# Improving Adaptability of Multi-Mode Systems via Program Steering

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# Multi-Mode Systems

- A multi-mode system's behavior depends on its environment and internal state
- Examples of multi-mode systems:
  - Web server: polling / interrupt
  - Cell phone: AMPS / TDMA / CDMA
  - Router congestion control: normal / intentional drops
  - Graphics program: high detail / low detail

# Controllers

- Controller chooses which mode to use
- Examples of factors that determine modes:
  - Web server: heavy traffic vs. light traffic
  - Cell phone: rural area vs. urban area; interference
  - Router congestion control: preconfigured policy files
  - Graphics program: frame rate constraints

# Controller Example

```
while (true) {
    if ( checkForCarpet() )
        indoorNavigation();
    else if ( checkForPavement() )
        outdoorNavigation();
    else
        cautiousNavigation();
}
```

- Do the predicates handle all situations well?
- Is any more information available?
- Does the controller ever fail?

# Improving Built-in Controllers

- Built-in controllers do well in expected situations
- Goal: Create a controller that adapts well to unanticipated situations
  - Utilize redundant sensors during hardware failures
  - Sense environmental changes
  - Avoid default modes if other modes are more appropriate
  - Continue operation if controller fails

# Why Make Systems Adaptive?

- Testing all situations is impossible
- Programmers make mistakes
  - Bad intuition
  - Bugs
- The real world is unpredictable
  - Hardware failures
  - External environmental changes
- Human maintenance is costly
  - Reduce need for user intervention
  - Issue fewer software patches

# Overview

- Program Steering Technique
- Mode Selection Example
- Program Steering Implementation
- Experimental Results
- Conclusions

# Program Steering Goals

- Create more adaptive systems without creating new modes
- Allow systems to extrapolate knowledge from successful training examples
- Choose appropriate modes in unexpected situations

