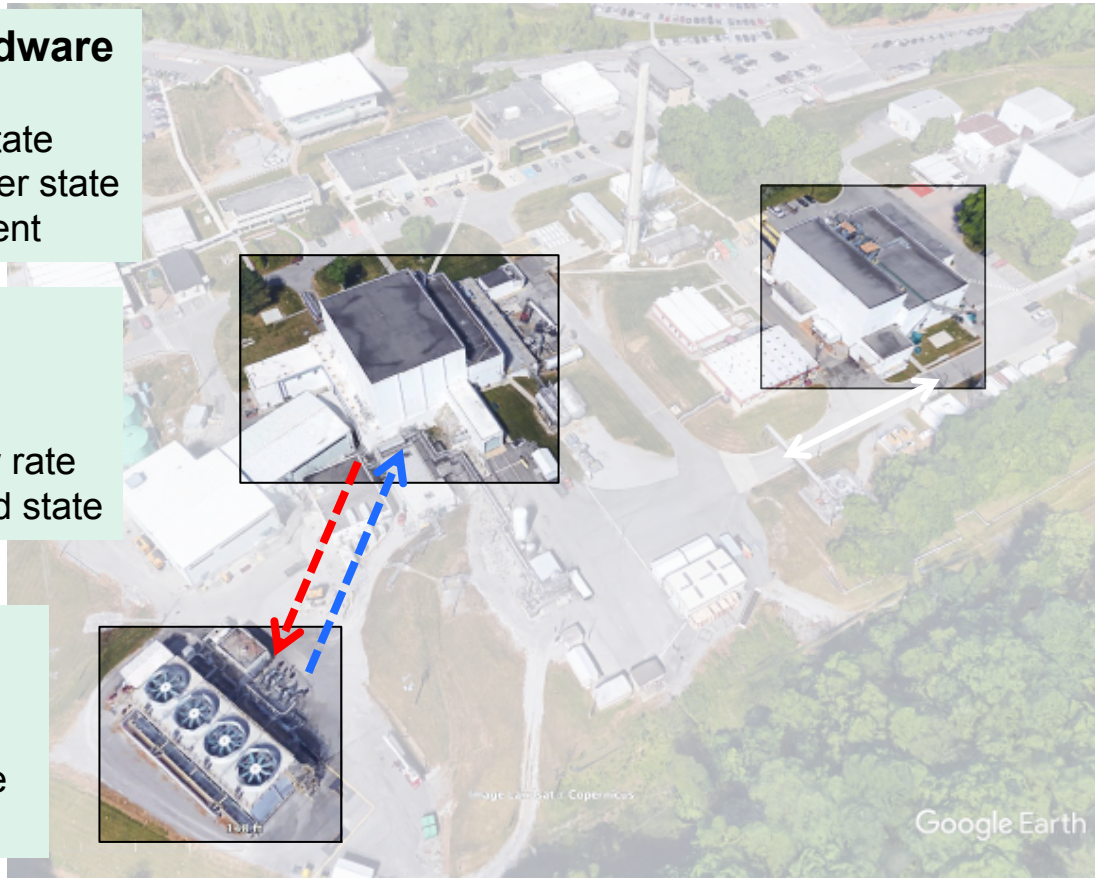
*REDC = Radiological Engineering Development Center

Process observables being measured

Key Hardware
- State
- Motor state
- Controller state
- Movement

Water flow
- Pipe state
- Pump state
- Water state and flow rate
- Valve movement and state

