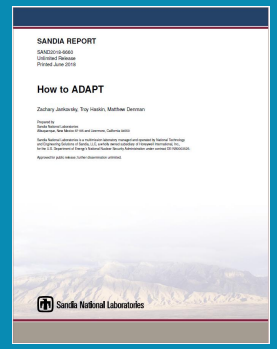
Recent Analysis and Capability Enhancements to the ADAPT Dynamic Event Tree Driver


SANDIA REPORT

SAND2016-6660
Unlimited Release
Printed June 2016

How to ADAPT

Zachary Jankovsky, Troy Haskin, Matthew Denman

Sandia National Laboratories


Annals of Nuclear Energy

Dynamic event tree analysis with the SAS4A/SASSYS-1 safety analysis code

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Acknowledgments

- This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories under a partnership with The Ohio State University Nuclear Engineering Program.
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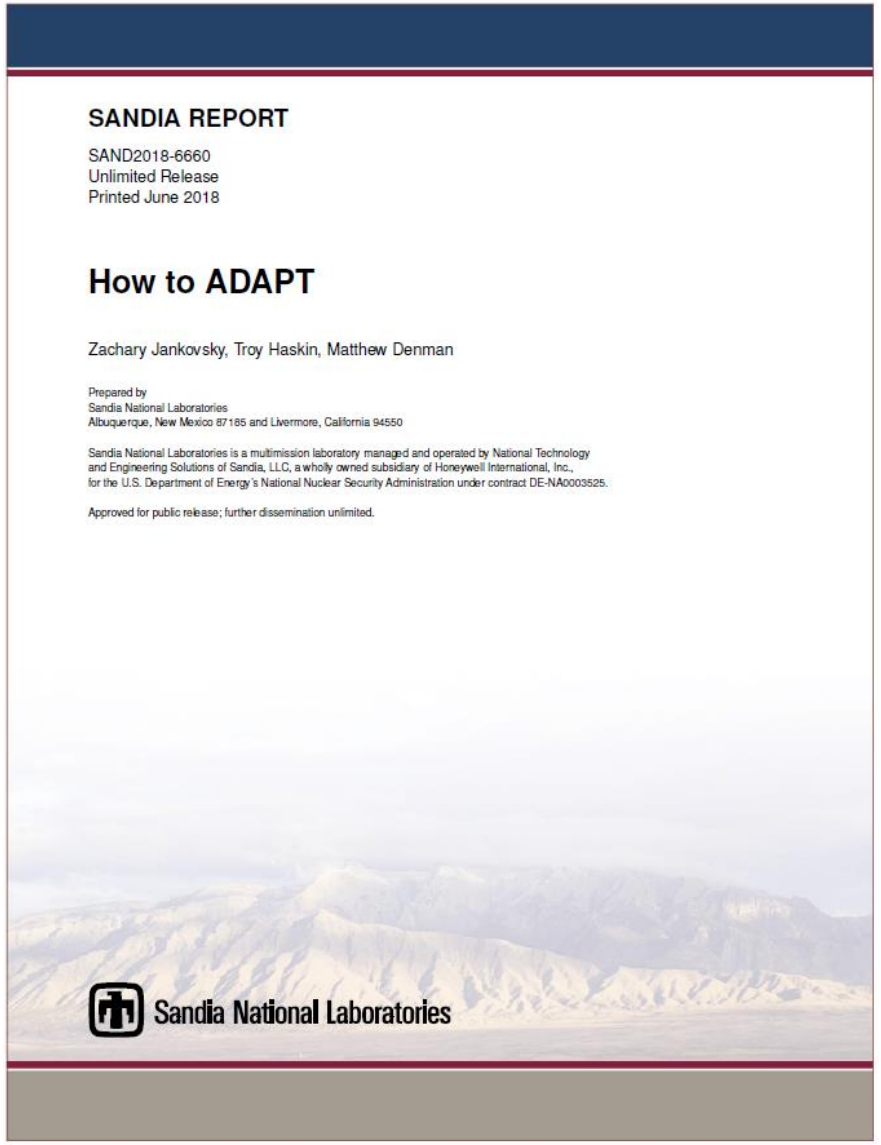
Outline

- Dynamic PRA
- ADAPT Overview
- Recent Analysis Tools
- Performance Improvements
- HPC Operation



