Lawrence Livermore National Laboratory

Resilient and Efficient High-Performance Computing via Application Behavior Analysis

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Good Old Days

Plentiful Resources

Optimize and Done

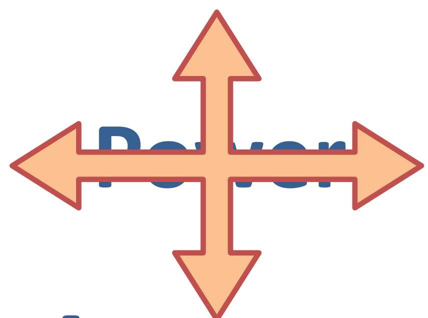
Future

Severe Resource Constraints

Future

Severe Resource Constraints

Power/Energy

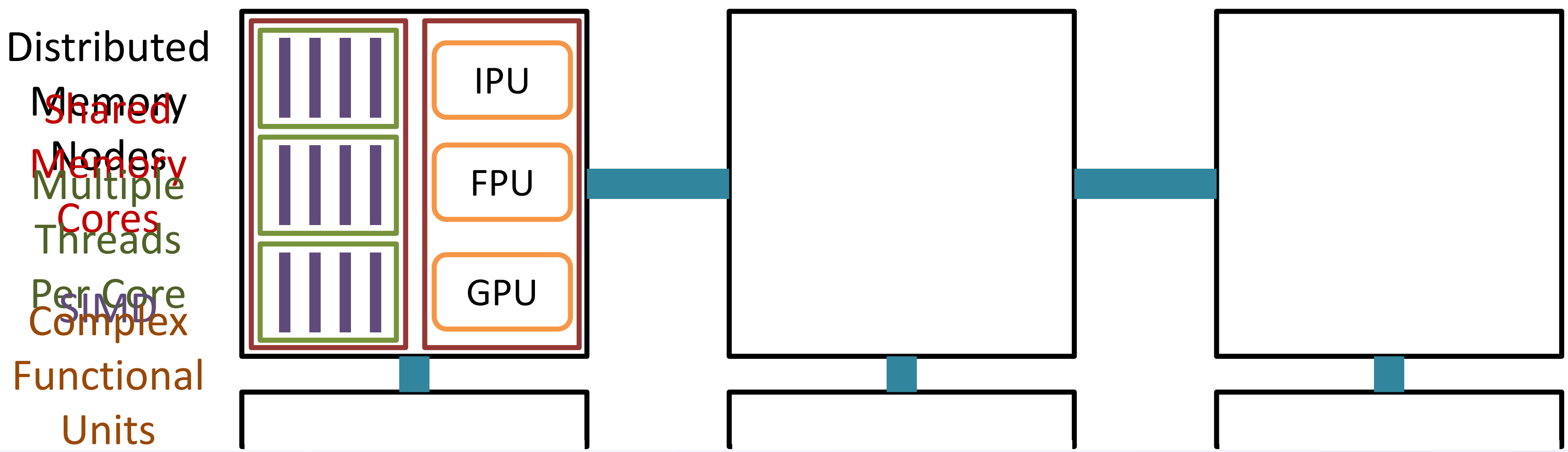
Performance  Usability

Accuracy

Many-Dimensional <u>Productivity</u> Optimization

Optimization solutions induce complexity in application and system design/behavior

- Systems Complexity
  - Failures (soft errors, fail-stop crashes)
  - Static and dynamic performance variation
    (dynamic voltage scaling, variable guardbands)
  - Complex, heterogeneous hierarchies



Optimization solutions induce complexity in application and system design/behavior

- **Systems Complexity**
  - Failures (soft errors, fail-stop crashes)
  - Static and dynamic performance variation
    (dynamic voltage scaling, variable guardbands)
  - Complex, heterogeneous hierarchies
- **Application Complexity**
  - Adaptation to problem structure
    (Adaptive refinement, sparse systems)
  - Dynamic load-balancing
  - Coupled multi-physics simulations

Key Challenge: co-managing applications and system to achieve high productivity

- Application and system flexibility induces very large interaction space:
  Challenge and Opportunity

Weather Simulation

– 1 ... sor

– ...

When is high precision needed?
- High wind speed?
- High temperature?
- …?

– Can vary precision over space/time regions

System

– La... essors

– P... m

– R...

s... e

When should system reduce frequency?
- High temperature?
- Erratic timing?
- …?

– Can reduce frequency if problems arise

Challenging to control within each component

Key Challenge: co-managing applications and system to achieve high productivity

- Application and system flexibility induces very large interaction space: **Challenge and Opportunity**

<u>Weather Simulation</u>

When is high precision needed?
- High wind speed?
- High temperature?
- …?

<u>System</u>

When should system reduce frequency?
- High temperature?
- Erratic timing?
- …?

Cross-component optimization is more productive and challenging

Need techniques that productively harness application and system flexibility

- Combination of individual components has very complex interactions
- Productive control requires analysis of behavior and intelligence to guide it
  - Migrate load based both on simulated wind speeds and processor temperature
  - Reduce voltage to save power while meeting accuracy bound in face of hardware errors
- Minimal changes to existing source code

Detailed **Analysis** of Application and System

↓

Informed **Action** Based on Analysis

Analysis

- Dynamic statistical modeling
- Sensitive to properties of input

Meas

- Applicatio system me
- Quantify a

nent

- and
- applications
- use new

- Two end-to-end use-cases that demonstate utility of approach in sparse linear algebra
  - Resilience
  - Performance
- Highlights of deeper ongoing research to translate approach to real applications and systems

- Guide developers, system administrators

Use-case:
Error detection in sparse linear algebra

- Problem: radiation and voltage variation cause random corruptions of computations
- Checking matrix-vector multiplication $\boldsymbol{Ax}$

$$\boldsymbol{c}^{T}(\boldsymbol{Ax}) \; ?= \; (\boldsymbol{c}^{T}\boldsymbol{A})\boldsymbol{x}$$

Result

Match

Arbitrary

check vector

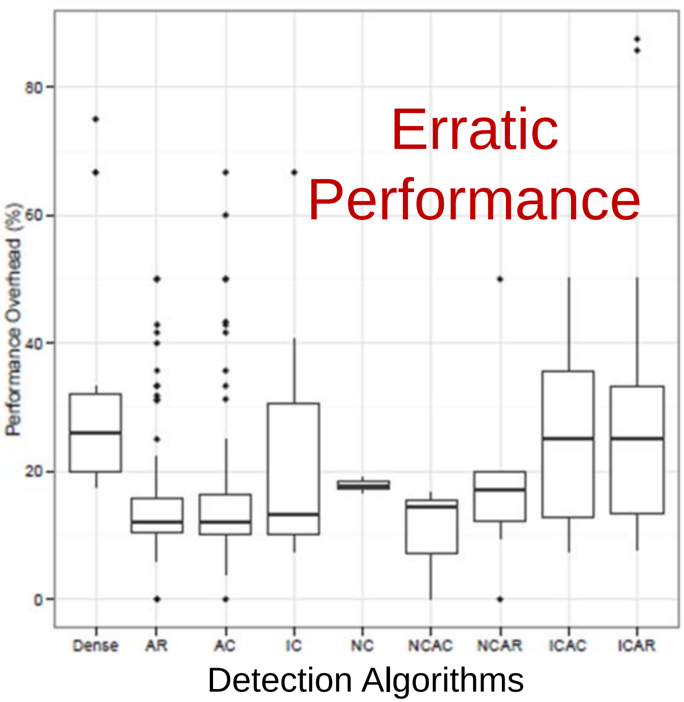
Computed offline

for each matrix A

- c can be vector of all 1s
- Or random choice of 90% 0s and 10% 1s
- Or Near A's null-space
- Or approximate solution to $\boldsymbol{c}^{T}\boldsymbol{A} = \boldsymbol{I}$