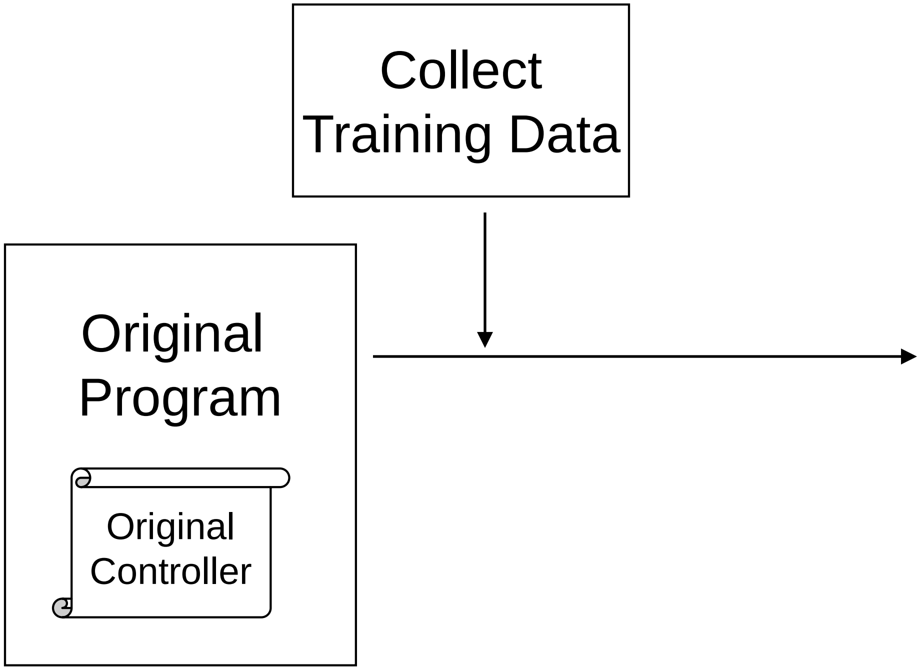
# Program Steering Overview

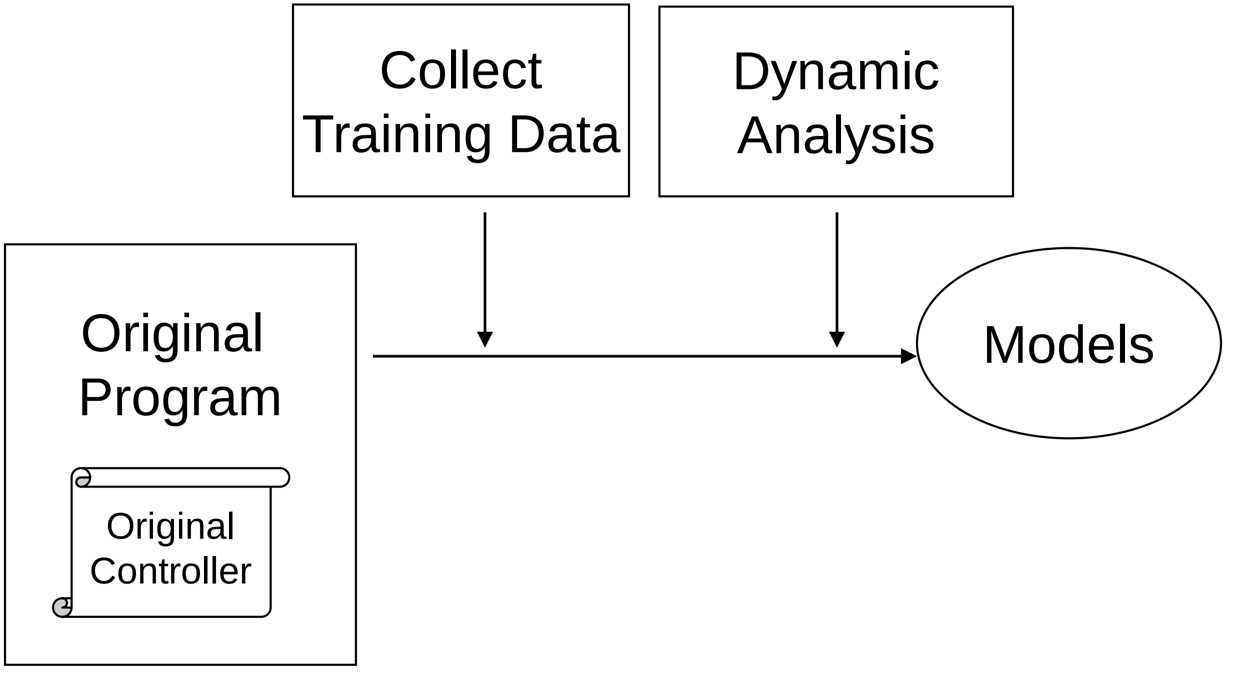
1. Select representative training runs

2. Create models describing each mode using dynamic program analysis

3. Create a mode selector using the models

4. Augment the original program to utilize the new mode selector


Collect
Training Data
Original
Program
Original
Controller


Collect
Training Data
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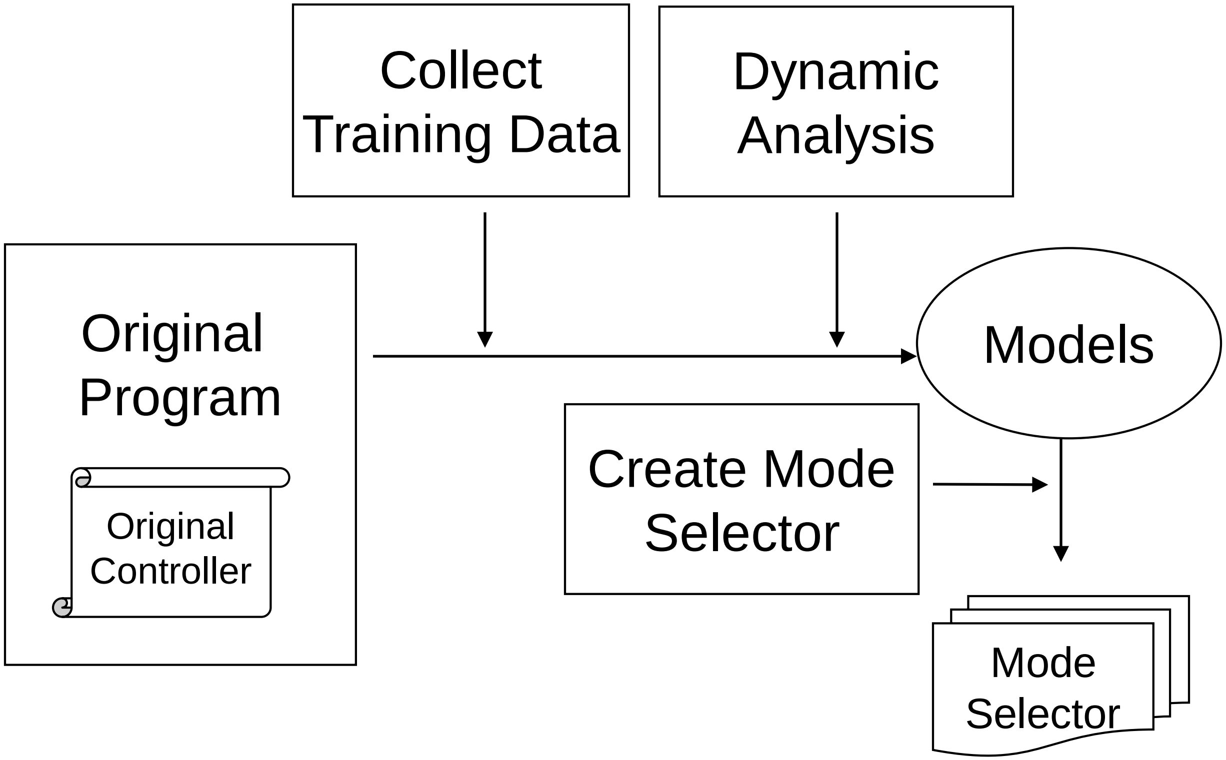
Models