SANDIA REPORT

SAND2018-6660
Unlimited Release
Printed June 2018

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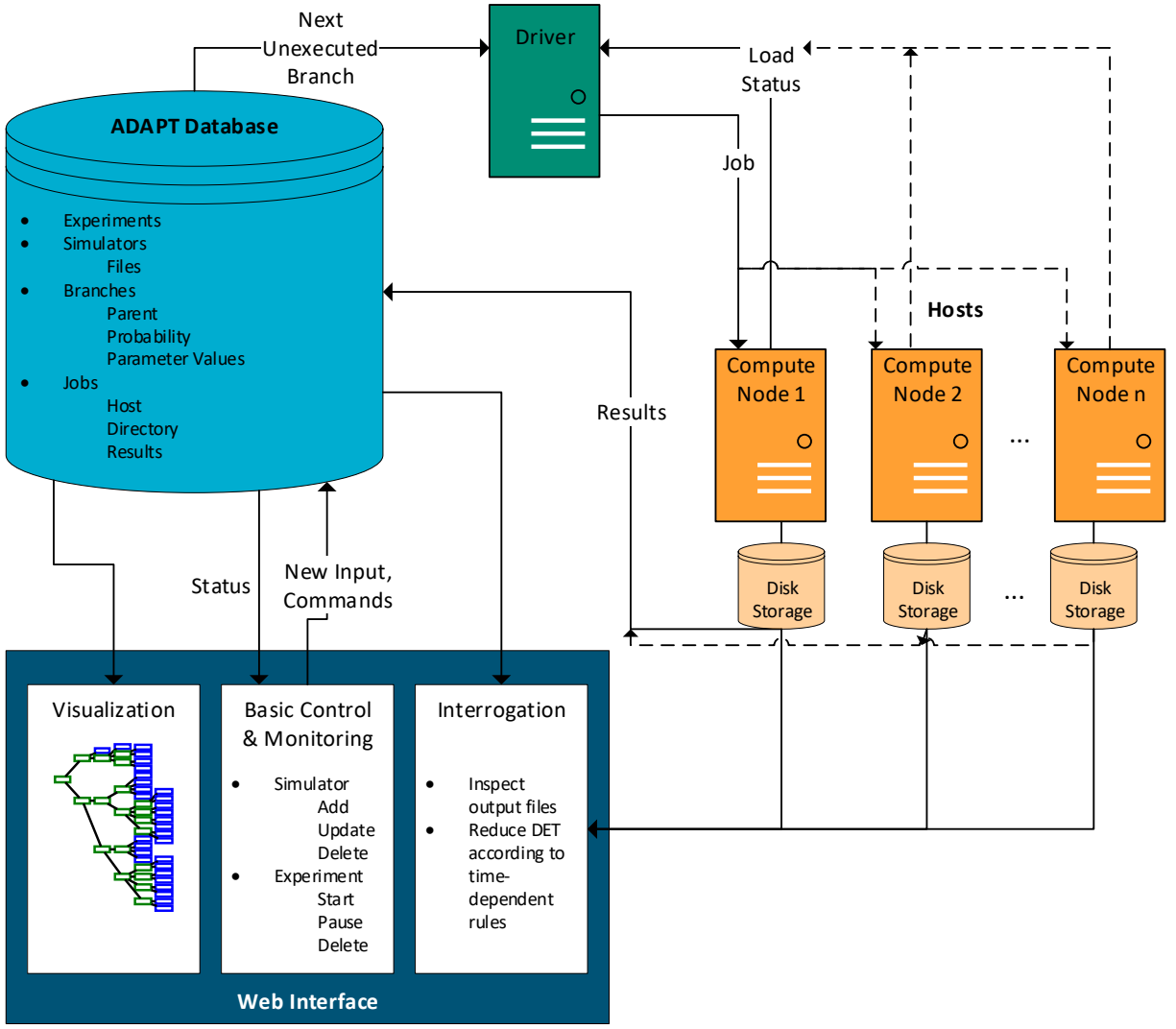
Dynamic Probabilistic Risk Assessment (PRA)

- Traditional PRA requires analysts to assume order of events
  - Does not explicitly account for timing of events
    - Will an event have different effects on incident progression based on its timing?
  - Uncertainties in event ordering may be higher in certain problem space
    - E.g., Level 2 PRA for nuclear power plants
- Dynamic PRA is driven by time-resolving models of the relevant phenomena
  - Events occur according to physically-meaningful rules
    - E.g., hydrogen igniter success is queried only when a combustible mixture has accumulated
  - Events may re-occur as appropriate (e.g., valve failure query on cycling)
  - Dynamic event trees (DETs) are easily incorporated into a traditional PRA

