# HPC with Enhanced User Separation

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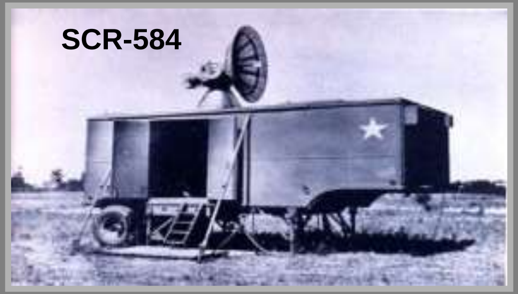
MIT LINCOLN LABORATORY
SUPERCOMPUTING CENTER

# Who We Are – a Little History


MIT Building 20

**Mission:** ***Development of radar systems and technology***

**Main projects:**
- **Surveillance radar**
- **Fire control radar**
- **Navigation systems**



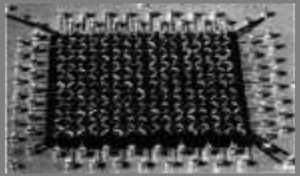

**4000 employees**
**Designed half of all US WWII radars**

**Est. 1951:** ***Air defense and technology development***

**Main projects:** **Semi-Automatic Ground Environment (SAGE)**

**Major Innovations:**


Real-Time Computing


Magnetic-core Memory


Light-pen CRT Interface



https://www.ll.mit.edu/sites/default/files/other/doc/2018-04/MIT_Lincoln_Laboratory_history_book.pdf

# MIT Lincoln Laboratory

## Department of Defense Federally Funded Research and Development Center

Massachusetts Institute of Technology

MIT Lincoln Laboratory

**Mission:** Technology in Support of National Security

**Key Roles:**
- System architecture engineering
- Long-term technology development
- System prototyping and demonstration

**FY23 Employees:** 4419

**FY23 Funding:** $1.39B

**Facilities:** 2.1M sq-ft

**Mission Areas:**
- Air and Missile Defense
- Homeland Protection
- Air Traffic Control
- Communication Systems
- Cyber Security
- Advanced Technology
- Space Control
- ISR Systems and Technology
- Tactical Systems
- Engineering
- Biotechnology & Human Systems

# History of Supercomputing at Lincoln Laboratory

1951 Whirlwind

1953 Magnetic-Core Memory Array

1956 TX-0

1958
- AN/FSQ-7 (Whirlwind II)
- Average Response Computer (ARC)
- CG-24
- TX-2

1962 Lincoln Instrument Computer (LINC)

1963 Sketchpad

1970 Fast Digital Processor (FDP)

1970 GENESYS

1974 Lincoln Digital Voice Terminal (LDVT)

1977 : Lincoln Digital Signal Processor (LDSP)

Late 1970s High-speed FFT pipelined processor

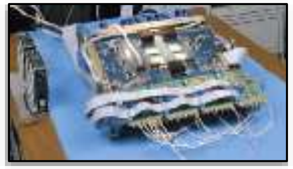
1978 Micro-Processor Based LPC Vocoder (LPCM)

1982 Compact LPC Vocoder

Early 1990s
- APT processor
- RAPTOR processor
- Space-Time Adaptive Processing Library (STAPL)

1992 Radar Surveillance Technology Experimental Radar (RSTER) processor

1999 Parallel Vector Library (PVL)



2002
- ISR Processing and Array Technology (IPAT) processor
- MatlabMPI

2003 pMatlab

2004 Knowledge-Aided Sensor Signal Processing and expert Reasoning (KASSPER) processor

2004
- pMapper gridMatlab
- LLGrid TX-2500

2007
- Parallel Vector Tile Optimizing Library (PVTOL)
- Real-Time Communication Layer (RTCL)

2012 D4M

2014 LLGrid TX-Green

2015 BigDAWG

2016 Lincoln Laboratory Supercomputing Center (LLSC)

1950 — 1960 — 1970 — 1980 — 1990 — 2000 — 2010



https://www.ll.mit.edu/r-d/cyber-security-and-information-sciences/lincoln-laboratory-supercomputing-center

# Lincoln Laboratory Supercomputing Center (LLSC) Role

**Mission Areas**

- Air and Missile Defense
- Homeland Protection
- Air Traffic Control
- Communication Systems
- Cyber Security
- Advanced Technology
- Space Control
- ISR Systems and Technology
- Tactical Systems
- Engineering
- Biotechnology & Human Systems

