SPHERE - Security and Privacy Heterogeneous Environment for Reproducible Experimentation

University of Southern California Information Sciences Institute,
Northeastern University, University of Utah

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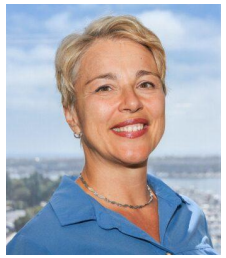
SPHERE Project Team



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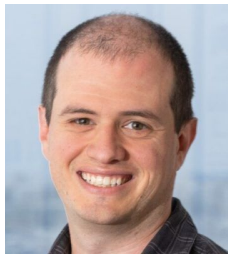

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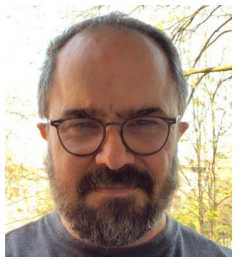

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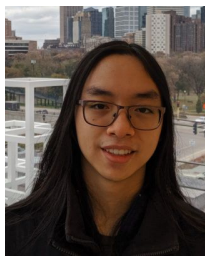

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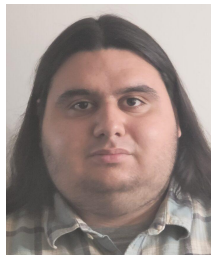

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Student workers (2-4) engaged on various time- limited tasks
Graduate students (1-4)
10 virtual interns per yr (3 yrs)
20 student interns per yr (4 yrs)
NEU co-op students - 2 per yr

Government Team

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SPHERE Advisory Board

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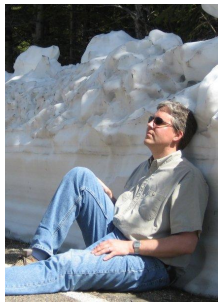

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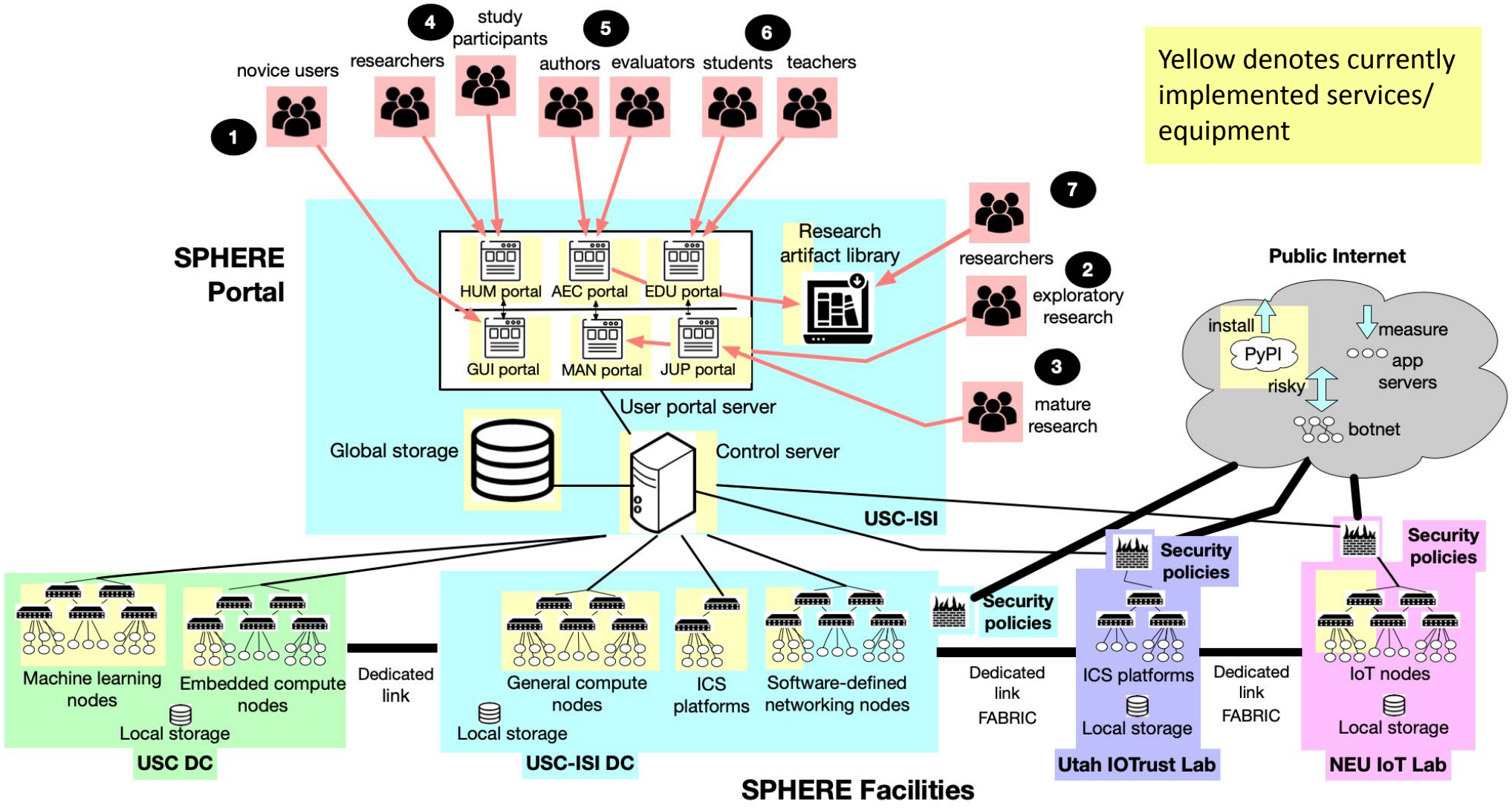
Motivation and Need