ADAPT Approach

- DET driver developed for/by SNL (2006-present)
  - Tracks DET database, launches jobs, and presents results
- Simulator- and domain-agnostic
  - Simulators must meet a short list of requirements
    - Capable of restarting from saved state with new input
  - Simulator interactions performed via signal files rather than shared memory
    - Traceability
    - Portability over diverse computational hosts



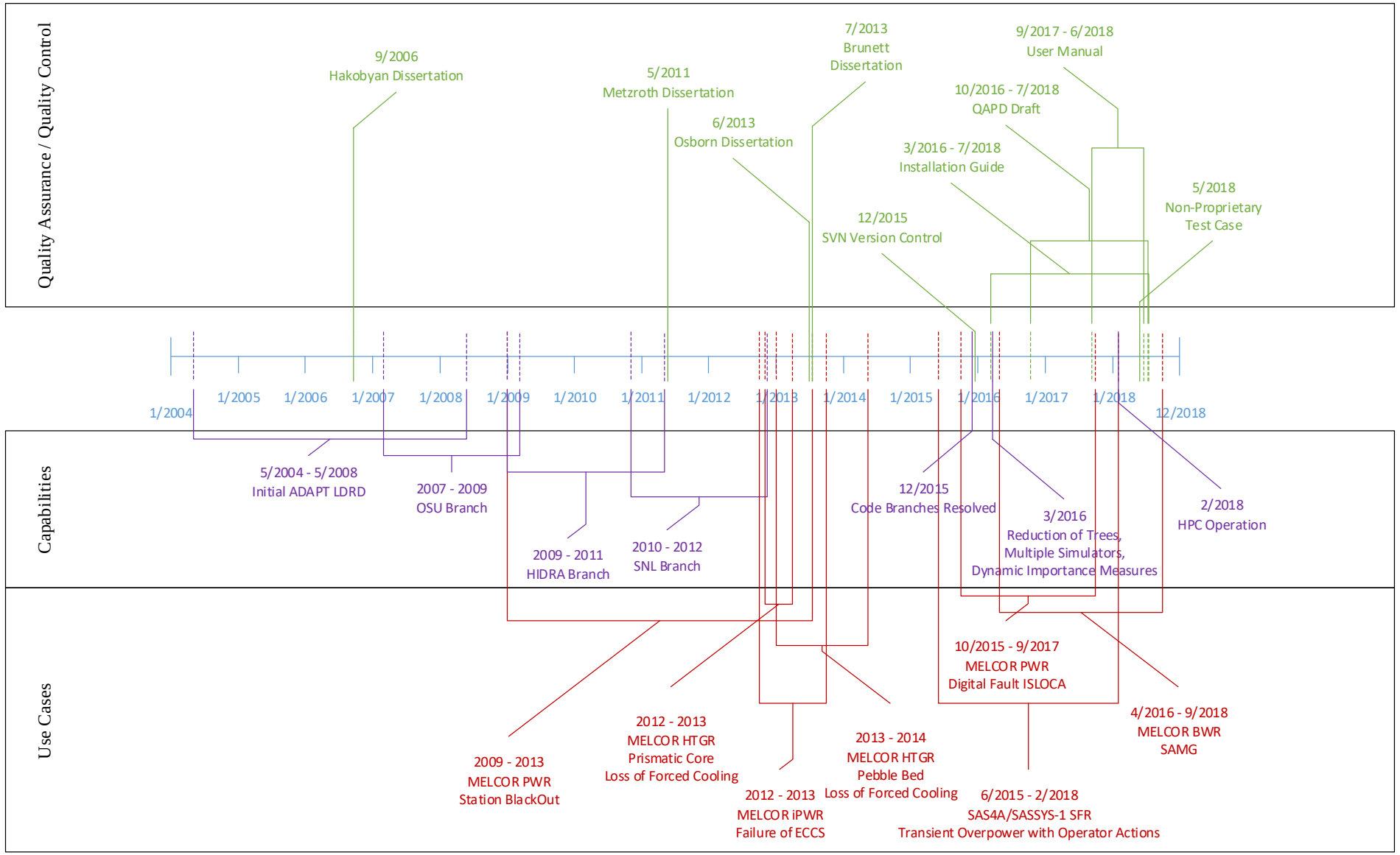
ADAPT Applications

Years	System	Incident	Simulator(s)
2006-2011	PWR	SBO	MELCOR
2009	SFR	Aircraft Crash	RELAP5
2013	PWR	SBO	MELCOR
2013-2014	PWR	SBO	MELCOR
2014	HTGR	LOFC	MELCOR
2015-2017	PWR	SBO	MAAP4
2015-2017	SFR	TOP	SAS4A/SASSYS-1
2015-2018	PWR	ISLOCA	MELCOR, RADTRAD
2015-2018	BWR	SBO	MELCOR
2016-2018	SNF Cask	Derailment	STAGE, RADTRAN