Heat Disposal
- Tower state
- Fan state
- Plume presence / size
- Temperature



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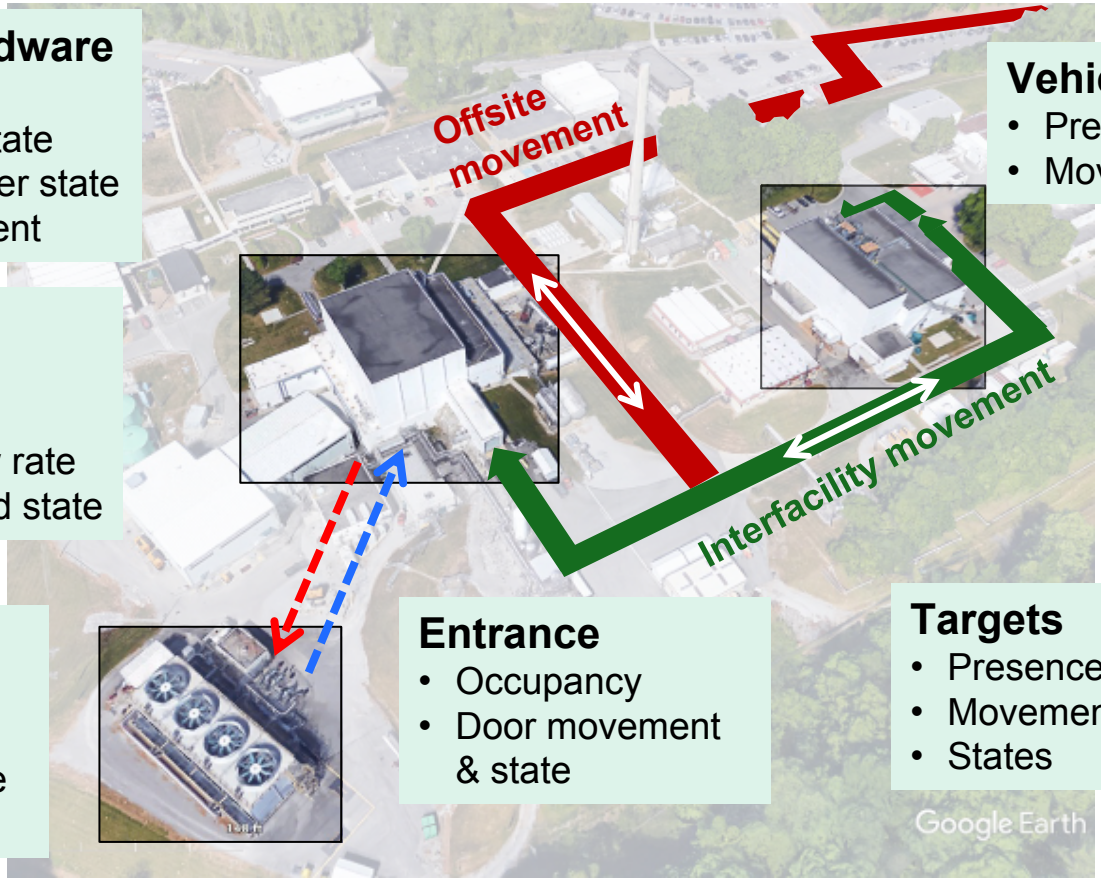
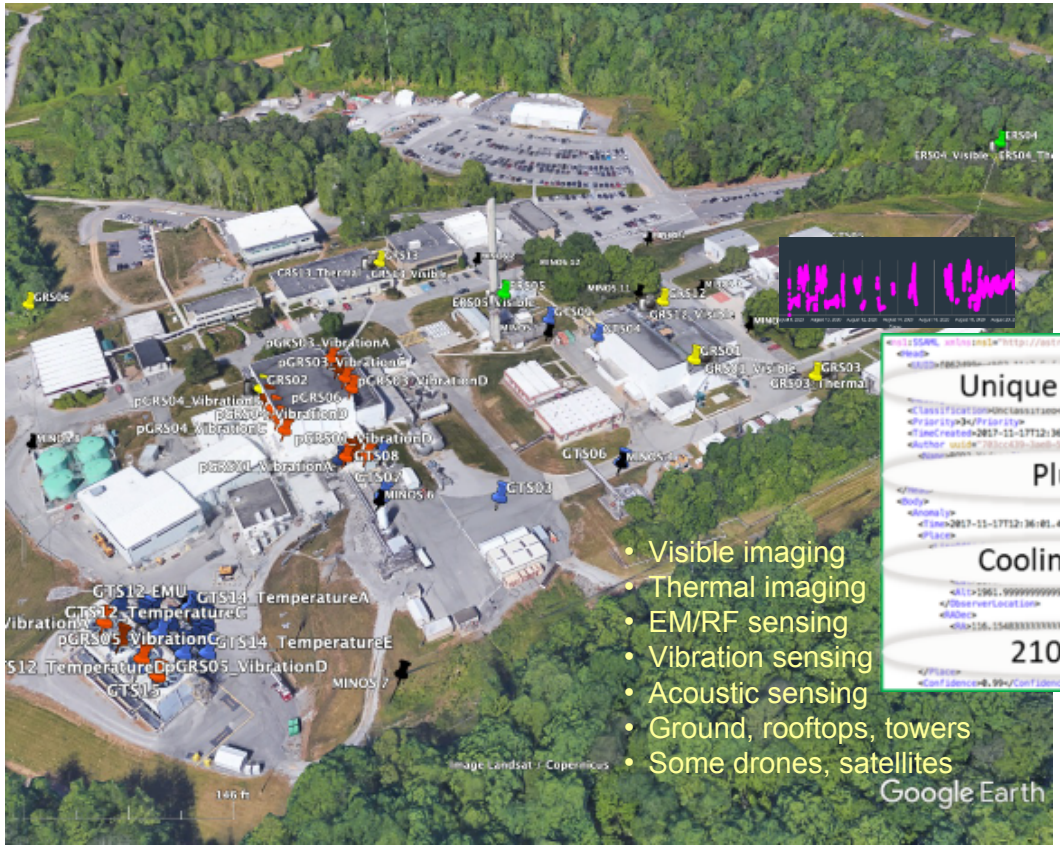