Collect Training Data
Dynamic Analysis
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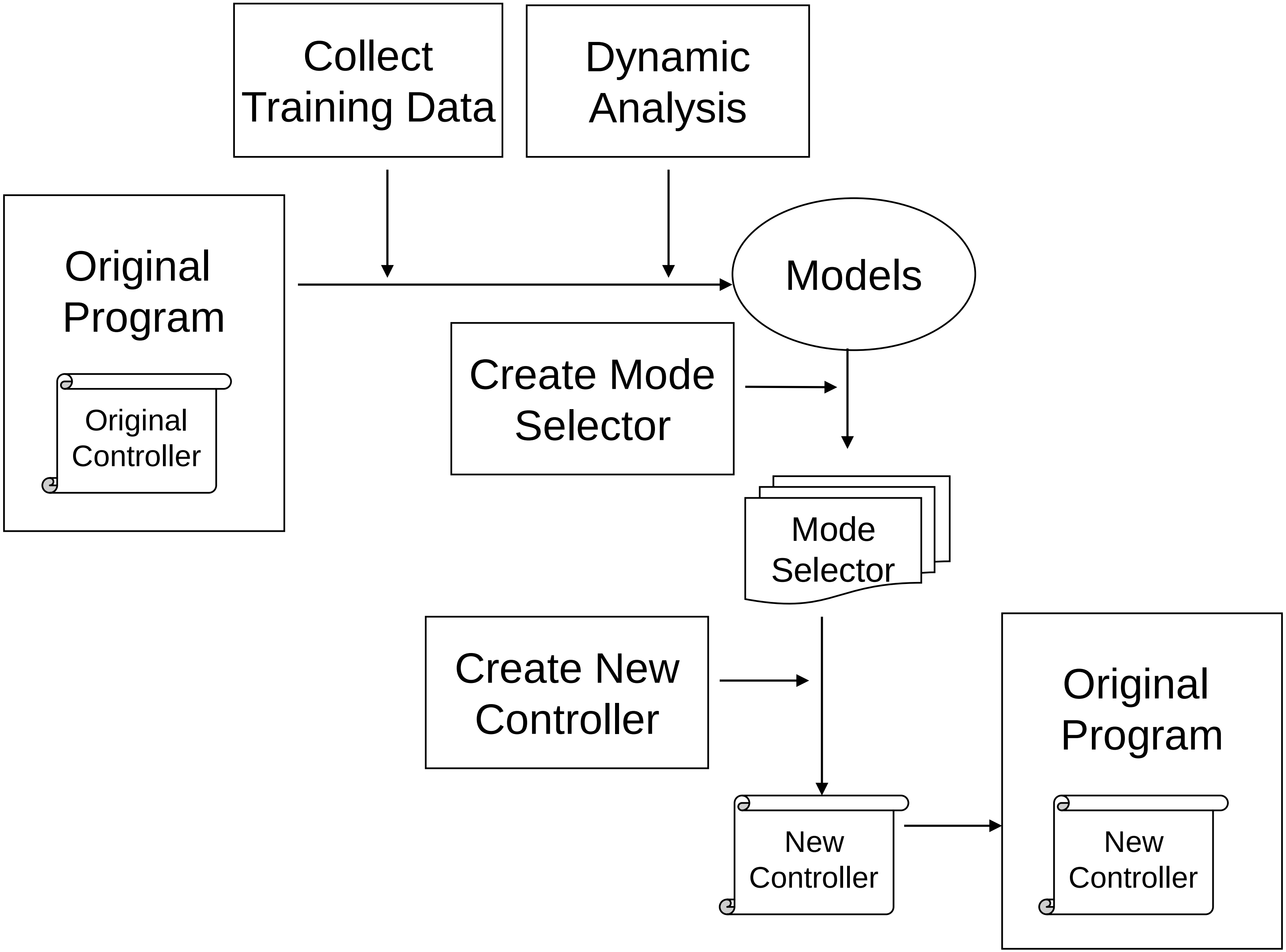
Create Mode Selector
Mode Selector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Create New Controller
New Controller
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New Controller