PWR: Pressurized Water Reactor
SFR: Sodium-cooled Fast Reactor
HTGR: High Temperature Gas-cooled Reactor
BWR: Boiling Water Reactor
SNF: Spent Nuclear Fuel

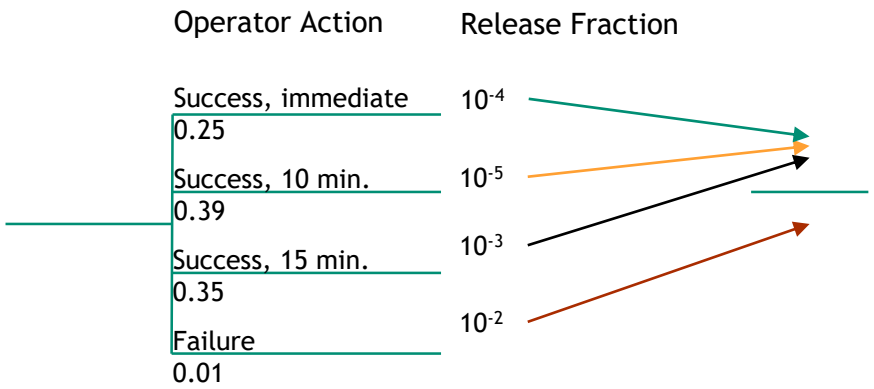
SBO: Station Blackout
LOFC: Loss of Forced Cooling
TOP: Transient Overpower
ISLOCA: Interfacing System Loss of Coolant Accident

ADAPT Timeline



Recent Analysis Tools (1/2)

- Dynamic Importance Measures (DYIs)
  - Compare expected values of chose consequences by branching condition value
    - Event occurrence vs non-occurrence, e.g.: $\frac{Release\ Fraction(operator\ action\ succeeds)}{Release\ Fraction(operator\ action\ fails)}$
    - Event extent vs non-occurrence, e.g.: $\frac{Release\ Fraction(operator\ action\ succeeds\ in\ 15\ minutes)}{Release\ Fraction(operator\ action\ fails)}$
    - Event extent vs all occurrence, e.g.: $\frac{Release\ Fraction(operator\ action\ succeeds\ in\ 15\ minutes)}{Release\ Fraction(operator\ action\ succeeds)}$
  - Mechanistically generate DYIs and rank to find impactful relationships

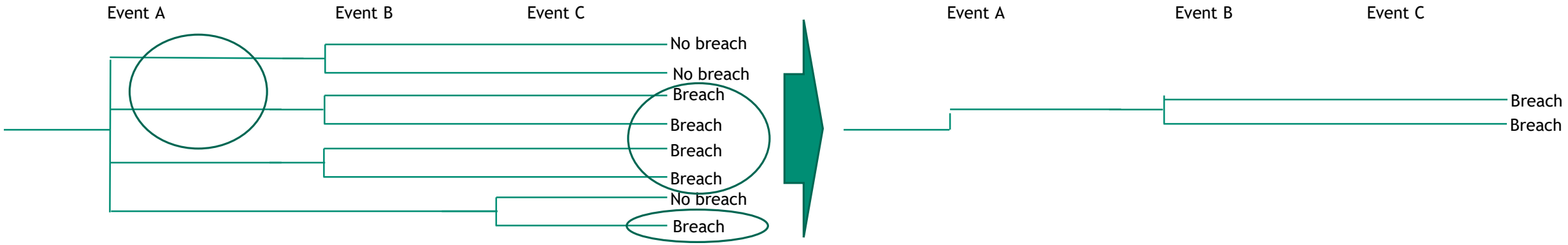


$$= \frac{Release\ Fraction(operator\ action\ succeeds)}{Release\ Fraction(operator\ action\ fails)} = \frac{\frac{0.25*10^{-4}+0.39*10^{-5}+0.35*10^{-3}}{0.25+0.39+0.35}}{\frac{0.01*10^{-2}}{0.01}} = 0.04$$

  - The expected value of the release fraction when the operator action succeeds is 0.04 times the expected value when the operator action fails.