- **Motivation:** Cyber threats affect every aspect of our daily lives, critical infrastructure, science, and government. Research solutions are simplistic, piecemeal, and opportunistic, and slow to reach the market
- **Community need:** Common, rich, representative research infrastructure, which meets the needs across all members of the community and facilitates reproducible and open science → vertical progress, integrated research, and more sophisticated solutions
- **Proposed:** SPHERE research infrastructure
  - Heterogeneous resources to meet nearly 90% of research needs in the community
  - Multiple user portals to meet the unique needs of different classes of users
  - Processes/incentives for the community to create and contribute reusable research artifacts, including experimental environments
  - Integrated reproducibility support to facilitate artifact sharing, evaluation, and reuse

High-Level Architecture

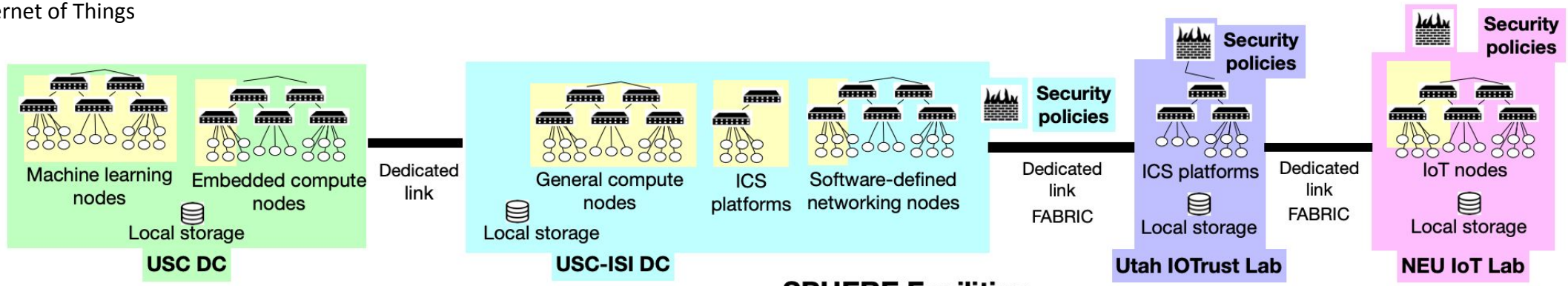


Multiple Types of Resources

- **Multiple** types of resources, needed for **emerging cybersecurity and privacy research**:
  - General compute nodes with trusted computing technology – research on network, cloud computing and system threats