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# Laptop Display Controller

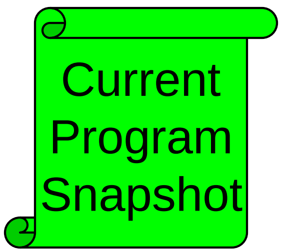
- Three modes
  - Normal Mode
  - Power Saver Mode
  - Sleep Mode
- Available Data:
  - Inputs:  battery life and DC power availability
  - Outputs: brightness

# Properties Observed from Training Runs

| Standard Mode | Power Saver Mode | Sleep Mode |
|---|---|---|
| Brightness >= 0 | Brightness >= 0 | Brightness == 0 |
| Brightness <= 10 | Brightness <= 4 | |
| Battery > 0.15 | Battery > 0.00 | Battery > 0.00 |
| Battery <= 1.00 | Battery <= 0.15 | Battery <= 1.00 |
| | DCPower == false | |

# Mode Selection Problem

What mode is most appropriate?



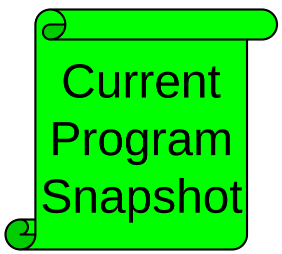

Brightness == 8

Battery == 0.10

DCPower == true

# Mode Selection

Mode selection policy: Choose the mode with the highest percentage of matching properties.

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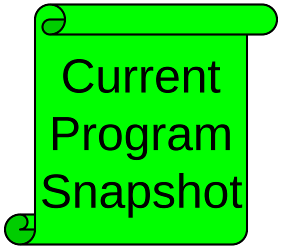
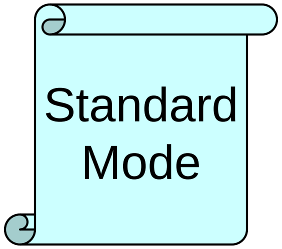



| | |
|---|---|
| Brightness == 8 | BRT >= 0 |
| | BRT <= 10 |
| Battery == 0.10 | BAT > 0.15 |
| | BAT <= 1.00 |
| DCPower == true | |

Score: 75%

# Mode Selection

Mode selection policy: Choose the mode with the highest percentage of matching properties.

| Current Program Snapshot | Standard Mode | Power Saver Mode |
|---|---|---|
| Brightness == 8 | BRT >= 0 | BRT >= 0 |
| | BRT <= 10 | BRT <= 4 |
| Battery == 0.10 | BAT > 0.15 | BAT > 0.00 |
| | BAT <= 1.00 | BAT <= 0.15 |
| DCPower == true | | DC == false |
| | Score: 75% | Score: 60% |

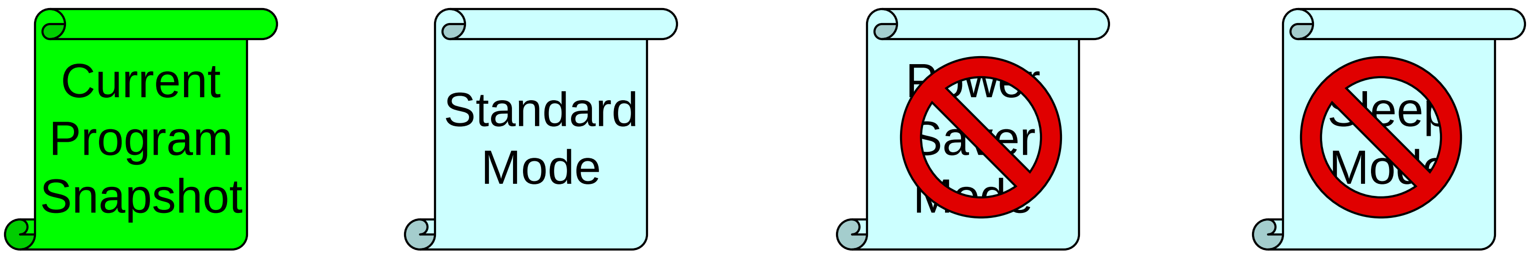
# Mode Selection

Mode selection policy: Choose the mode with the highest percentage of matching properties.