Recent Analysis Tools (2/2)

- Multiple Simulator Analyses
  - Allows a DET to be driven by any number of simulators
  - Each branching condition transfers to pre-determined simulator
    - Processing steps must be defined for each allowed transition
      - E.g., MELCOR-MELCOR, MELCOR-MACCS, MACCS-MACCS, but not MACCS-MELCOR
- Reduction of DETs according to time-dependent rules
  - E.g., return only sequences where operator action succeeded in 11 minutes or less and vessel breached
  - All ADAPT analysis tools may be used on the reduced DET
    - Compare conditional insights to base DET



Performance Improvements (1/2)

- Inherited codebase
  - Designed around ~2006 hardware/software environments
    - Ample opportunity for high ROI improvements
- File operations are costly
  - Results distributed across multiple machines/filesystems
  - Parallelize gathering of results
    - Scales to 98% of $1/n_{cores}$ time required to gather a single variable for all DET branches
    - **Next step: establish ADAPT post-processing scheme to distribute work to additional nodes**
  - Cache results
    - When results are demanded, check if files have changed in any branch of the DET
      - If no change, use a cached copy of results
        - 4x wall time reduction for finished DET
      - If files have changed, pull fresh data
    - **Next step: check branches individually**
      - Further reduction in un-necessary duplication when some branches have changed

Performance Improvements (2/2)

- Database operations are costly
  - Significant overhead in each query
    8,300 queries with one result each take 1,400 times the wall time of a single query with 8,300 results
  - Reduce number of queries
    - Remove database queries from for loops
    - Pull all relevant data in a single query and loop over results in memory
  - Example: pulling relationships of all branches in a DET
    - Previously performed iteratively
      - Database query for each relationship
    - Now entire branches table is pulled in one query
      - Relationships calculated locally
      - Saves 60% wall time
        - Used in many post-processing routines

HPC Operation - Motivation

- Historical use of ADAPT
  - Desktop computer: 40 cores, 10 TB storage
    - Full control over scheduling
  - Local cluster: 200 cores, 200 TB storage
    - High control over scheduling
- Combinatorial explosion
  - Each additional branching condition may significantly expand DET
  - Branch input may require simulator to run for minutes to weeks
  - Easy to generate a DET that is computationally impractical to finish
    - And can be difficult to predict the eventual size of a DET
- Opportunity (Sandia example)
  - Available corporate clusters: 100,000 cores, 10PB storage
    - Little control over scheduling