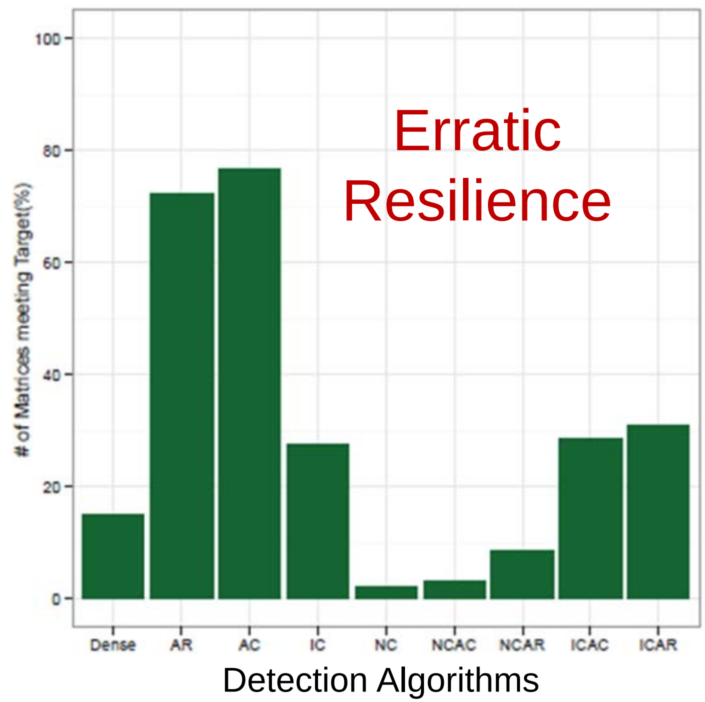
Performance and quality of error detectors varies highly across matrixes

Performance Overhead
of Error Detection



Good

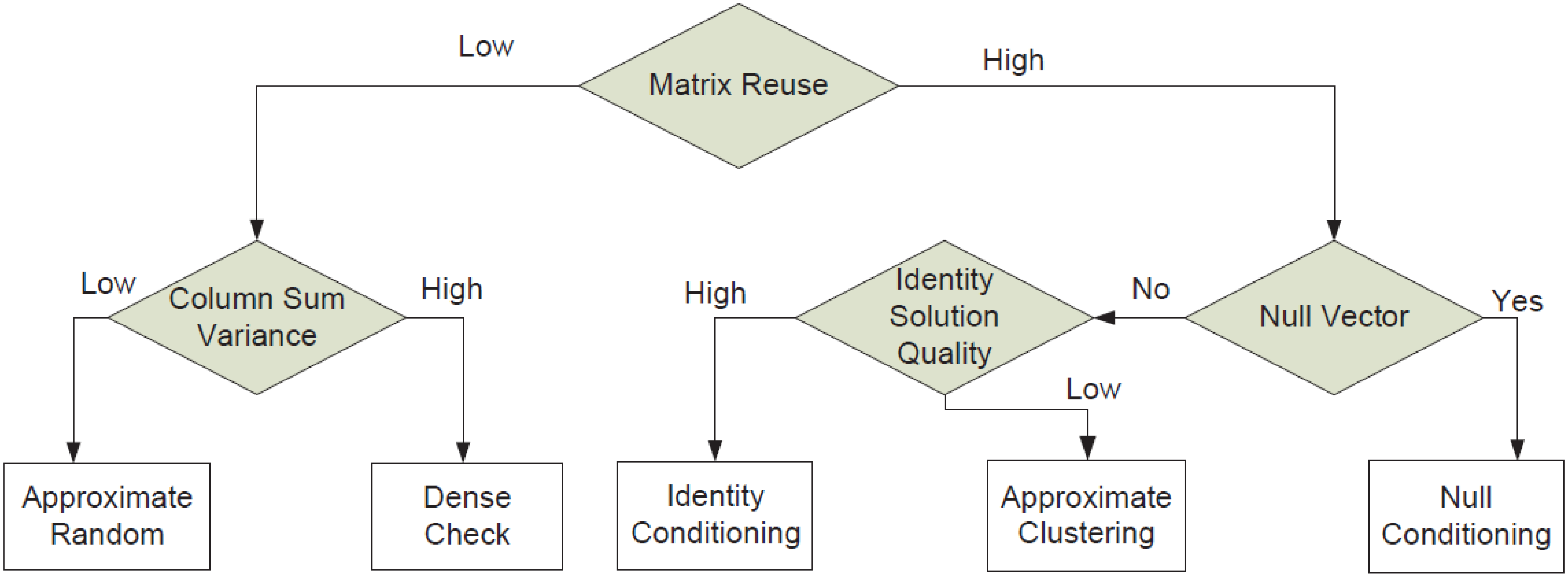
Accuracy of Error Detection
(Fraction of runs with high F-Score)