Entrance
- Occupancy
- Door movement & state

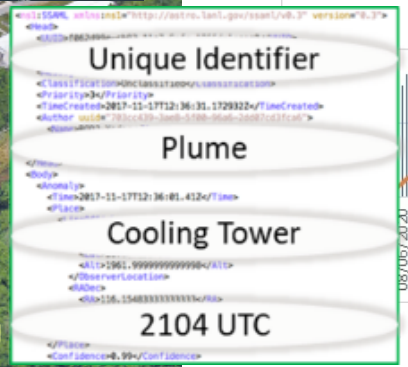
Vehicles & Containers
- Presence (at locations)
- Movement

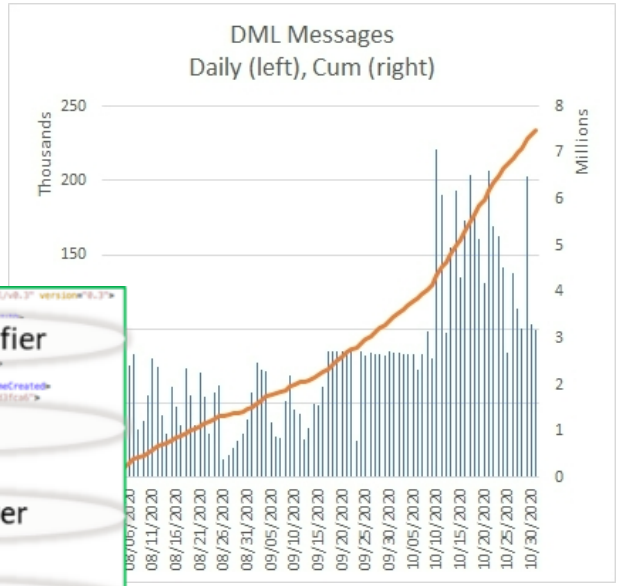
Targets
- Presence (at locations)
- Movement
- States

PD sensors have been collecting since 15 Jul 2020



- Visible imaging
- Thermal imaging
- EM/RF sensing
- Vibration sensing
- Acoustic sensing
- Ground, rooftops, towers
- Some drones, satellites