| Current Program Snapshot | Standard Mode | Power Saver Mode | Sleep Mode |
|---|---|---|---|
| Brightness == 8 | BRT >= 0 | BRT >= 0 | BRT == 0 |
| | BRT <= 10 | BRT <= 4 | |
| Battery == 0.10 | BAT > 0.15 | BAT > 0.00 | BAT > 0.00 |
| | BAT <= 1.00 | BAT <= 0.15 | BAT <= 1.00 |
| DCPower == true | | DC == false | |
| | Score: 75% | Score: 60% | Score: 66% |

# Mode Selection

Mode selection policy: Choose the mode with the highest percentage of matching properties.




| | | | |
|---|---|---|---|
| Brightness == 8 | BRT >= 0 | BRT >= 0 | BRT == 0 |
| | BRT <= 10 | BRT <= 4 | |
| Battery == 0.10 | BAT > 0.15 | BAT > 0.00 | BAT > 0.00 |
| | BAT <= 1.00 | BAT <= 0.15 | BAT <= 1.00 |
| DCPower == true | | DC == false | |
| | Score: 75% | Score: 60% | Score: 66% |

# Second Example

Mode selection policy: Choose the mode with the highest percentage of matching properties.

Current Program Snapshot

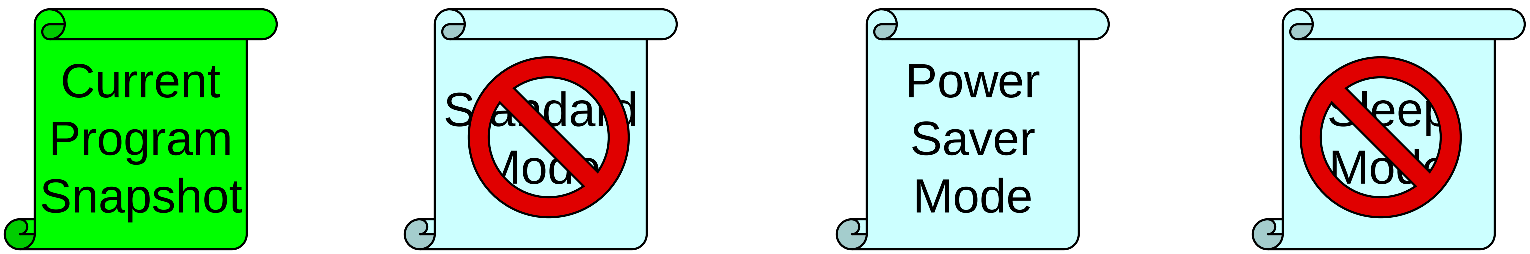
Brightness == 8

Battery == 0.10

DCPower == false

# Second Example

Mode selection policy: Choose the mode with the highest percentage of matching properties.




| | | | |
|---|---|---|---|
| Brightness == 8 | BRT >= 0 | BRT >= 0 | BRT == 0 |
| | BRT <= 10 | BRT <= 4 | |
| Battery == 0.10 | BAT > 0.15 | BAT > 0.00 | BAT > 0.00 |
| | BAT <= 1.00 | BAT <= 0.15 | BAT <= 1.0 |
| DCPower == false | | DC == false | |
| | Score: 75% | Score: 80% | Score: 66% |