Good

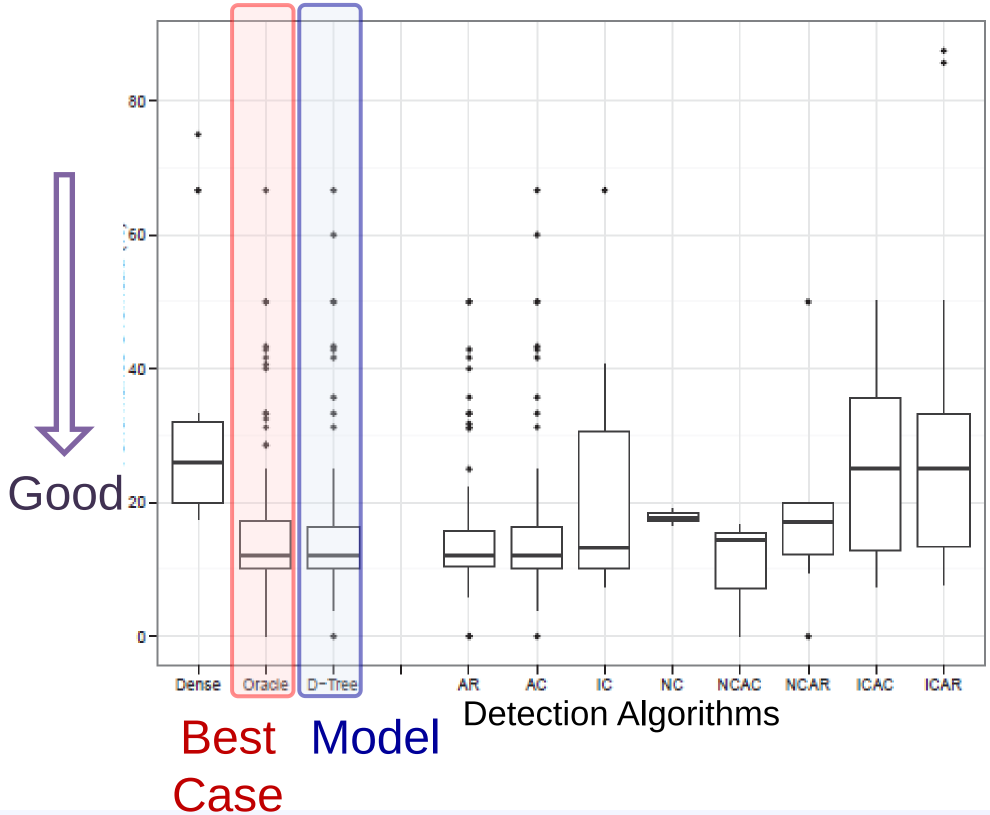
Measured over 100 sparse matrixes

Trained a matrix-sensitive statistical model of detector effectiveness



Model-guided error detector consistently efficient and accurate across input space

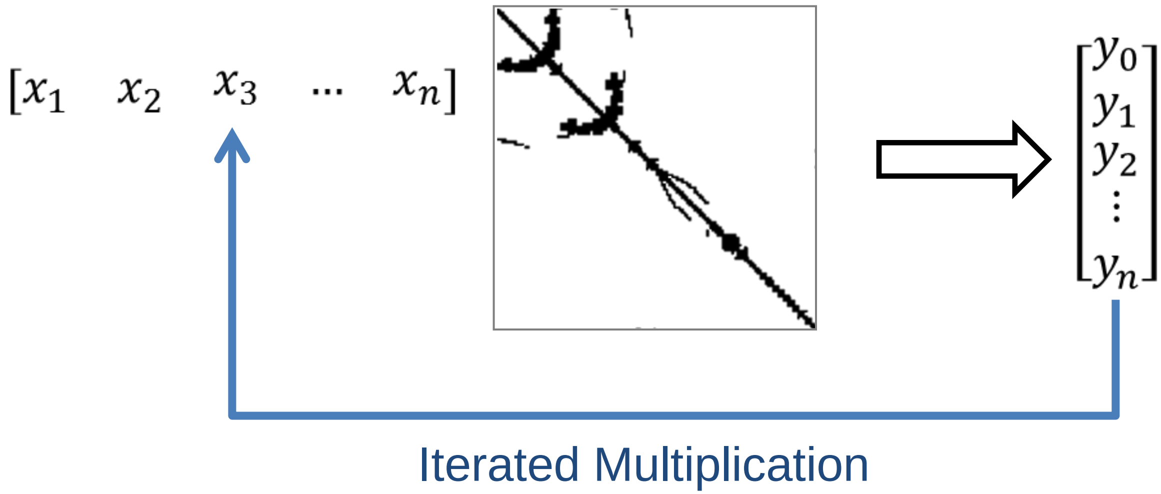
Performance Overhead of Error Detection



Accuracy of Error Detection
(Fraction of runs with high F-Score)

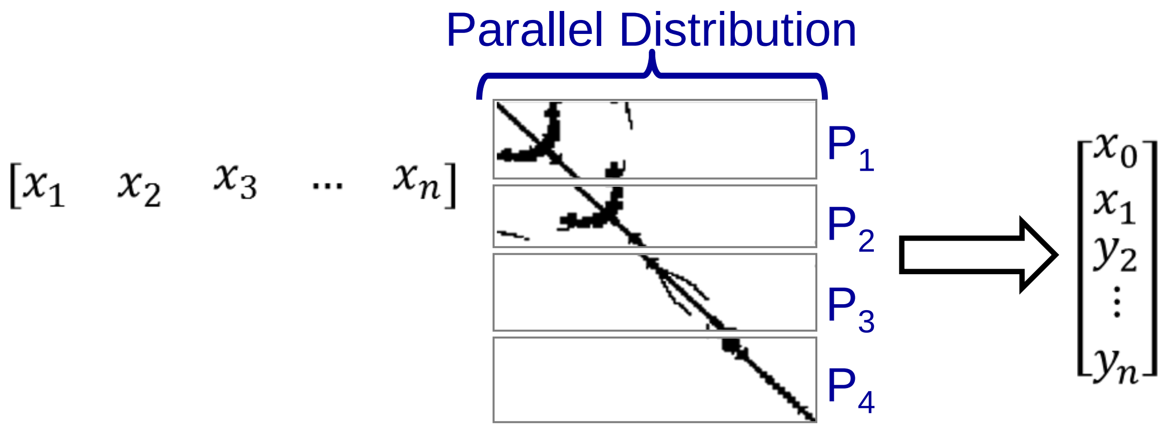
Use-case:
Optimization for sparse linear algebra

- Sparse iterative solvers repeatedly execute matrix-vector multiplication



Parallel performance depends on load balance and communication volume

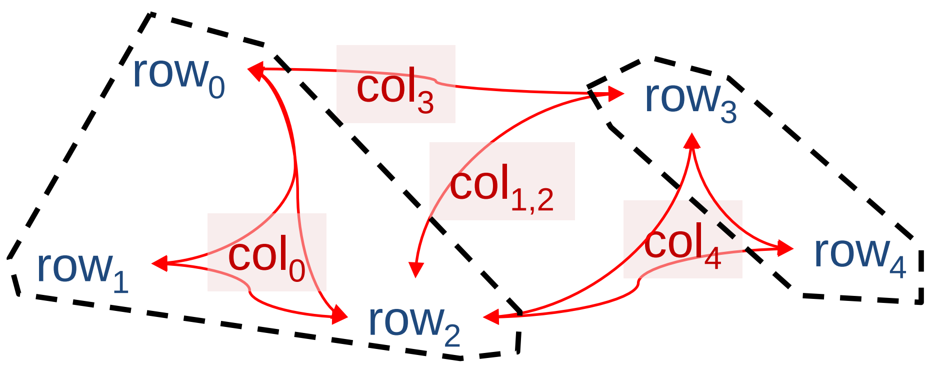
- Sparse iterative solvers repeatedly execute matrix-vector multiplication



- Rows distributed to
  - Balance computation
  - Reduce communication (values computed in iteration i sent to subset of row blocks for iteration i+1)