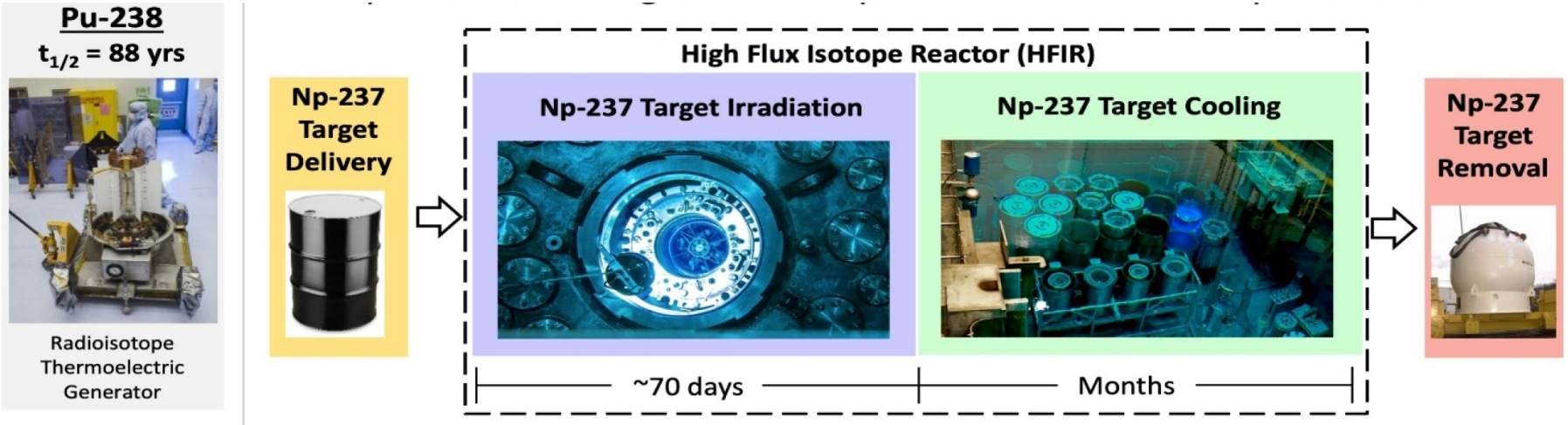




Edge Sensors emit Sensed Information text messages 24/7

Use Cases provide a context for test and evaluation

- Use Case 1 (UC1) hypothesis: ***The target facility is performing activities consistent with the production of a short-lived medical isotope***.