HPC Operation – A Note on Terminology

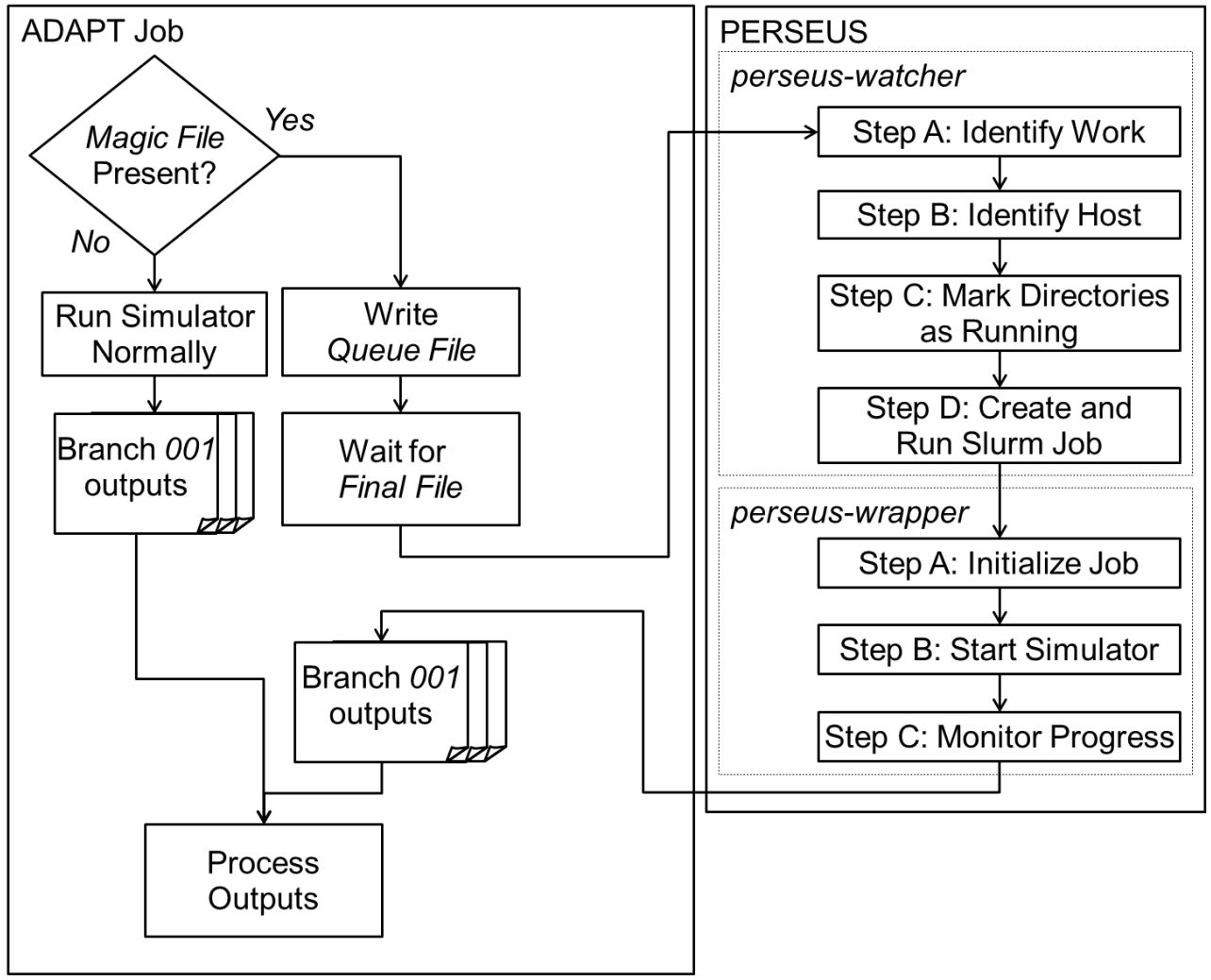
- ADAPT branch:
  - A segment of the analysis with a set of uncertain system parameters that remain constant until a branching condition is reached
- ADAPT job:
  - An attempt to run the input associated with a branch on a particular computational host
- HPC job:
  - A script that is run on a particular computational host until it completes or meets a time limit
    - May include multiple ADAPT jobs

HPC Operation - Constraints

- ADAPT job scheduling
  - Historically has used ssh/scp commands to communicate with computational hosts
    - No special software required on computational hosts
  - Resources allocated a core at a time
  - ADAPT jobs may run until finished with no time limit
- HPC job schedulers have strict requirements
  - Scheduler-specific submission tool
  - Resources typically allocated a node at a time
  - Limited run time
- ADAPT jobs are independent
  - HPC capacity vs capability
- ADAPT jobs are unpredictable in time requirement
- Simulators typically used with ADAPT are single threaded
  - Node-based submission not advantageous