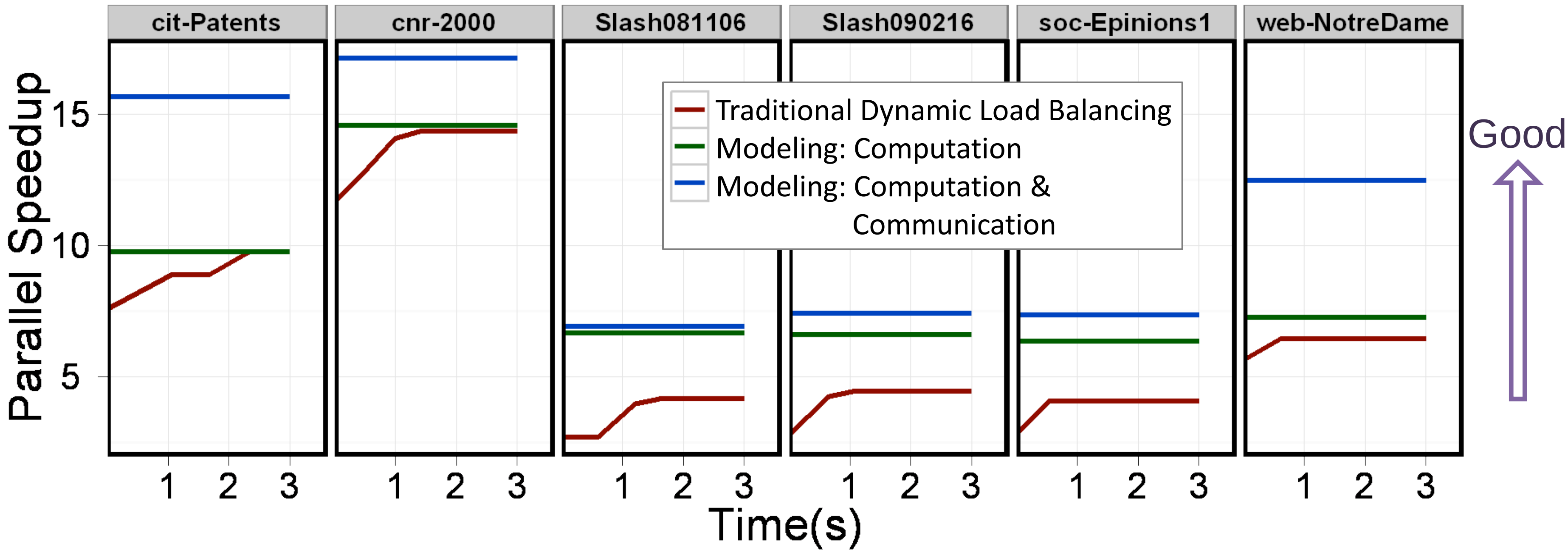
Computation and communication modeling simplifies data-dependent optimization

- **Computation model for each row**
  - Non-zero count (CPU use)
  - Distance from first to last column (Memory locality)
  - Statistically model row execution time
- **Communication model**
  - Columns shared by two rows



Partition graph to allocate load

Model-based scheduling improves performance and speeds scheduling



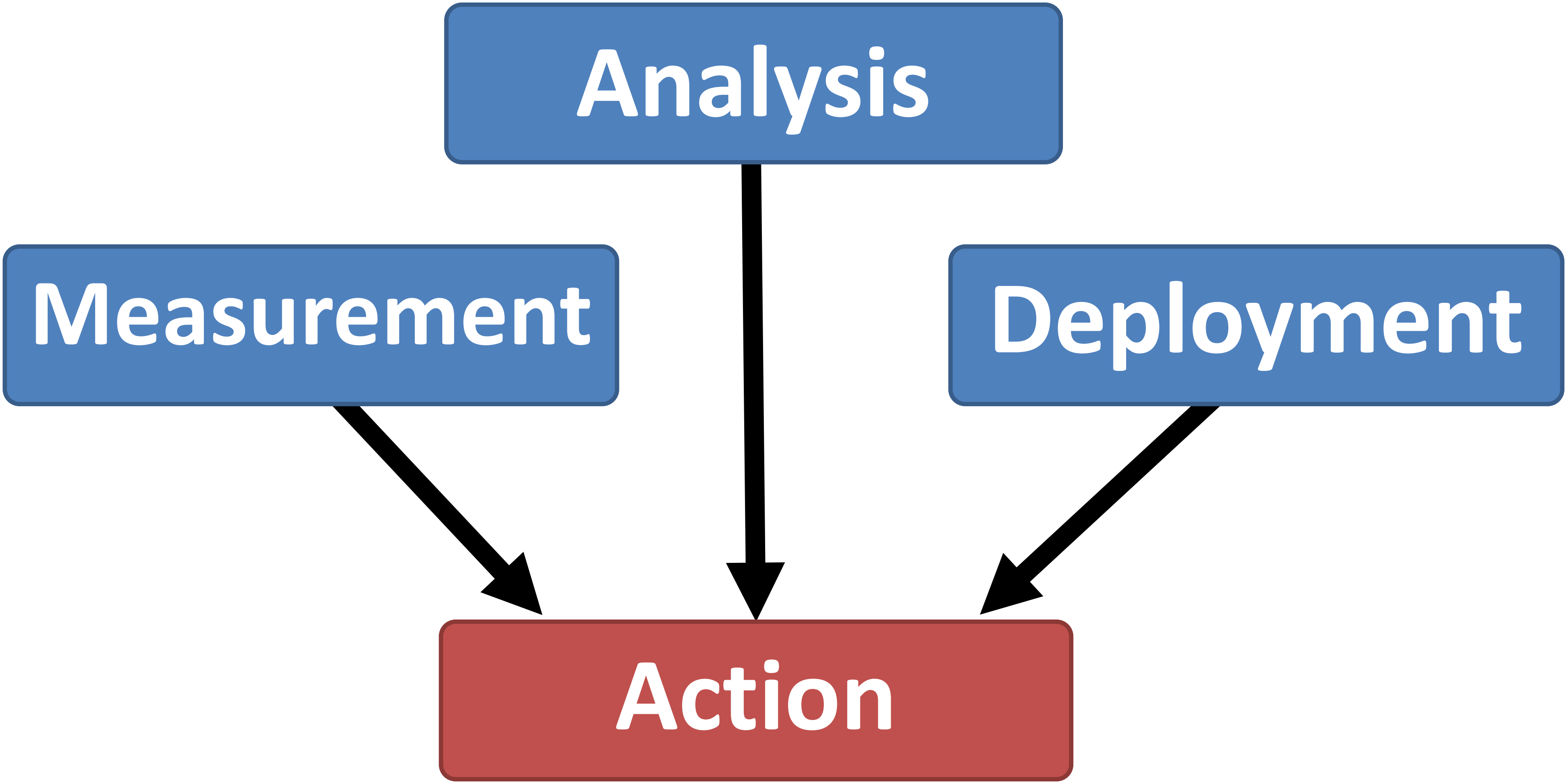
A general approach to performance optimization

- Developer describes application structure via simple interface
  - Identifies tasks
  - Tasks: provides numbers that correlate with compute time (e.g. #non-zeros)
  - Task pairs: provides numbers that correlate with communication time (e.g. #columns)

Easy to use
Like a type system

- Separate statistical framework measures, models and schedules in data-sensitive manner
- Single system takes into account both application and system properties

Beyond use-cases: Building strong pillars for real-world intelligent applications

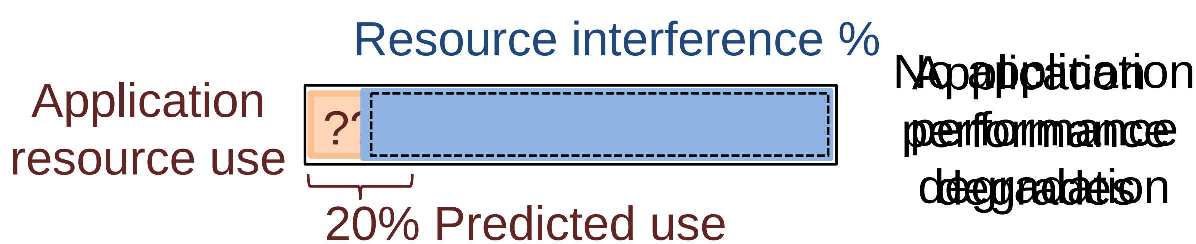


Developing more actionable measurements of application behavior

- Can easily measure execution time, or performance counters (e.g. cache misses)
- Information can not answer basic questions:

  “If threads A and B run on same core how much will they slow down?”