Use Cases provide a context for test and evaluation

Physics constrains tempo of activity sequences and ensures transferability

Pu-238

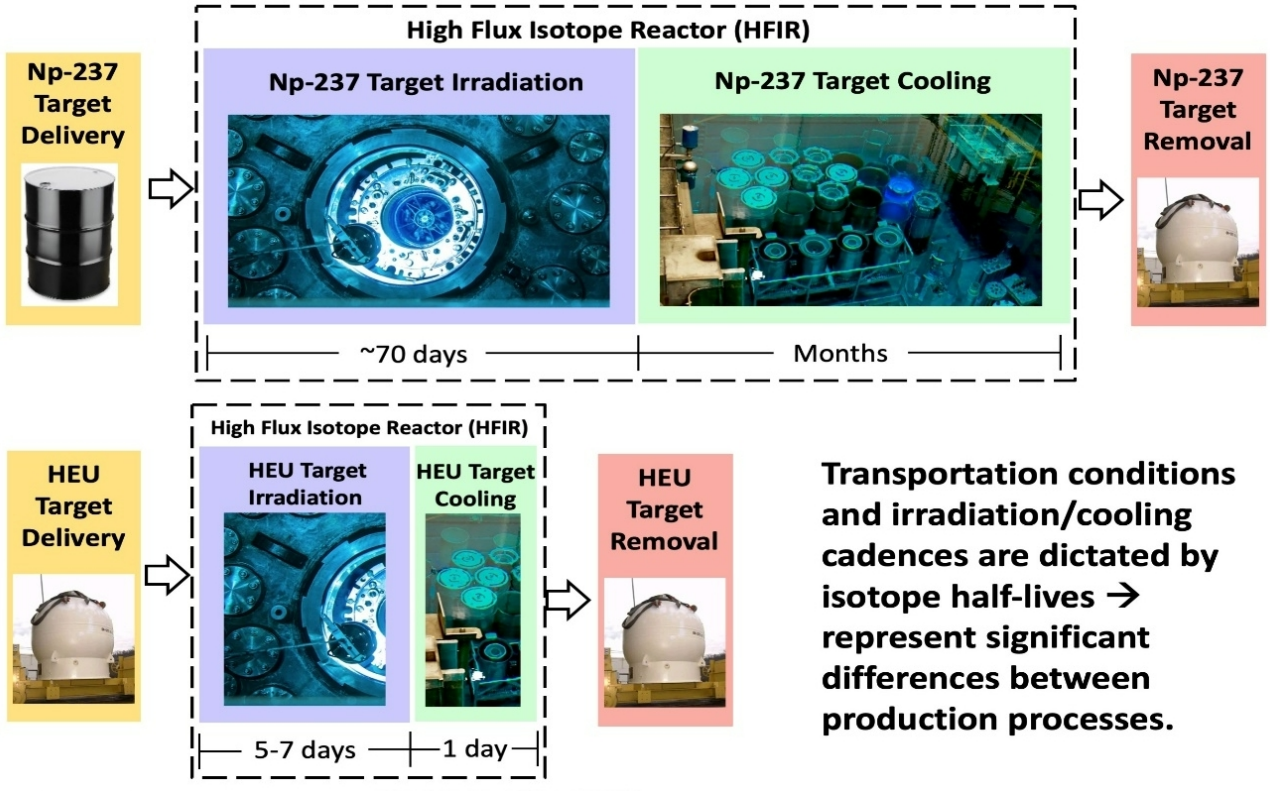
$t_{1/2}$ = 88 yrs

Radioisotope Thermoelectric Generator

Mo-99

$t_{1/2}$ = 66 hrs!

Medical Isotope Generator



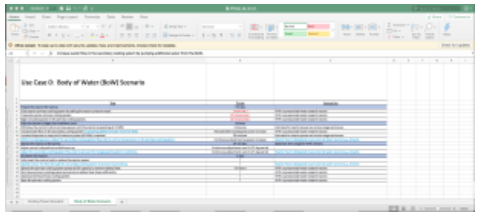
Transportation conditions and irradiation/cooling cadences are dictated by isotope half-lives → represent significant differences between production processes.

Encoding Domain Knowledge for UC1

Initial SME elicitation

Primer (text)

Geospatial labeling



First-cut sequence “script”

General Domain Ontology

Functional Tools

- **Sequence Model** – Informs Dynamic Bayesian Networks and Case-Based Reasoning
- **High-Level Process Model** – Generative simulator of state vectors for Machine Learning
- **Lexicon** – Defines “language” for agent-based communication

Maximize transferability →

- Focus on science-constrained activities
- Operate “abstractly” (avoid designing for HFIR)

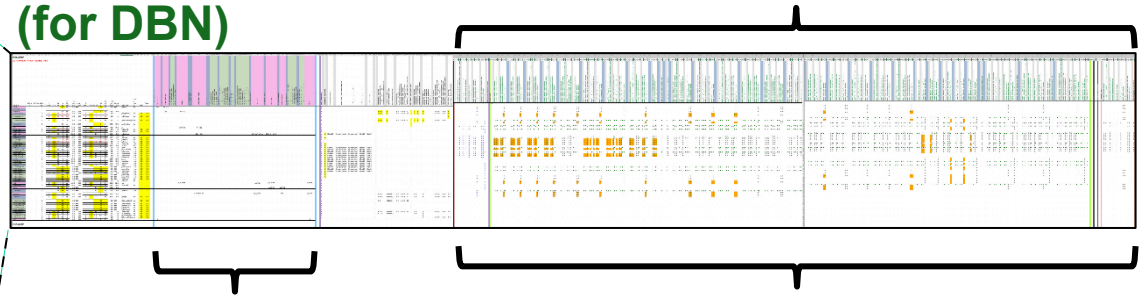
Functional tool examples

Sequence Steps

- 4_reactorOperation
- 4.2_reactorOperationPrepare
- 4.2.1_reactorOperationPrepareLoad
- 4.2.2_reactorOperationPrepareSealRctorVessel
- 4.2.3_reactorOperationPreparePressurizePrimary
- 4.2.4_reactorOperationPreparePreOpChecks
- 4.3_reactorOperationStartup
- 4.3.1_reactorOperationStartupWdrawRods
- 4.3.2_reactorOperationStartupIncrSecondaryFlow
- 4.3.3_reactorOperationStartupIncrPowerTo85MW
- 4.3.4_reactorOperationStartupIncrPowerCoolTower
- 4.4_reactorOperationRun
- 4.4.1_reactorOperationRunCoolTower
- 4.5_reactorOperationShutdown
- 4.5.1_reactorOperationShutdownInsertRodsReducePower

Sequence Model (for DBN)