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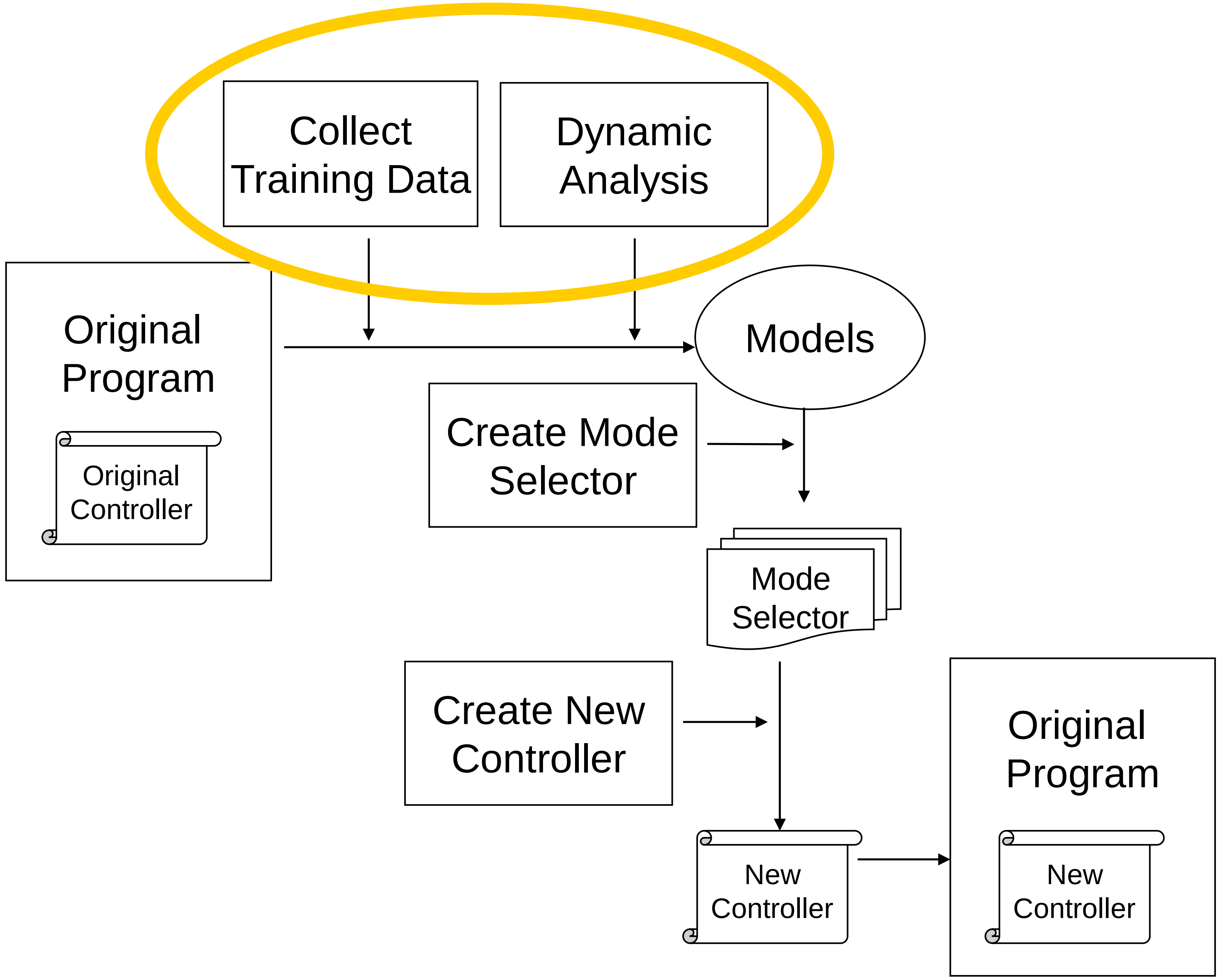