- Developing measurements that capture application utilization of system



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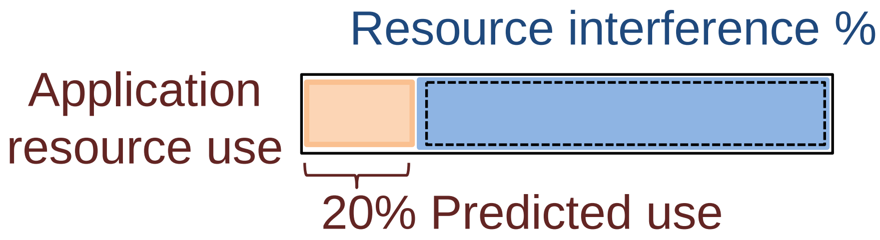
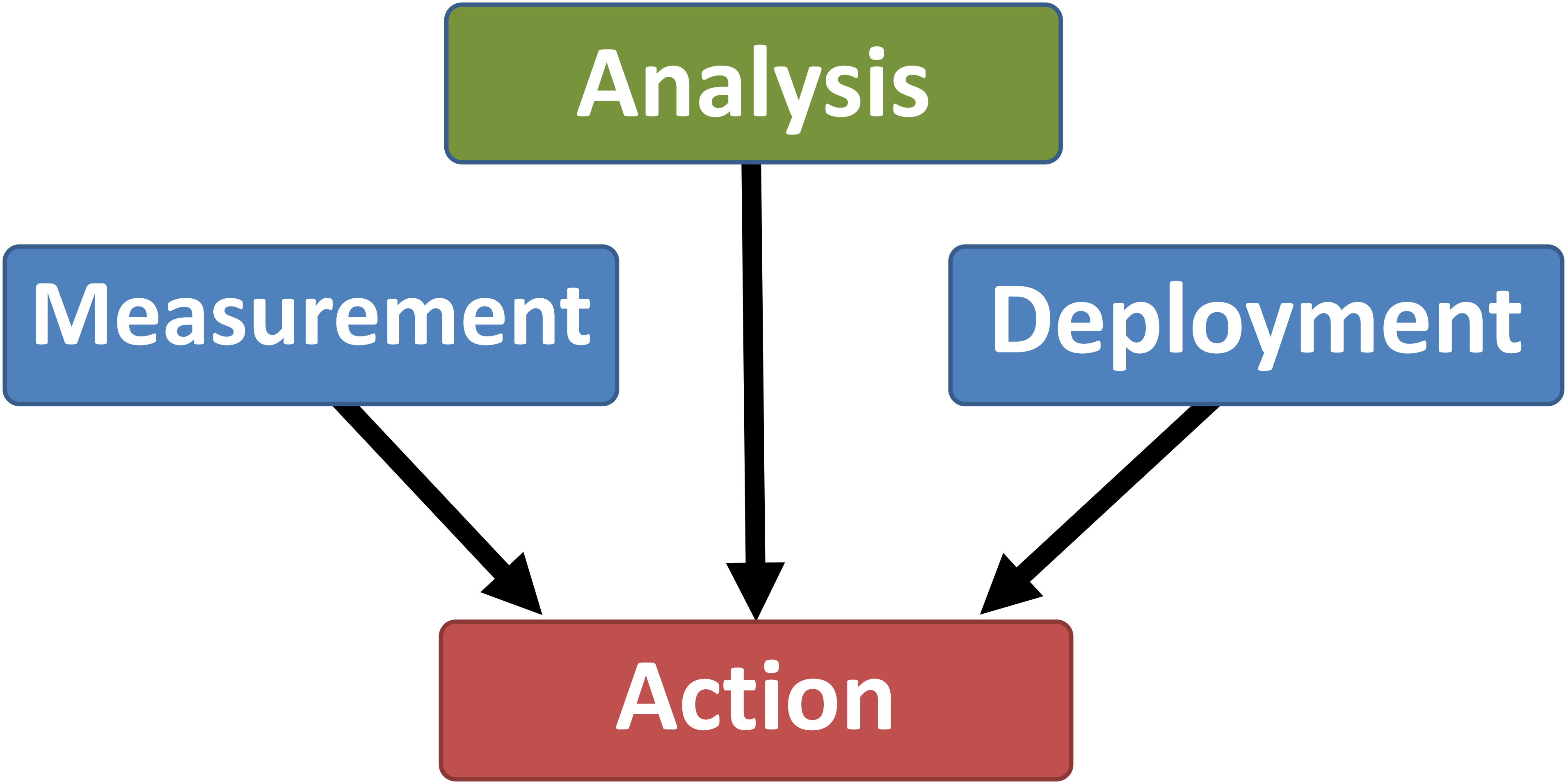


- Currently support: storage and bandwidth of shared caches, network bandwidth

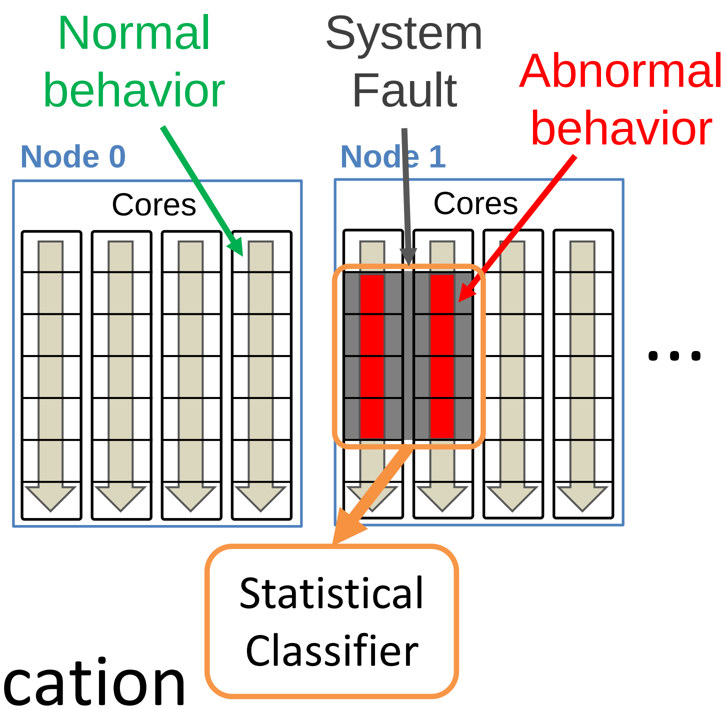
- In development: CPU resources, file system