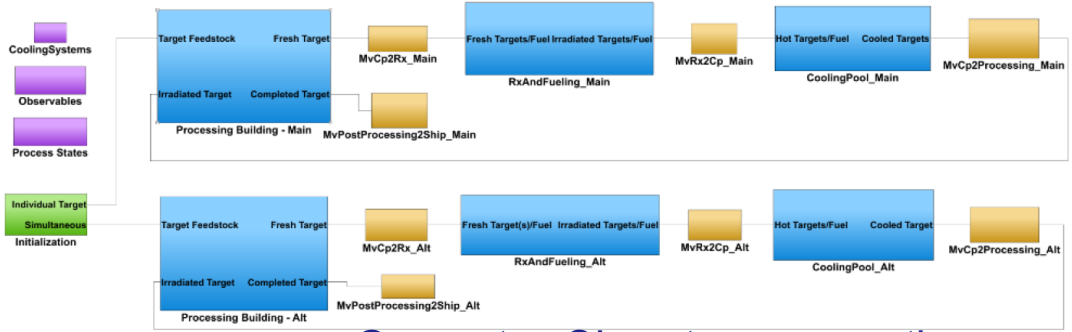
Sensed Information (SI) Messages



State Transition Matrix

SI Emission Probability

Simulink-Based HLPM Simulator (for ML training)



Generates SI vectors versus time

The system is designed for *updating* Knowledge

Hypothesis Example: HFIR is producing a short-lived isotope (e.g. ^{99}Mo)