**Vast Data & Computation**


OSINT | Weather | HUMINT | C2 | Ground | Maritime | Air | Space | Cyber

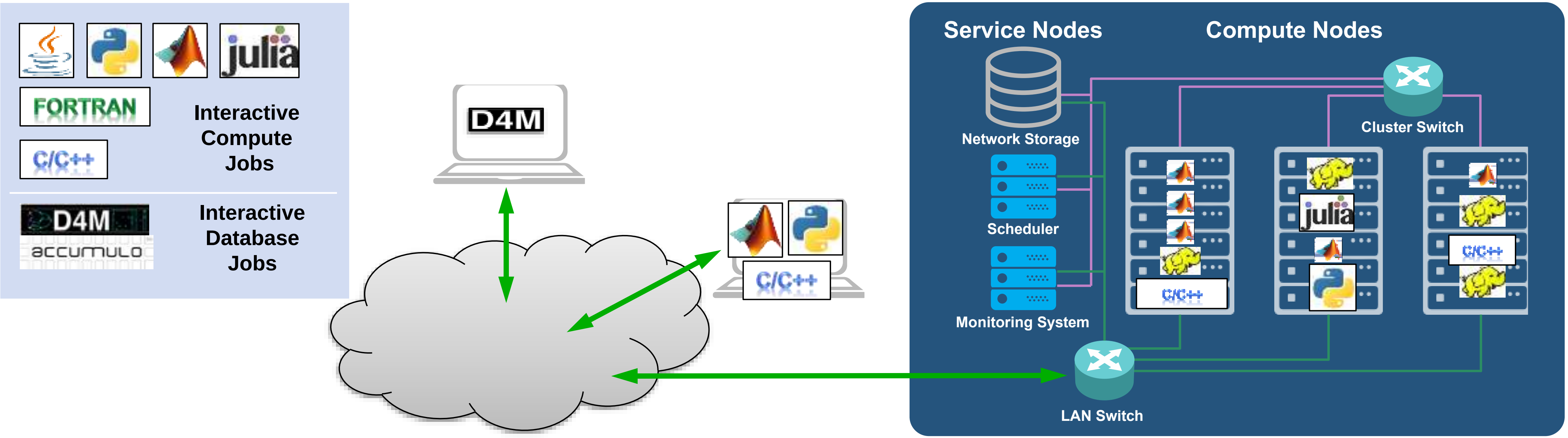
**LLSC develops & deploys unique, energy-efficient supercomputing that provides cross-mission**

- Data centers, hardware, software, user support, and pioneering research
- 100x more productive than standard supercomputing[1]
- 100x more performance than standard cloud[2]



[1]*Interactive Grid Computing at Lincoln Laboratory*, Bliss et al., LL Journal, 2006
[2]*Scalability! But at what COST?*, McSherry et al., HotOS XV, 2015

# Broaden the Definition: Interactive HPC




- LLSC provides a software platform that allows users to
  - Launch interactive compute jobs from their desktop
  - Share large volumes of project data
- The LLSC experience provides
  - Reference datasets pre-positioned in databases
  - Software modules and training to reduce user ramp up time

- Rapid Prototyping
  - Algorithm development
  - Data analysis
  - Machine learning training
- Application Steering
  - Real-time / streaming data analytics
  - Debugging/validation
- Visualization



N. T. Bliss, R. Bond, J. Kepner, H. Kim, and A. Reuther, "Interactive Grid Computing at Lincoln Laboratory," *Lincoln Lab. J.*, vol. 16, no. 1, p. 165, 2006.

# Outline

- **What's different about HPC?**
- **Path Forward**
- **Implementation**
- **Results & Conclusion**

# What's different about HPC?

- Every HPC user is a software developer
  - … but software development is not most users' primary domain of expertise!
  - Very few HPC users have workflows that don't require them to write code
  - This can present in many different ways: writing algorithms in Python/Julia/Matlab/Octave, setting up processing pipelines, performing analysis, creating multi-workflow orchestration via shell scripts, developing a complex distributed simulation using C and MPI …
- Some of the code is early prototype "version 0"
  - It's going to have bugs
  - It's not going to have any security built in (yet)
- Even venerable HPC libraries have little security built-in
  - MPI frameworks do not encrypt data or authenticate peer ranks
  - Efforts to extend them with security have seen little adoption[1,2]



1. *An Empirical Study of Cryptographic Libraries for MPI Communications*, Naser et al., IEEE CLUSTER 2019
2. *Scalable Cryptographic Authentication for High Performance Computing*, Prout et al, IEEE HPEC 2012