Building strong pillars for real-world intelligent applications



Detection and localization of system faults requires precise models of application behavior

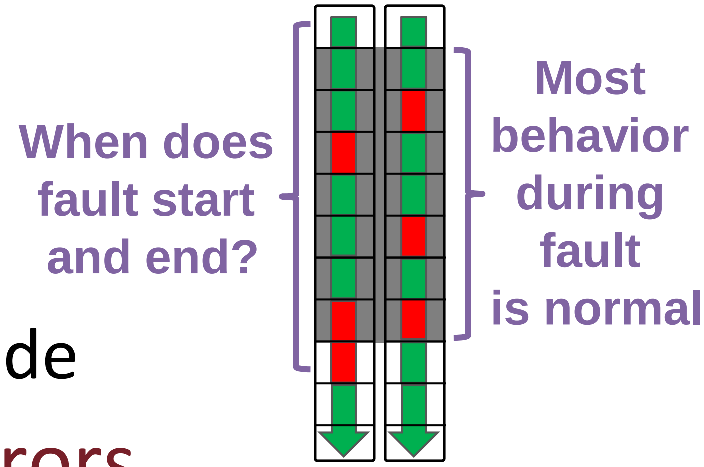
- Fault affects a fraction of application threads
- To detect fault type (CPU, Memory, Network)
  - Inject known fault types into application
  - Train statistical classifier on application behavior during each
  - Predict type based on application behavior in production



Application response to faults depends on unknown factors

- In reality faults have inconsistent effect on applications
  - CPU slowdowns only affect CPU-intensive code regions
  - Errant daemons primarily affect concurrently running code
- Difficult to detect, localize errors
- Characterization becomes very hard

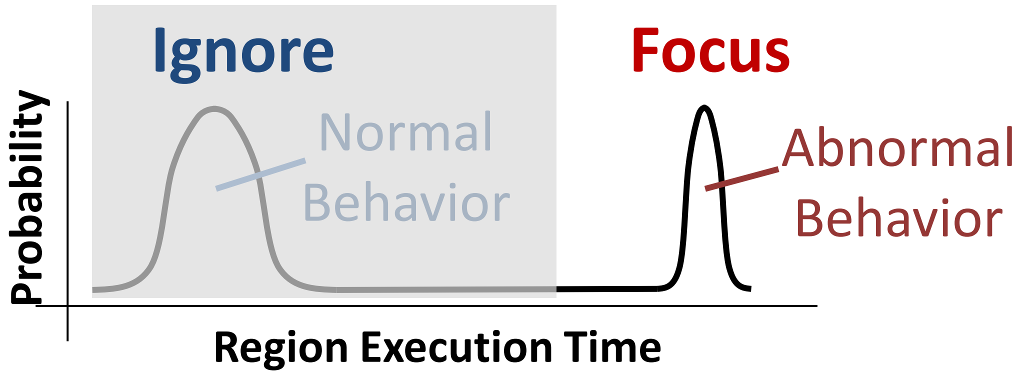
Even if fault duration is known during training most events are not representative of fault



Can improve accuracy by extracting hidden influence from observations

- During fault only few events are abnormal
- Only these truly represent the fault
  - Filter events in faulty runs to only train statistical model on abnormal events
  - Ignore others

Model Trained for Given Code Region



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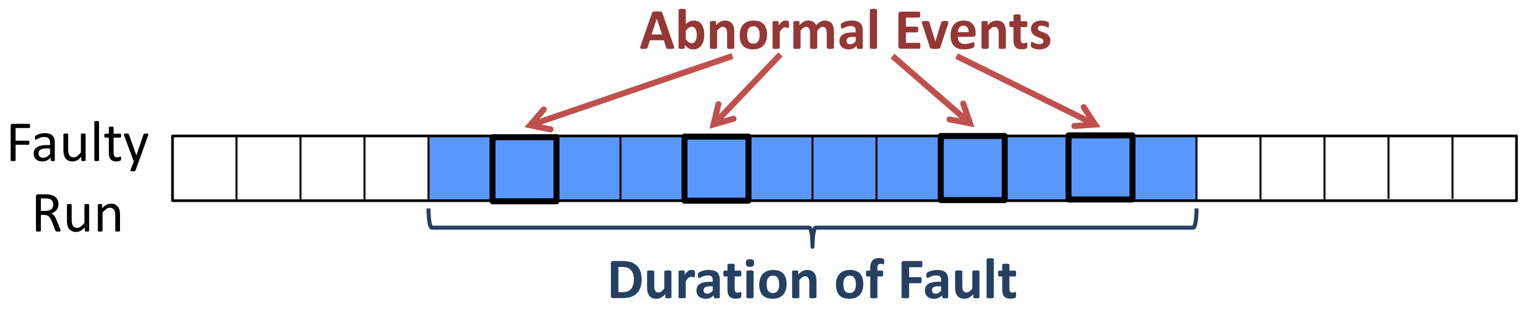
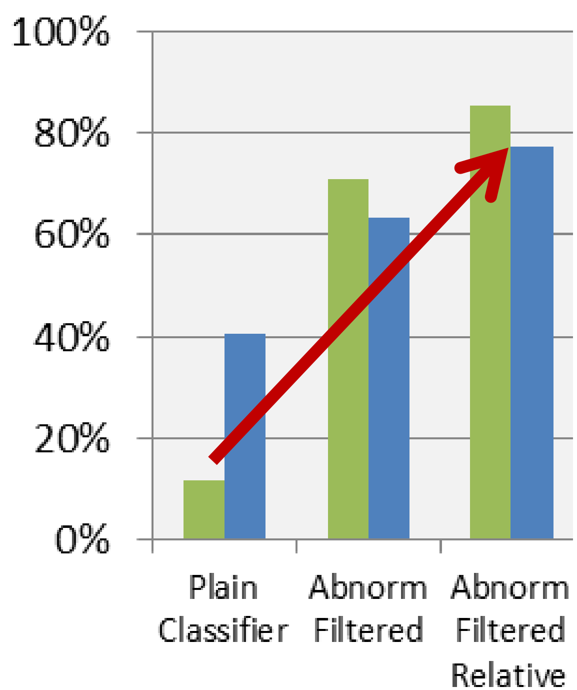
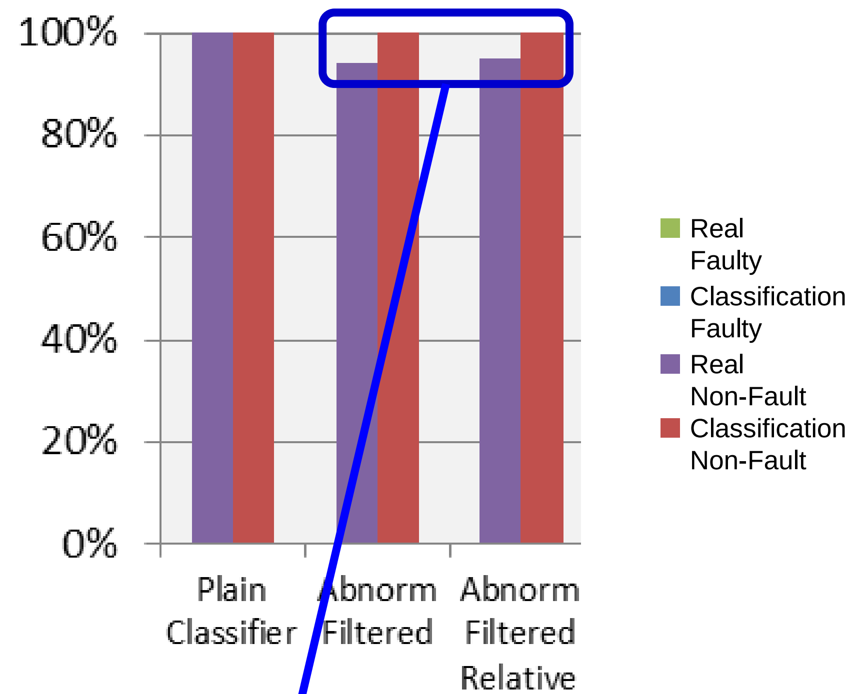