  - Embedded compute nodes (e.g., in phones, tablets, etc.) – research on distributed threats, threats on distributed computing, attacks on specific CPU architectures
  - ICS platforms (PLCs) – research on threats on industrial systems and critical infrastructure
  - GPU nodes – incorporate machine learning into solutions
  - Programmable nodes (FPGAs) and switches – facilitate transition to market
  - IoT nodes (smart home nodes and personal devices) – research on threats on IoT

GPU – graphical processing unit
CPU – central processing unit
PLC – programmable logic controller
FPGA – field-programmable gate array
IoT – Internet of Things

Flexible security policies, support select, safe communication with the Internet



SPHERE Facilities

NEU IoT Lab

SPHERE RESEARCH INFRASTRUCTURE

Remote access to a set of 500 consumer IoT devices

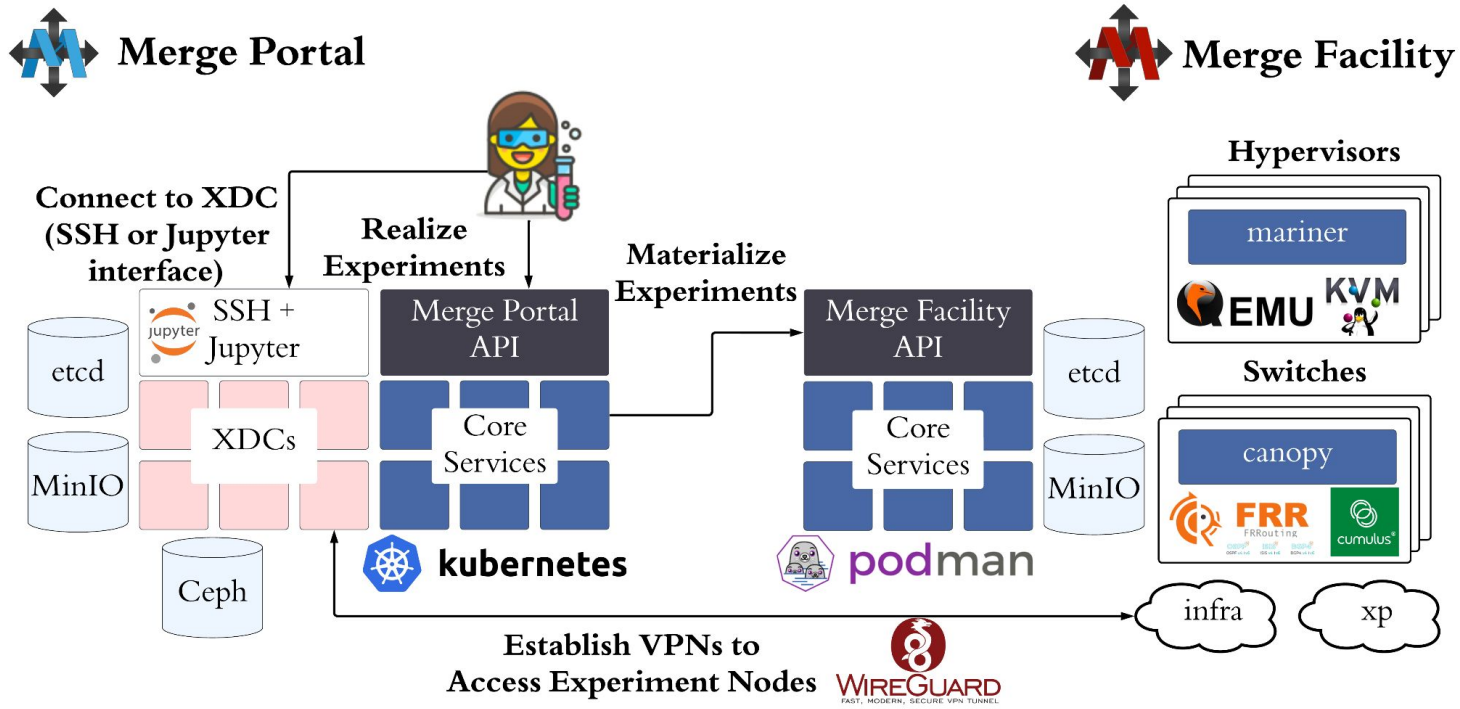
- Device reservation (individual devices or groups of devices)
- Network isolation and management:
  - Remote network access to the devices (VPN / VLANs)
- Remote sensor access
  - Cameras, microphones
- Remote actuator access
  - Speakers, button pushers, robotic arms, power control, infrared control
- Companion apps on physical/virtualized phones
- Logging and access to network traffic and sensor/actuator data