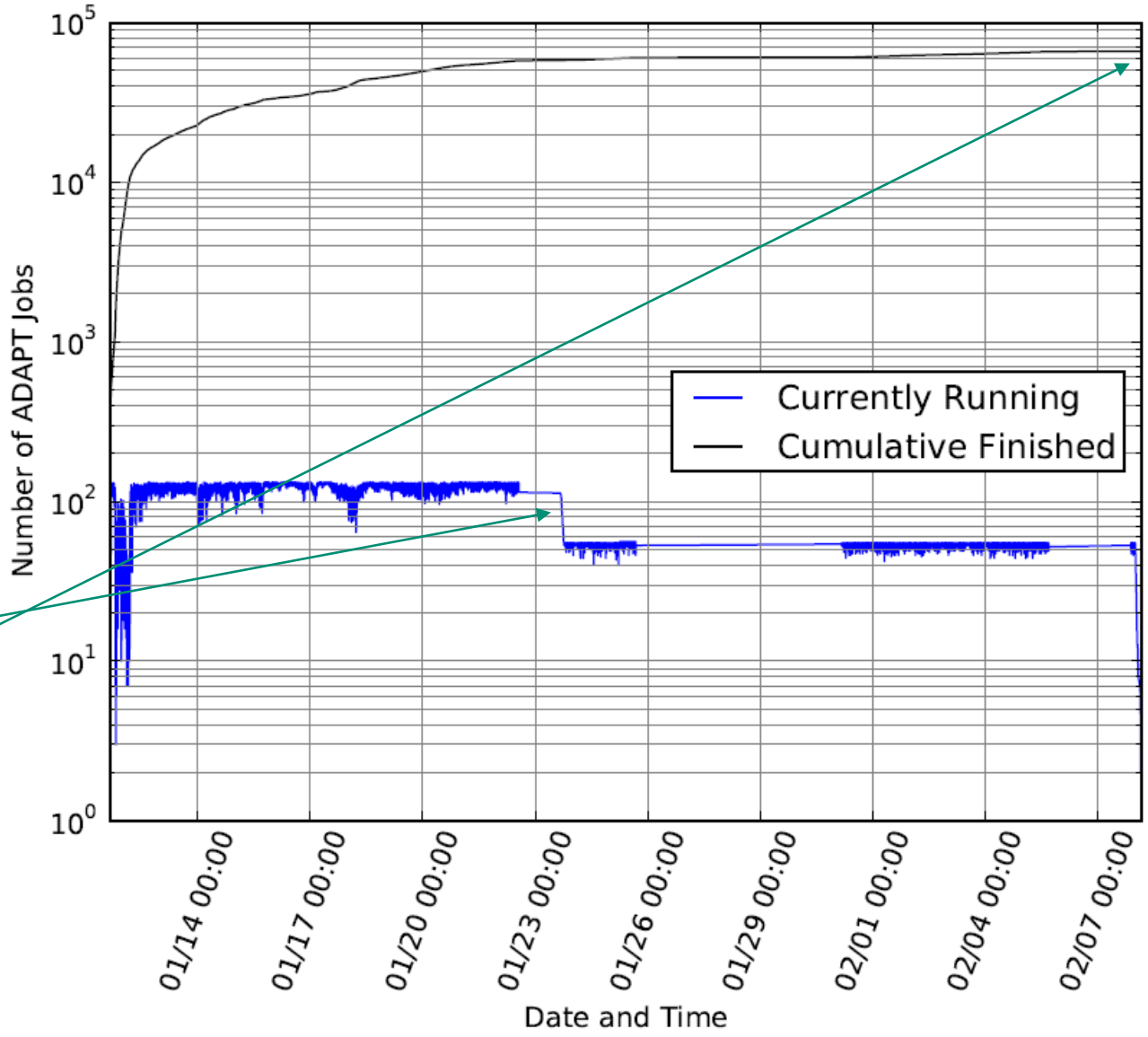
HPC Operation – Proof of Concept Approach

- Intercept running ADAPT jobs
  - Run normally on local cluster until simulator execution
  - Bundle enough ADAPT jobs to fill an HPC node and submit an HPC job
  - At end of HPC job time limit:
    - If an ADAPT job has finished, signal that HPC work is done
    - If an ADAPT job has not finished, return it to the local cluster for another round on the HPC
  - ADAPT job closeout process does not change
- Production implementation will integrate HPC as an ADAPT computational host type