# What's different about HPC?

- Users are often required to run both software from large open source frameworks and proprietary closed-source programs
  - Neither are typically designed with a HPC environment in mind
  - Both have unique challenges making them difficult or impossible to modify to better suit this environment
- Software is not the product
  - In many cases the primary goal of running the program is to generate data that will appear in a plot
- Obvious security concerns running this code:
  - It's interacting with sensitive data
  - It's distributed using the HPC network
  - It's on a shared use system

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# Path Forward

- **How do we manage this risk?**
- **Option 1: Make the code better**
  - **Focus on improving the most commonly-used software and development libraries and frameworks, providing easy to use security primitives**
  - **Training users to be better, security-focused programmers**

- **Challenges:**
  - **Doesn’t solve issue of where to run “version 0” of code**
  - **Doesn’t address large open source frameworks or closed-source commercial software**
  - **There is a daunting variety of software run on our system, we can’t fork everything**
  - **Still requires users to prioritize writing secure code, and use any primitives provided**
  - **We get new users all the time**

# Path Forward

- How do we manage this risk?
- Option 2: Make the HPC system itself better
  - Every software developer needs a coding sandbox, a safe testbed for the initial development of new code
    - For when you *know* the code still has bugs, including security-relevant bugs
    - Enabling fast exploration of capability
    - Not all coding efforts will turn into successful projects, some are intentional one-offs
    - Even for much more mature code, software designed with HPC in mind rarely fully considers security
  - Core security responsibility cannot be delegated to unprivileged users
    - If everyone is responsible for something, no one is

**Can we make a system where all core security concerns are addressed at the system level?**

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# Implementation

- Enhanced separation: Enforcing the separation between users, isolating them so they can't observe or interact with each other
- Several categories of cross-talk that need to be considered:
  - Processes / jobs (local / global)
  - Filesystem (local / shared)
  - Network & web forwarding
  - Accelerators (GPUs, etc)

# Implementation: Local Processes

**Restrict locally visible Linux process information: hidepid=2 on /proc/ mount**

- **Hides processes and command lines belonging to other users or system daemons**
- **Solves entire class of information leakage issues**
  - **Mitigated SLURM CVE-2020-27746 in advance: x11 authentication key exposed on command line**
- **Critical on shared nodes (login, data transfer)**

```
aprout@login-3:~$ ps -ef
UID          PID    PPID  C STIME TTY          TIME CMD
aprout    253759 3840877  0 15:47 pts/55   00:00:00 ps -ef
aprout   3840832       1  0 14:27 ?        00:00:02 /lib/systemd/systemd --user
aprout   3840877 3840860  0 14:27 pts/55   00:00:00 -bash
aprout@login-3:~$
```

**Better user experience: users only see things they should care about**

# Implementation: Scheduler Jobs (global processes)

- **Restrict globally visible scheduler information: SLURM privatedata configuration**
  - **Hides other users jobs, usage, scheduling and accounting information, etc.**
  - **Shares many of the same information leakage concerns as local processes**
  - **Many job properties could contain private information: name, command, working directory**

```
aprout@login-3:~$ sbatch -p xeon-p8 -a 0-2 --wrap '/bin/sleep 90'
Submitted batch job 27347457
aprout@login-3:~$ squeue
             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
        27347457_0   xeon-p8     wrap   aprout  R       0:01      1 d-18-8-2
        27347457_1   xeon-p8     wrap   aprout  R       0:01      1 d-18-8-2
        27347457_2   xeon-p8     wrap   aprout  R       0:01      1 d-18-8-2
aprout@login-3:~$
```

```
root@login-3:~# squeue | wc -l
1448
root@login-3:~#
```

**Better user experience: users only see things they should care about**

# Implementation: Filesystem

- **Goal: Users should be unable to share data with any other user**
  - **Except through intentional use of an approved project group**
- **User private groups: the default UNIX group for every user contains only themselves**
- **HPC File Permission Handler[1]: Linux kernel patches to restrict filesystem permissions**
  - **Security mask (smask): Block the use of world bits for unprivileged users**
    - **Similar to "umask 007", but immutable and enforced (even on chmod)**

```
aprout@login-3:~$ touch /tmp/test; chmod o+rwx /tmp/test
aprout@login-3:~$ ls -lah /tmp/test
-rw-rw---- 1 aprout aprout 0 Nov 10 14:56 /tmp/test
```