MERGE Control Software

Microservice Architecture for Modularity and Resilience

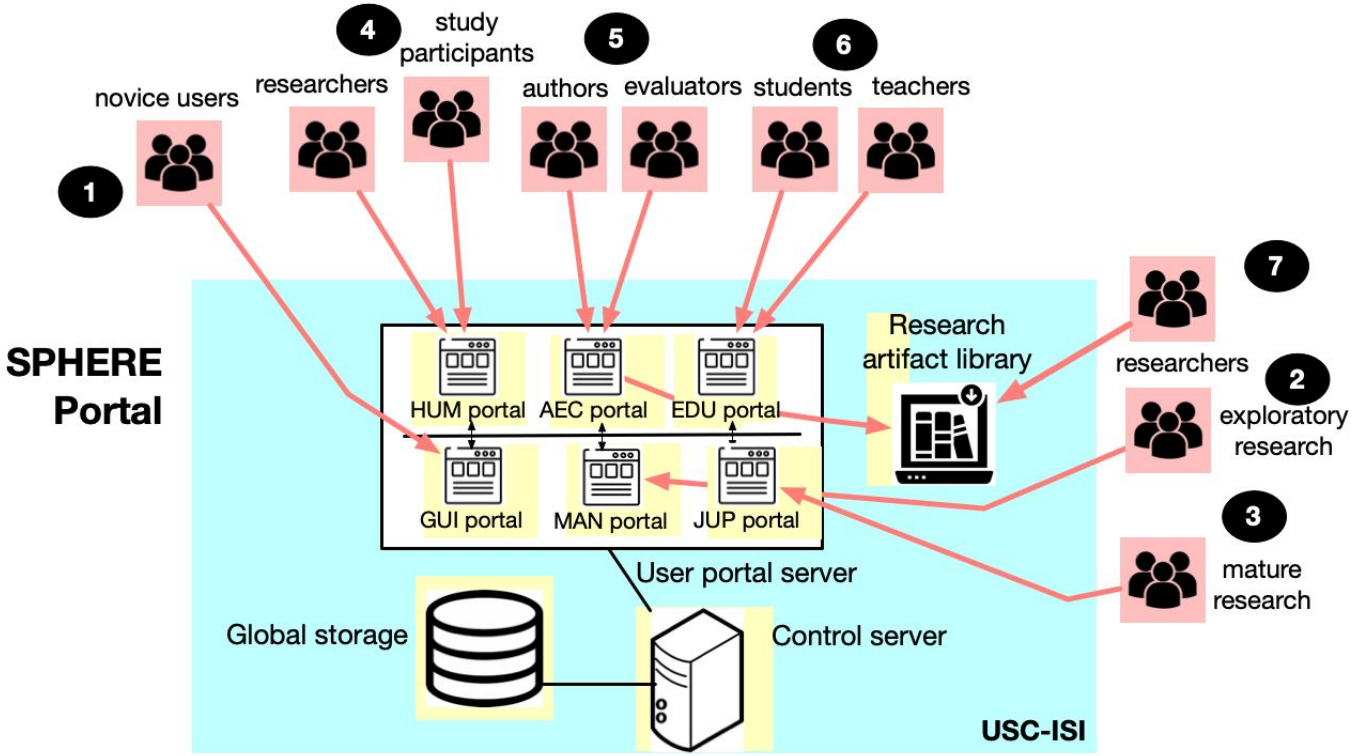
The Merge Portal and Facilities codebases use microservice architectures to flexibly integrate homegrown and third-party services to implement the Merge APIs