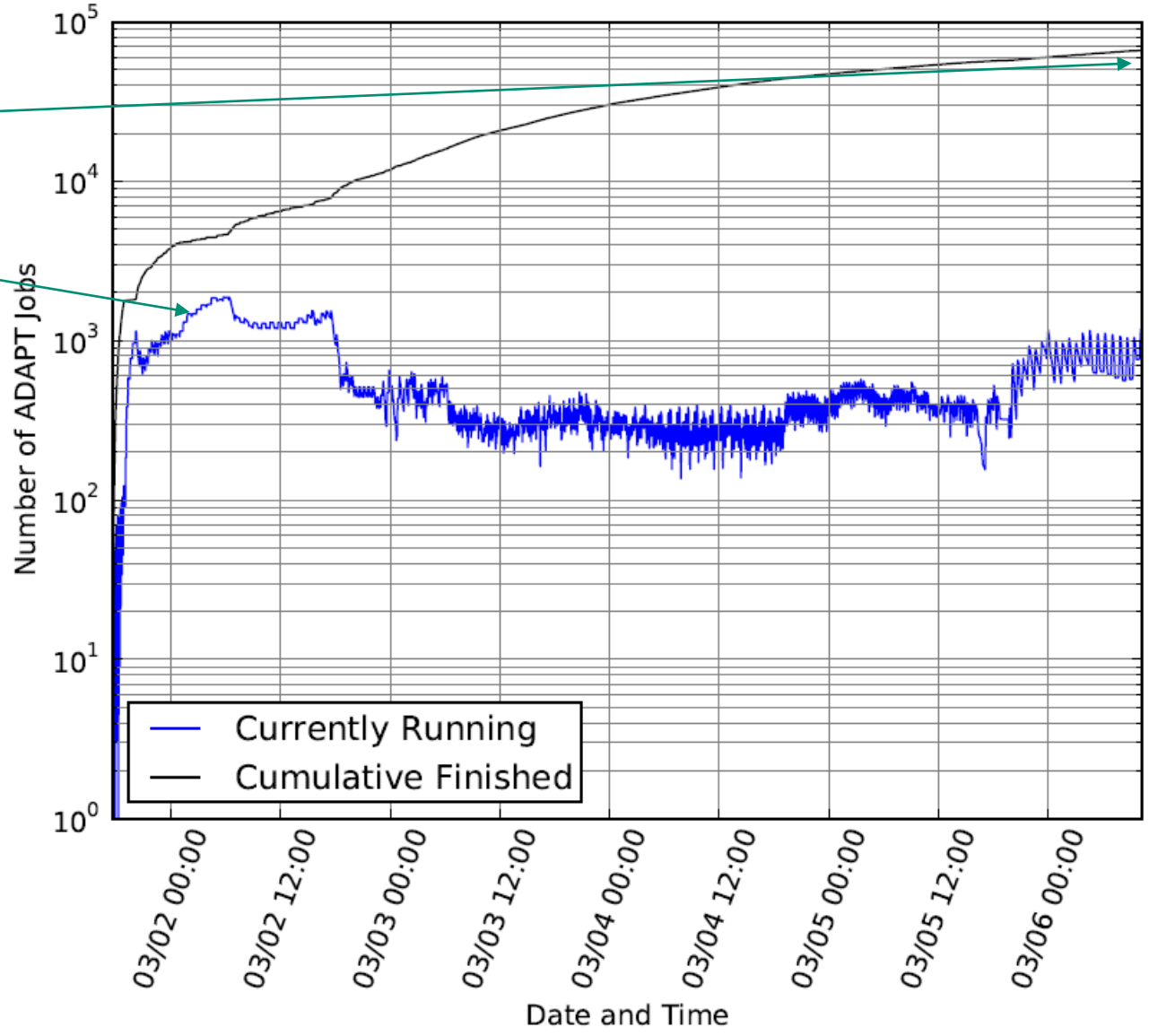
HPC Operation – Test Case on Local Cluster

- Pressurized water reactor interfacing system loss of coolant accident
  - MELCOR severe accident simulator and RADTRAD dose calculation simulator
    - Only MELCOR branches sent to HPCs
  - Uncertain capacity of systems for overpressurization
  - Uncertain success and timing of operator mitigating actions
- Test case run first on local cluster
  - Maximum 132 cores
  - Required to share capacity with another ADAPT case (down to 55 cores)
  - 66,076 branches completed in 27.5 days



HPC Operation – Test Case on HPCs

- Test case run next on HPCs
  - Same progress as small cluster run (66,076 branches completed) in 4.7 days
    - 6x reduction in wall time required for same progress
  - Significant variation in open ADAPT jobs over time
    - Varies with HPC load
- Potential for savings increases with number of queued branches



HPC Operation - Feedback

- Common HPC work packages request multiple nodes and run to completion with little interaction
  - E.g., computational fluid dynamics or finite element analysis problems
- ADAPT on HPCs presents an atypical workload
  - ADAPT frequently polls HPCs for load status to identify HPCs with idle nodes
    - Because single nodes are requested at a time, queueing may be avoided
    - Will be made moot if HPC federation is implemented
  - If all ADAPT jobs in an HPC job finish early, the HPC job finishes early
- HPC administrators took notice
  - Frequent ssh connections to HPC head nodes to check status
  - Significant numbers of HPC jobs not running to requested time
  - Frequent and significant traffic to and from a remote system on the network
  - Coordinated with administrators to identify and test process improvements

Summary

- DPRA can give additional insight to complex event progressions
  - What physical parameters are impactful?
  - How does the timing of human interaction affect the outcome?
- ADAPT is a flexible DET generation and analysis platform
  - Limited only by availability of appropriate simulators
  - Easily adaptable to various computational environments
  - Extensible data analysis tools
    - Scalable from hundreds to 1M+ branches