  - **Restrict file access control lists to group members only**
    - **Cannot grant permission to a group unless you're a member of said group**

```
aprout@login-3:~$ setfacl -m u:areuther:rwx /tmp/test
setfacl: /tmp/test: Operation not permitted
aprout@login-3:~$ setfacl -m g:areuther:rwx /tmp/test
setfacl: /tmp/test: Operation not permitted
aprout@login-3:~$ setfacl -m g:gridteam:rwx /tmp/test
aprout@login-3:~$
```

1. Source code available at: https://github.com/mit-llsc

# Implementation: Network – internal

- **Goal: only permit network connections between processes where client & server are running as the same user**
  - **With ability to extend to project groups on an opt-in basis**
- **No modification of end-user code**
  - **We'd tried providing cryptographic primitives before[1], very little adoption**
    - **Would require a mandate, and a never-ending "policing it" effort**
    - **Not a solution for closed source code**
  - **No ability for user to turn it off**
- **User-Based Firewall[2] (UBF) for TCP & UDP traffic**
  - **IPTables NetFilter Queue module (nfqueue) used to send new connections to userspace daemon for decision**
  - **Only "new" connections are sent, IPTables conntrack handles existing connections**
  - **ident[3]-like query sent to far system to get user information, same query run locally**
  - **Connection allowed if same user, or connector is a member of listener process primary group**
  - **Implicitly controls most IB/RDMA traffic: most frameworks use TCP connection for setup**

1. *Scalable Cryptographic Authentication for High Performance Computing*, Prout et al, IEEE HPEC 2012
2. *Enhancing HPC Security with a User-Based Firewall*, Prout et al, IEEE HPEC 2016. Source code available at: https://github.com/mit-llsc
3. *Identification Protocol*, US Department of Defense, RFC1413 Feb 1993

# Implementation: Network – external

- **Goal: Enable easy access to web-services running as jobs on the HPC cluster from end-user web browsers**
  - **With always-on enforced authentication provided by the system**
  - **Without TLS certificate warnings**
- **Point solutions existed, but require integration effort, increased attack surface, and often used incompatible authentication schemes**
  - **Multi-user solutions: JupyterHub, RStudio, …**
  - **One-offs: TensorBoard, VisualStudio Code Server, …**
- **Web application forwarding via HPC portal[1]**
  - **Allows users to forward access to web applications running as part of jobs**
  - **Avoids ad-hoc port forwarding through SSH, TLS certificate warnings, user misconfigurations**
  - **Authentication required to HPC Portal and UBF connection rules applied**
    - **Supports password-less smartcard-only systems**

1. *Enhancing HPC Security with a User-Based Firewall*, Prout et al, IEEE HPEC 2016. Source code available at: https://github.com/mit-llsc

# Implementation: Accelerators

- GPUs do not use a traditional security model for data resident in memory
  - No concept of data ownership, data segmenting within the GPU[1,2]
- Assign GPUs as a single-user resource
  - Not relevant when whole node scheduling when pam_slurm restrictions are in place
  - Modify permissions on relevant character special files in /dev/ to allow only the user private group of the user allocated that GPU via SLURM
  - GPUs not assigned to the user are not visible at all
- Clear GPU memory before reassignment
  - GPU has no implicit way to know when it’s being reassigned
  - Previous user’s data will remain in GPU memory, registers
  - Vendor-provided steps taken to clean GPU performed in SLURM epilog



1. *CUDA Leaks: Information Leakage in GPU Architectures*, Di Pietro et al, ACM TECS 2013
2. *Confidentiality Issues on a GPU in a Virtualized Environment*, Maurice et al, FC 2014

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# Results

- Opportunities for accidental data leakage between users are greatly reduced
  - A few paths still exist: file names in world-writable directories (e.g. /tmp, /var/tmp), abstract namespace unix domain sockets, direct IB verbs communication
- Enhances reliability as well
  - Even if users chose same port number for a network service, they can’t crosstalk and corrupt each others’ data
- Limits the damage of misbehaving code
  - Contains the “blast radius” of any issues to just that user’s account
- The user experience is enhanced because they don’t need to sort through irrelevant information about other users processes/jobs
- Compliance people are happier
  - No more blurring the line between who is responsible for security: it’s a system service

# Conclusion

- Every HPC user is a software developer
- Software development is not their primary domain of expertise, and never will be
- By enabling strong user separation at every point in the system, you protect the confidentiality and integrity of the data
- By reducing the burden on the user to worry about these things, the usability of the system is enhanced as well
- By making security a system-provided service, data owners can have increased confidence about having their data on a multi-tenant system

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# Contact

**Source Code: https://github.com/mit-llsc**