Improved technique detects fault's location, time and type



Faulty Runs

Significant increase in rate of fault characterization

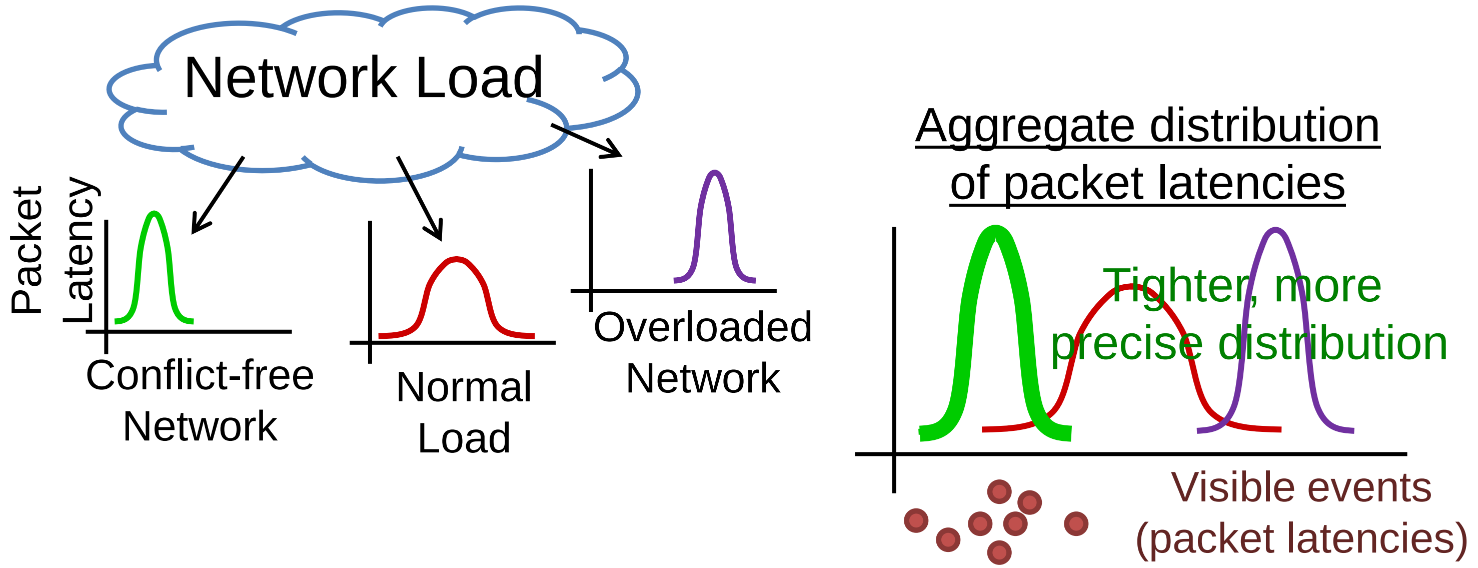


Non-Faulty Runs

Small increase in false positive rate

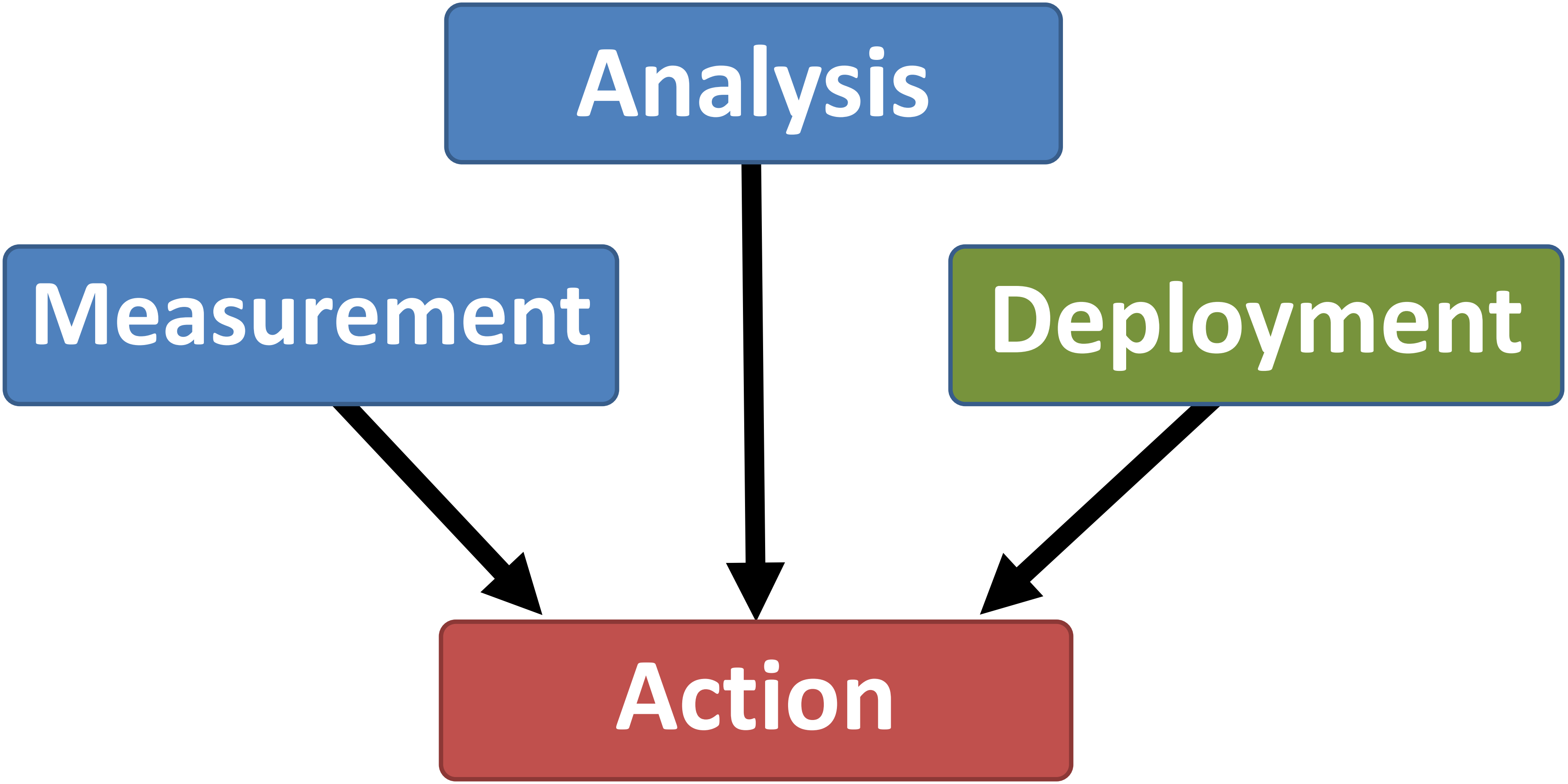
Hidden variable inference: general approach to modeling behavior of complex systems