1

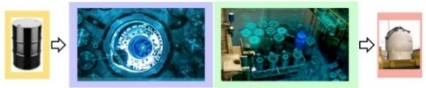
Nuclear Domain SME

Foundational Knowledge

- Ontology
- Sequence Model
- Activity Simulator
- Geospatial Context

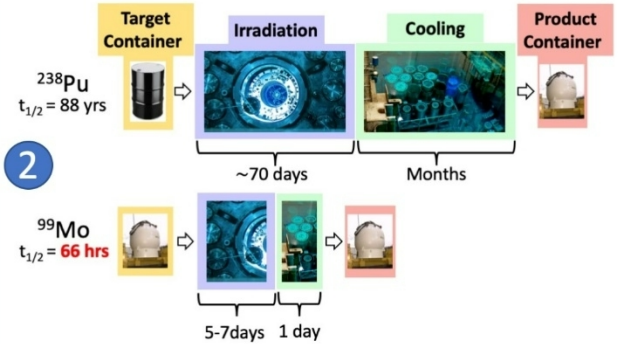
Autonomous System

Knowledge Advancement



Convergence: No – site only produces long-lived isotopes

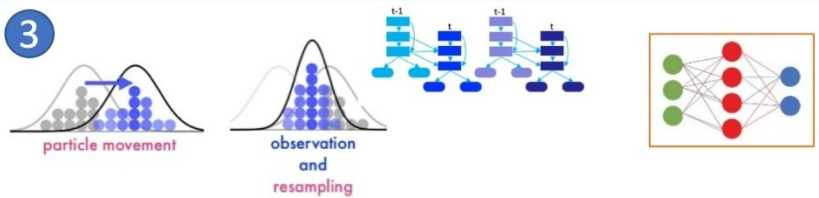
Isotope Production Sequences



2

Domain-Driven observations of containment, movement and reactor operation

3



Dynamic Bayesian Networks

Machine Learning

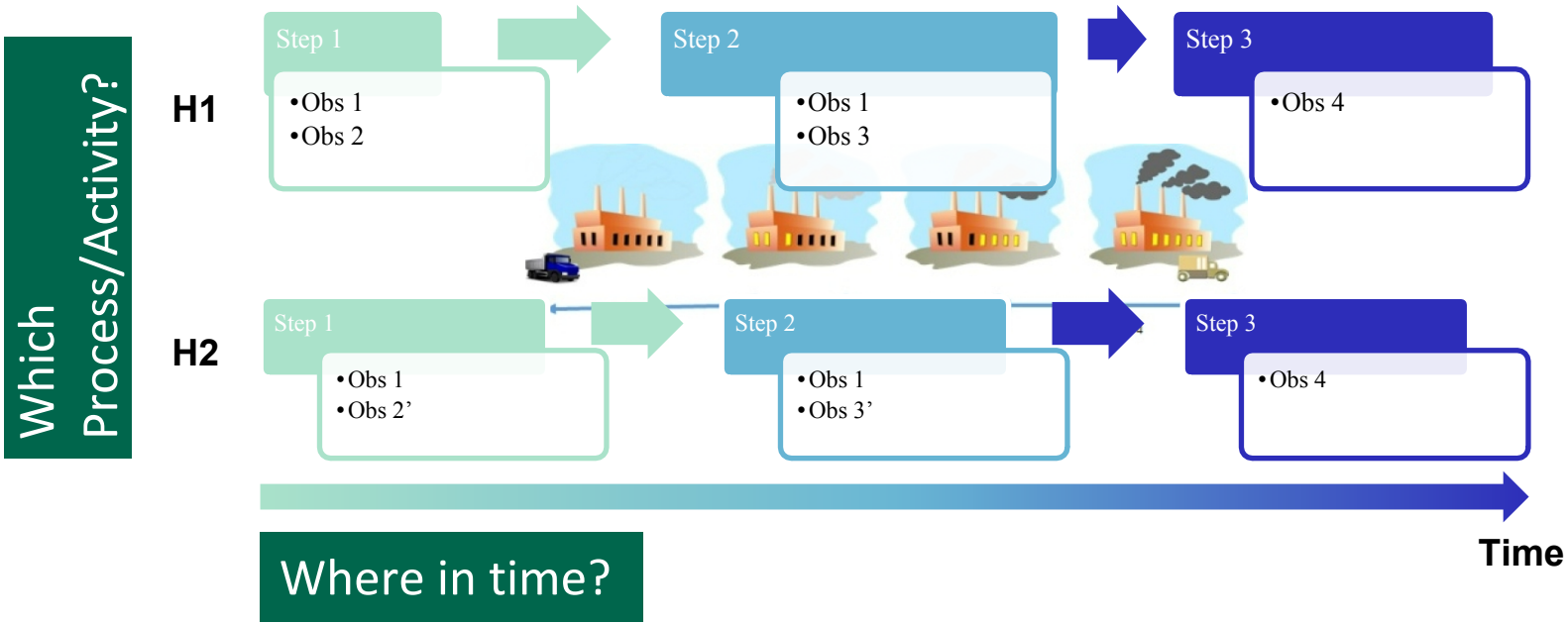
AI-Based Inferencing

Instantiated ontology

As Knowledge advances, a Site-Specific Ontology is developed

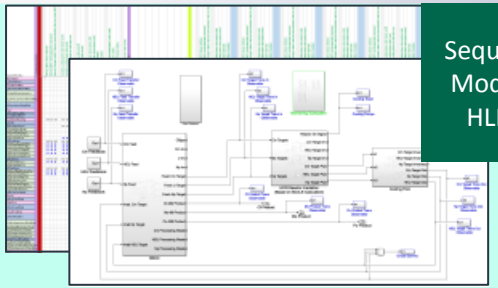
System purpose: characterize industrial activities

- Current focus on two questions about an industrial site:
  - What process/activity are they doing?
  - Where are they in the process?



Embedding Foundational Knowledge into Inference Algorithms

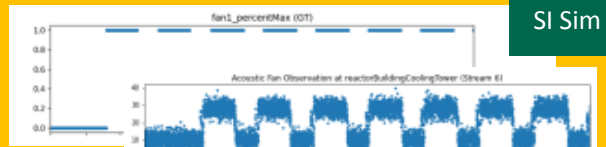
Foundational Knowledge



Sequence Model & HLPM

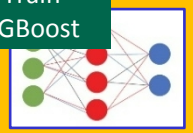
Sensor & exploitation Design info, performance characteristics, deployment…

Data-Driven ML: Use simulator

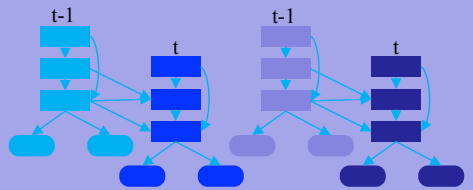


SI Sim

Train XGBoost



Design DBN



Knowledge-Driven DBN: Design based on FK

Domain Aware Inference Methods at work

- Preliminary result:
  - DBN and ML Inference algorithms tested on simplified model (Nov 2019).
  - ML Inference algorithms trained and tested on simulated SI messages.
- Ongoing work and next steps
  - Testing and debugging inference methods on real HFIR data.
  - Knowledge iteration cycle with SMEs.

Simulated UC1 SI

Conclusion

- Persistent DyNAMICS is developing an autonomous *system* to characterize industrial processes
- The system uses Domain-Informed AI to characterize the “script” of industrial processes that combine technical actions and “patterns of life”
- This serves to:
  - Bridge the gap between sparse data and automated inferences.
  - Maximize transferability
  - Maximize explainability
- Subject Matter Expertise is the key enabler!