Merge supports multiple facilities, which may be managed by different teams and contain different hardware and software



Any compute/network infrastructure implementing the Merge Facility API can be commissioned as a Merge testbed facility

User Portals

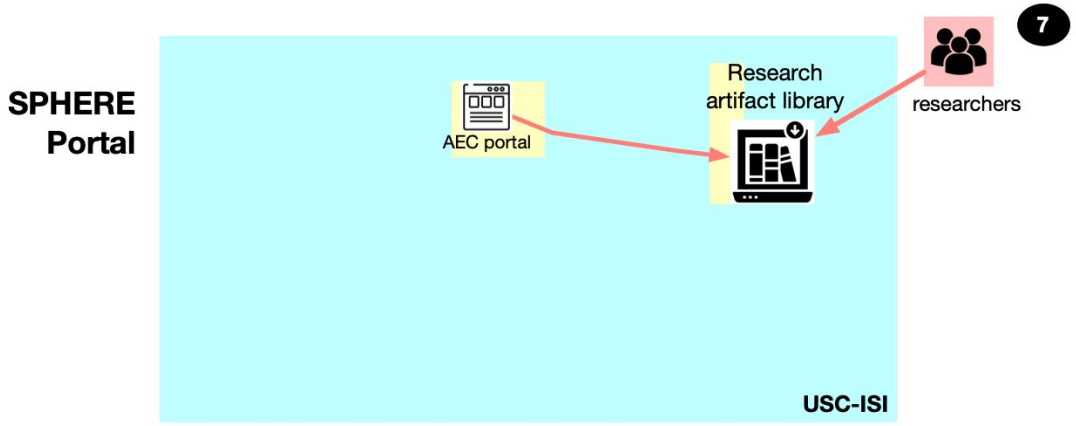


- Multiple user portals, supporting different types of users and use modalities
  - Manual, scripted, and GUI-only use support exploratory, mature, and novice research
  - Dedicated support for AECs, education, and human user studies

GUI – graphical user interface
AEC – artifact evaluation committee

Research Artifacts

- Artifacts support reproducibility, comparison, and extension of prior work
- Include software, data, workflows, and reusable experimentation environments
- Allow researchers to build on prior work rather than recreate environments and tools from scratch



- Acquired through partnerships with artifact evaluation committees and community contributors
- Integrated into SPHERE for evaluation, sharing, and reuse
- Enable more relevant, reproducible, and cumulative CS&P research

CS&P – cybersecurity and privacy

History

- **Over the past 20 years:** USC-ISI designed, built and operated DETERLab
  - 389 research project teams from 278 institutions, and involving 1,042 researchers from 205 locations and 46 countries
  - 230 classes from 147 institutions and helped educate more than 20,000 students
- **2019:** Merge software for testbed control and management
  - Built w/ modern open-source tools for large-scale, high-fidelity, robust experimentation
  - Merge has run several of our testbeds for the past four years – DCOMP, Searchlight, RedStar, and modernized DeterLab
- **Modernized software and hardware:** via NSF CCRI grant 2019-2022 and ARO DURIP grant 2019-2021
  - 48 new nodes, 6 new switches, Merge software, user transition
- Modernized DETERLab became the first seed to grow SPHERE as part of its general compute enclave

Prior Government Programs

USC-ISI has leveraged DETERLab or other Merge-based testbeds to provide T&E support (methodologies, tools, scenarios development, testbeds) for numerous DARPA programs:

- **Safer Warfighter Communications (SAFER):** DETERLab served as the testbed and experimentation platform for the development and evaluation of technologies advancing the state-of-the-art in non-blockable and anonymous communication
- **Edge-Directed Cyber Technologies for Reliable Mission Communication (Edge-CT):** DETERLab served as the testbed and experimental platform build realistic models of networks and workloads to help develop and evaluate prototypes
- **Dispersed Computing (DCOMP):** Merge-based DCOMP testbed was used for program evaluation with simultaneous experiments with hundreds of nodes interconnected through complex network topologies
- **Extreme DDoS Defense (XD3):** DETERLab served as the test platform to evaluate performer technologies
- **Searchlight:** Merge-based Lighthouse testbed supported extensive virtualization built around QEMU/KVM and Sandia's Minimega virtual machine automation platform to evaluate performer technologies

Unique Research Capabilities

SPHERE RESEARCH INFRASTRUCTURE

- **Relevance:** Experiments with emerging technology and specialized hardware, not currently available to many researchers, support 90%
- **Realism:** Experiments that combine different hardware devices to create realistic scenarios
  - e.g., IoT nodes with GPU nodes and programmable switches to filter attacks
- **Reproducibility:** Experiments on common RI, with extensive support for artifact sharing and reuse, facilitate vertical development
- **BPC:** Different experimentation portals cater to users with different abilities and interests, lowering barrier to entry
- **Impact:** Faster pace of innovation in CS&P and faster technology transition to practice

IoT – Internet of Things
GPU – graphical processing unit
RI – research infrastructure

BPC – Broadening Participation in Computing
CS&P – cybersecurity and privacy

Team Background

- **DeterLab:** the only public cybersecurity testbed for **18 years**
- Additional testbeds for formal eval. of DARPA programs
- **Merge:** mature testbed management software, running all three testbeds
- **Mon(IoT)r:** largest private IoT testbed and datasets
- Prior NSF funding: **SEARCCH** (reprod.), **DEW** (reprod., usab.), **DeterLab modernization** (RI)
- Many publications on experimentation, reproducibility, IoT privacy
- Founded **CSET workshop**, led NSF-funded **CEF study**, organized **CEF 2022** and **Cybersecurity Artifacts 2022** workshops, pioneered use of testbeds in education

389 research groups
1K researchers
237 classes
20K students

ported to 4 partner institutions

560 downloads

IoT - Internet of Things
SEARCCH – Sharing Expertise and Artifacts for Reuse through a Cybersecurity Community Hub

DEW – Distributed Experiment Workflows
CSET – Cyber Security Experimentation and Test, running for 17 years
CEF – Cybersecurity Experimentation of the Future

Research Benefits

- Enable realistic, sophisticated CS&P experiments using resources many researchers cannot access locally
- Let researchers build on shared environments and prior work rather than start from scratch
- Support reproducibility, comparison, validation, sharing, and reuse of results and artifacts
- Expand experimental capabilities through remotely accessible shared infrastructure
- Help authors and AECs evaluate, preserve, and extend research artifacts
- Enable more integrated, cumulative research and faster progress toward mature solutions

CS&P – cybersecurity and privacy
AECs - artifact evaluation committees

Educational Benefits

- Enable hands-on labs, assignments, demonstrations, and defense/offense exercises without comparable local infrastructure
- Give undergraduate and graduate students experience with modern systems, emerging technologies, and research practices
- Support educational use through a dedicated education portal for instructors and students
- Engage students through on-site and virtual internships in testbed development, research, and artifact porting
- Help prepare a larger, better-equipped CS&P workforce

CS&P – cybersecurity and privacy

Summer 2026 Interns

- 23 students participated in SPHERE internships
  - 18 in person: 13 at USC-ISI, 2 at NEU, 3 at Utah
  - 5 virtual interns from universities across the U.S.
- Projects advanced SPHERE functionality, usability, reproducibility/ reuse, and operations
- Intern work contributed new capabilities, improved infrastructure and tools, and reusable research artifacts
- Students gained hands-on experience with research infrastructure, CS&P experimentation, sw/hw development, and reproducibility
- Interns worked closely with SPHERE researchers and developers, with many contributions integrated into the testbed