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# Training

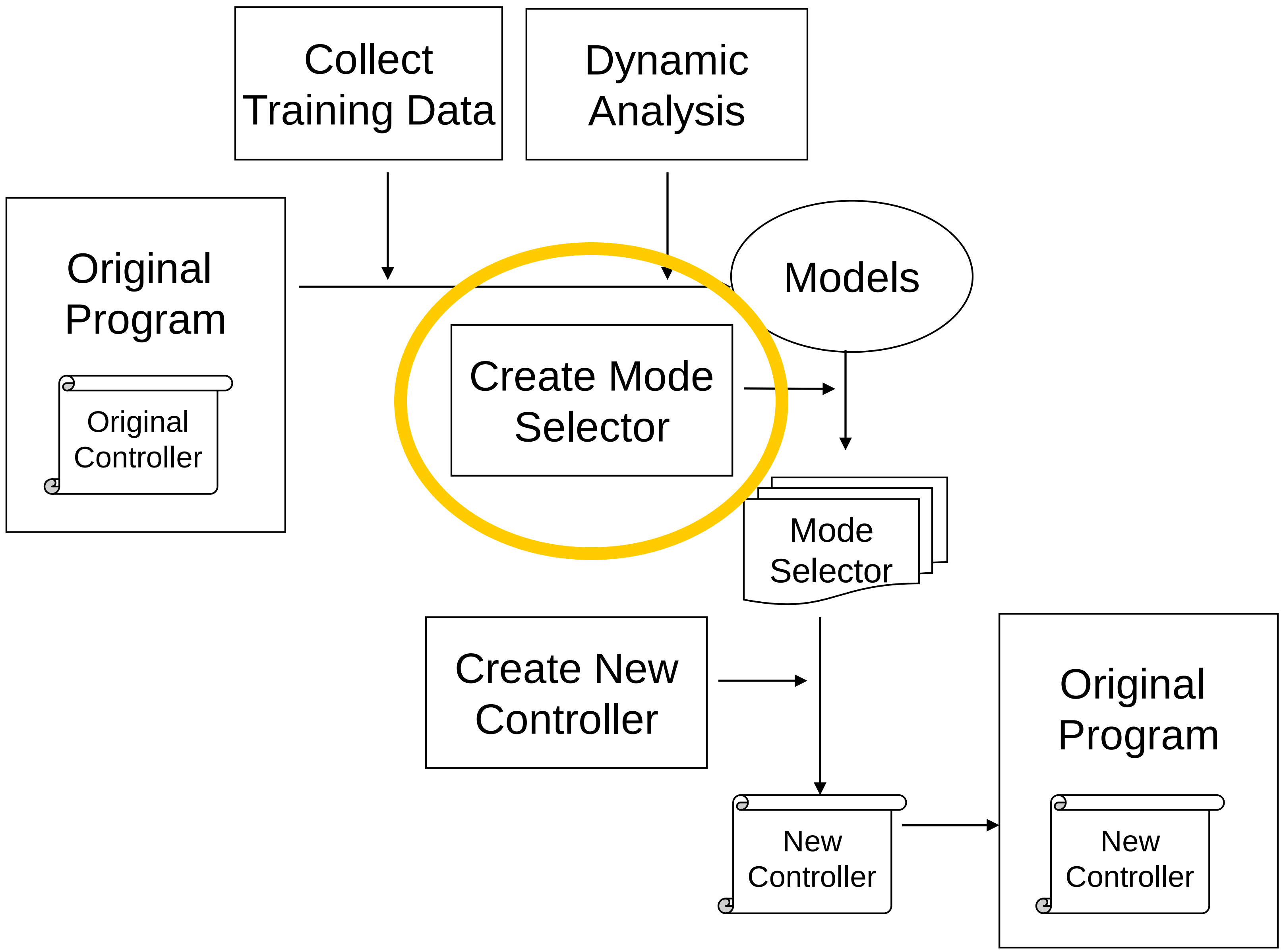
- Train on successful runs
  - Passing test cases
  - High performing trials

- Amount of training data:
  - Depends on modeling technique
  - Cover all modes

# Dynamic Analysis

- Create one set of properties per mode
- Daikon Tool
  - Supply program and execute training runs
  - Infers properties involving inputs and outputs
  - Properties were true for every training run
    - this.next.prev == this
    - currDestination is an element of visitQueue[]
    - n < mArray.length

http://pag.csail.mit.edu/daikon/



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# Mode Selection Policy

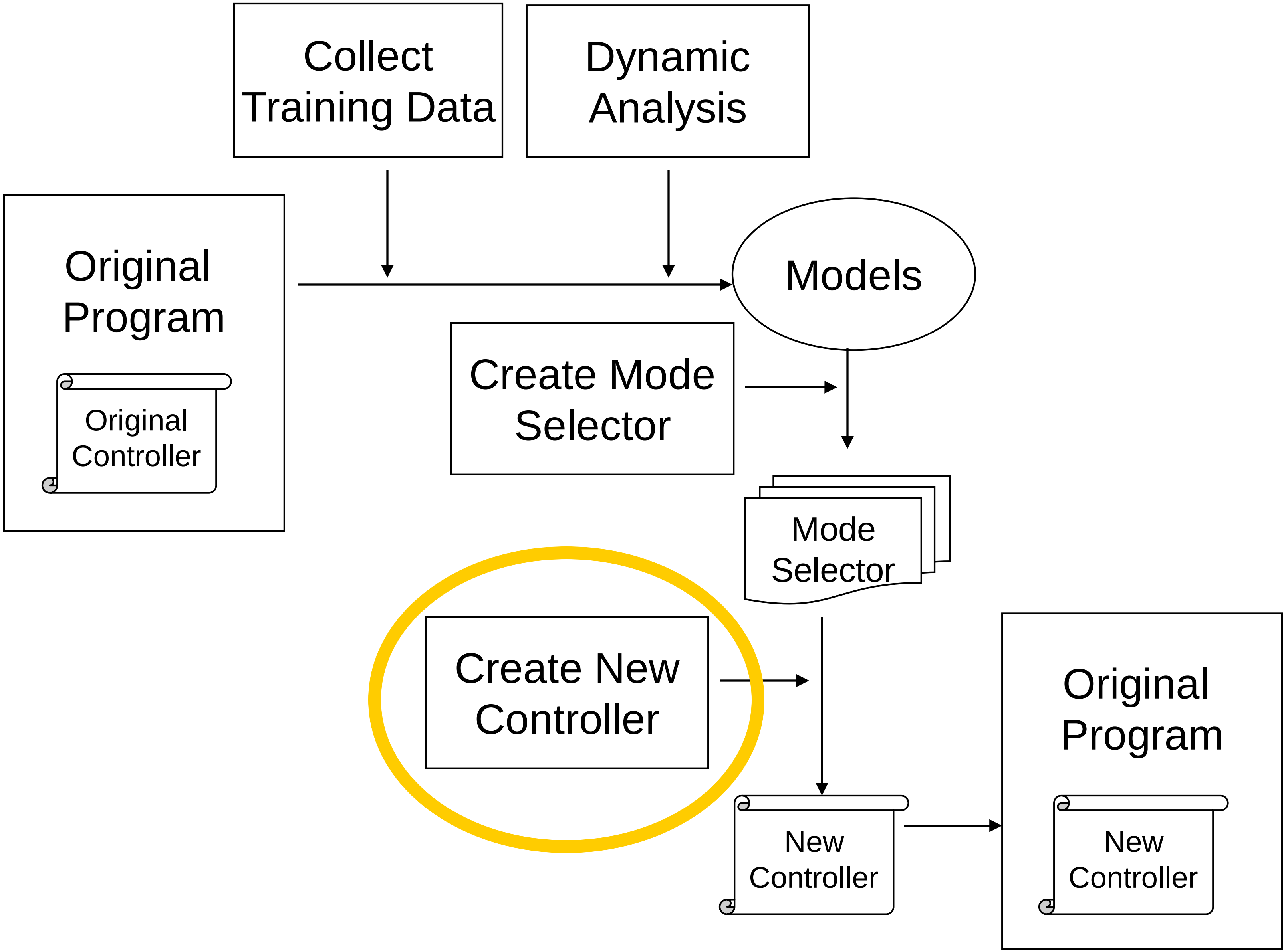
Check which properties in the models are true in the current program state.