- System behavior depends on hidden state



- Infer system state from observed events
- Can predict future events more accurately

Building strong pillars for real-world intelligent applications

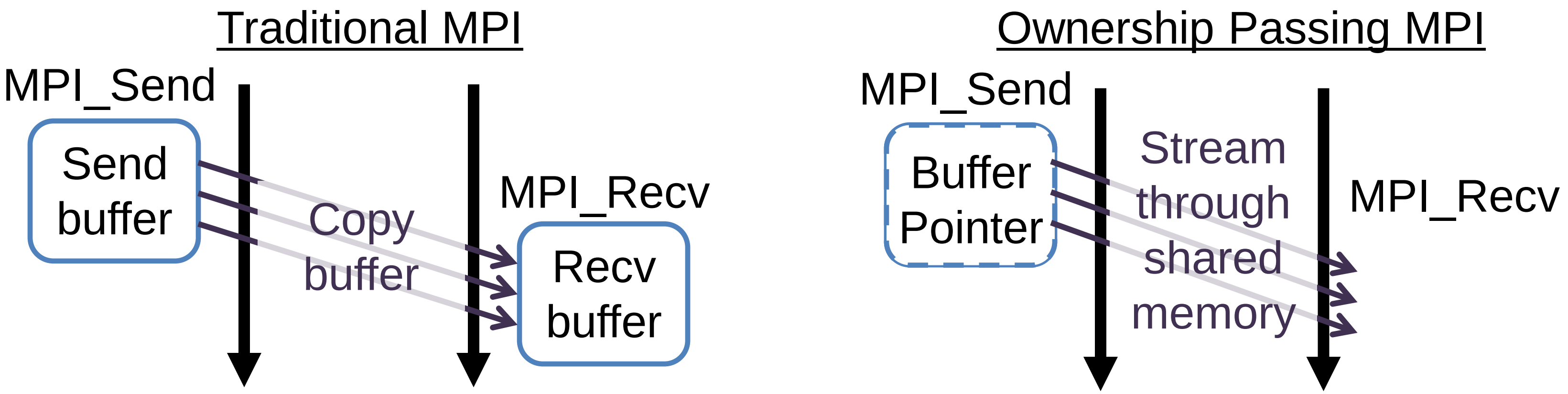


Compiler analyses enable more complex optimizations

- Modeling makes it possible to exploit and manage existing application flexibility
- Compiler transformations can create new flexibility
- Developing compiler analyses to enable library-specific transformations
- Current focus: MPI applications

Exploiting full capabilities of libraries requires library-aware transformations

- Developed MPI for shared memory hardware
  - Implements MPI ranks as threads
  - Communicates via direct copies or passing pointers



- Developing analysis in ROSE compiler to transform legacy MPI code to extended API

Developing compositional symbolic analysis framework to enable aggressive optimizations

- Our analyses must run on real applications
  - Very complex control flow and data management
  - Requires multiple analyses to disambiguate common expressions (e.g. *p, a[i*c])
  - Writing, combining all required analyses beyond capabilities of individual research groups
- We are developing a new compositional symbolic analysis framework
- Enables analyses to use each others' results without knowledge of APIs or abstractions

Example: analyzing even simple programs requires multiple analyses

- Client analysis needs the value printed

Original Program → **Value Analysis** → **Points-To Analysis** → **Value Analysis**

Original Program

```
int x=5;
int y=12;
int* p;

if(x<y) p = &x;
else p = &y;

print *p+5;
```

Value Analysis

```
int x=5;
int y=12;
int* p;
if(TRUE) p = &x;
else p = &y;
print *p+5;
```

Points-To Analysis

```
int x=5;
int y=12;
int* p;
p = &x;
print x+5;
```

Value Analysis

```
int x=5;
int y=12;
int* p;
print 10;
```

- Composition of independent analyses enables complex transformations of real applications

Analysis

- Dynamic statistical modeling
- Sensitive to properties of input data, system, hidden state

Measurement

- Application behavior, not system metrics
- Quantify algorithm accuracy

Deployment

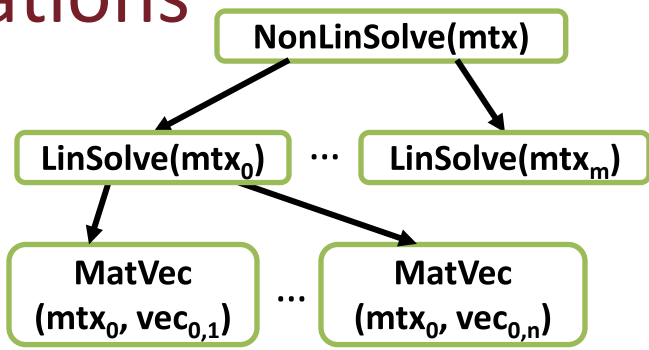
- Include adaptivity and measurement into applications
- Transform code to use new optimizations

Action

- Configure application and system based on analysis results
- Guide developers, system administrators

Prototyping modeling and adaptivity research in custom-designed work manager

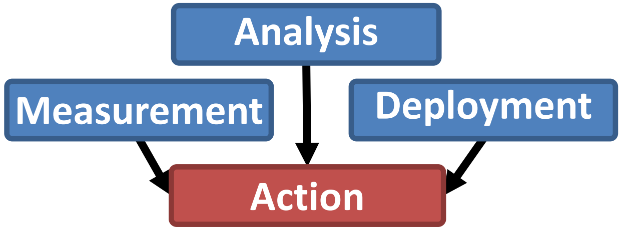
- It is very complex to incorporate model guidance into existing runtimes
- Have developed a custom work manager to prototype optimizations
  - Explicit tasks and dependencies
  - Easy to incorporate new models and dynamic optimizations



- Results directly applicable to real-world runtime systems (e.g. Charm++, Hadoop)

Application Behavior Analysis enables productive use of complex applications and systems

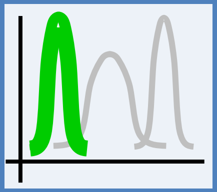
- Severe resource constraints force applications and systems to become more flexible and complex



- Behavior analysis and modeling required to productively use applications and systems
  - Have demonstrated utility of approach in representative use-cases
  - Ongoing research on increasing capability and generality of approach

Analysis

Discovering hidden system state from observations



Measurement

Measuring application resource use

Deployment

Composable symbolic compiler analyses

```
int x=5;
int y=12;
int* p;

if(x<y) p = &x;
else p = &y;

print *p+5;
```

Action

Simple testbed workflow manager for application/system co-optimization