CS&P – cybersecurity and privacy

Example Intern Projects

AI agents for experiment automation (ISI)

Natural-language agents automated experiment design and deployment, reducing setup time by 2-6x

Facility Modeling GUI (ISI)

Visual tools made SPHERE facility models easier to create, inspect, validate, and maintain

Remote smart-lock experimentation (NEU)

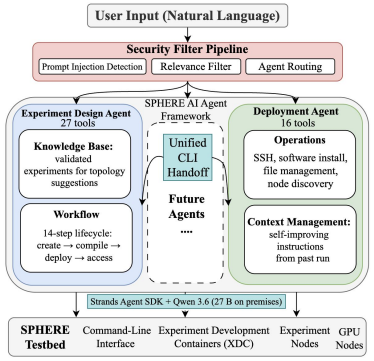
Integrated SPHERE's first remotely controllable smart lock using a reusable 3D-printed fixture and motorized actuator

Reusable ICS infrastructure (Utah)

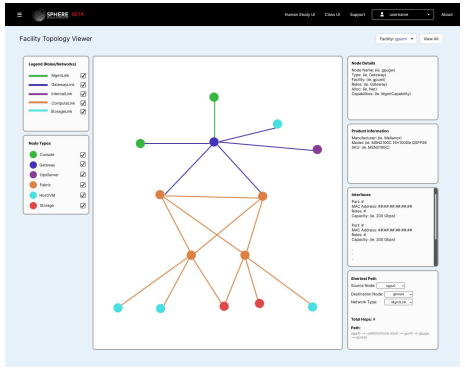
Developed reusable, high-fidelity ICS environments spanning process models, HMIs, human factors, and enclave hardware

Research artifact reuse (virtual interns)

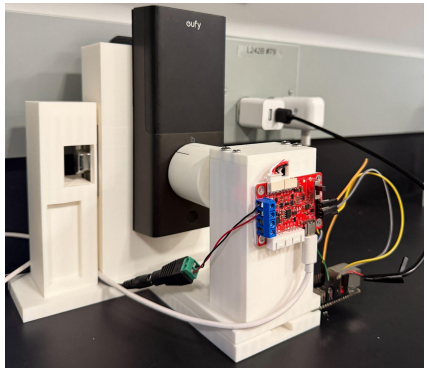
Attempted 167 recent CS&P artifacts and reproduced 106 for reuse on SPHERE



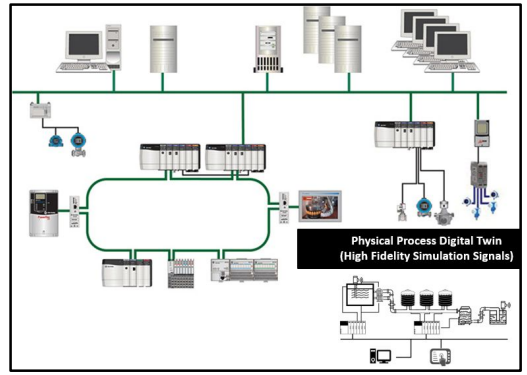
AI-agent framework



Facility topology viewer



Smart lock fixture



ICS experiment

Recent CS&P artifacts packaged for reuse on SPHERE	**167** attempted	**106** reused

Societal Benefits

- Accelerate development of more rigorous, mature CS&P technologies and their transition to practice
- Enable industry, critical-infrastructure stakeholders, and government to evaluate and mature solutions before deployment
- Help integrate CS&P protections into new and emerging technologies before widespread deployment
- Strengthen protection of people, data, services, scientific infrastructure, and critical infrastructure from cyber threats
- Benefit society through faster development and adoption of better-tested, more trustworthy technologies

Community Outreach

- Needs discovery to inform our project activities and awareness to encourage beta use
- Presentations, posters, and other activities at major conferences
  - Major cybersecurity conferences: NDSS, S&P, USENIX Security, CCS, ACSAC
  - Other conferences: IoT, ICS, SC, etc.
  - NSF events: RIW, Cybersecurity Summit, MERIF, SaTC PI meeting
    Other communities: Tapia, Grace Hopper, SACNAS NDiSTEM
- Engage researchers via surveys and interviews
  - Target diverse research communities, such as networking, ICS, IoT, SDN, etc.
- Adjust SPHERE development to meet community needs

Google form at https://bit.ly/SPHERE-Needs-Survey

NDSS – Network and Distributed System Security
S&P – IEEE Symposium on Security & Privacy
CCS – ACM Conference on Computer & Communication Security
ACSAC – Annual Computer Security Applications Conference

RIW – Research Infrastructure Workshop
SaTC – Secure and Trustworthy Cyberspace
SACNAS – Advancing Chicanos/Hispanics & Native Americans in Science
NDiSTEM – National Diversity in STEM

Open to Beta Users

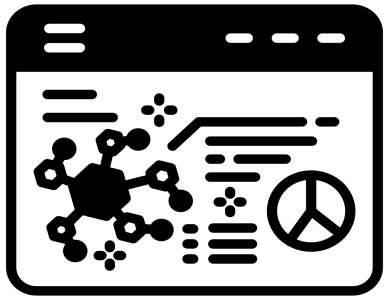
- These users help us grow and improve before we open to larger audience
- Currently around 130 researchers and 200-1000 students per semester
- Users get access to cool new hardware and features
  - Log in remotely via browser, create custom topologies of general purpose VMs (control VM resources, network topology, bandwidth and delay)
  - Access nodes via SSH w/ sudo privileges
  - Experiment directly on nodes or via Jupyter notebooks
  - Able to reach into the Internet, can also support incoming connections
  - Chat-based user support

Component	Dev Started	Available for Use
SPHERE Infrastructure	Oct 2023	Mar 2024
General purpose nodes	May 2024	Oct 2025
GPU nodes	Nov 2024	Apr 2025
ICS platforms	Nov 2024	Oct 2025
Embedded compute nodes	May 2025	Jan 2026
IoT nodes	Oct 2023	Aug 2025
Programmable nodes	Sep 2025	Mar 2026

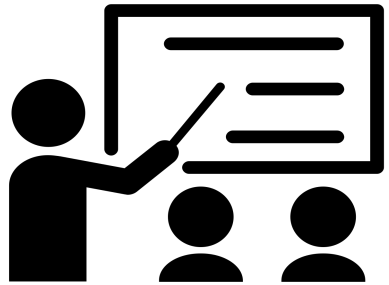
How You Can Help!

Promote and leverage SPHERE at your organizations!

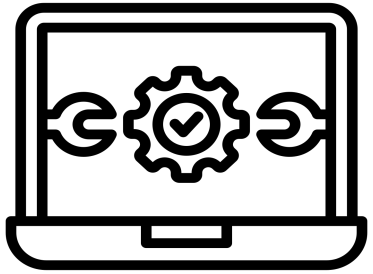
Researchers can use SPHERE to conduct new, innovative research



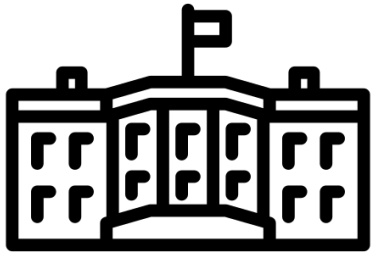
Faculty and students can use SPHERE for educational purposes



IT staff can use SPHERE to test and evaluate new solutions and technologies



Govt PMs can use SPHERE (or other Merge testbeds) to support their programs



Thank you!

If you use SPHERE in your research and a publication, we would appreciate a citation. Currently, the best reference for SPHERE is:

Jelena Mirkovic, David Balenson, Brian Kocoloski. Enabling Reproducibility through the SPHERE Research Infrastructure. USENIX ;login: Online, USENIX Association. December 16, 2024. https://www.usenix.org/publications/loginonline/enabling-reproducibility-through-sphere-researchinfrastructure

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