For each mode, calculate a similarity score (percent of matching properties).

Choose the mode with the highest score.

Can also accept constraints, for example

- Don’t select Travel Mode when destination null
- Must switch to new mode after Exception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# Controller Augmentation

Call the new mode selector during:

- Uncaught Exceptions
- Timeouts
- Default / passive mode
- Randomly during mode transitions

Otherwise, the controller is unchanged

# Why Consider Mode Outputs?

- Mode selection considers all properties
- Output properties measure whether mode is behaving as expected
- Provides inertia, avoids rapid switching

- Suppose brightness is stuck at 3 (damaged).
  - No output benefit for Standard Mode.
  - More reason to prefer Power Saver to Standard.

# Why Should Program Steering Improve Mode Selection?

- Eliminates programmer assumptions about what is important
- Extrapolates knowledge from successful runs
- Considers all accessible information
- Every program state is handled

- The technique requires no domain-specific knowledge

# What Systems Can Benefit from Program Steering?

- Discrete transitions between modes
- Deployed in unpredictable environments
- Multiple modes often applicable

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# Droid Wars Experiments

- Month-long programming competition
- Teams of simulated robots are at war (27 teams total)
- Robots are autonomous
- Example modes found in contestant code: Attack, defend, transport, scout enemy, relay message, gather resources

# Program Steering Upgrades

- Selected 5 teams with identifiable modes
- Ran in the original contest environment
- Trained on victorious matches
- Modeling captured sensor data, internal state, radio messages, time elapsed

# Upgraded Teams

| Team | NCNB Lines of Code | Number of Modes | Properties Per Mode |
|---|---|---|---|
| Team04 | 658 | 9 | 56 |
| Team10 | 1275 | 5 | 225 |
| Team17 | 846 | 11 | 11 |
| Team20 | 1255 | 11 | 26 |
| Team26 | 1850 | 8 | 14 |

The new mode selectors considered many more properties than the original mode selectors

# Evaluation

- Ran the upgraded teams in the original environments (performed same or better)
- Created 6 new environments
  - Hardware failures: random rebooting
  - Deceptive GPS: navigation unreliable
  - Radio Spoofing: simulate replay attacks
  - Radio Jamming: some radio messages dropped
  - Increased Resources: faster building, larger army
  - New Maps: randomized item placement

# Examples of Environmental Effects

- Hardware Failures
  - Robot did not expect to reboot mid-task, far from base
  - Upgraded robots could deduce and complete task
- Radio Spoofing
  - Replay attacks resulted in unproductive team
  - Upgraded robots used other info for decision making

# Program Steering Effects on Tournament Rank

## Hardware Failures

| Team | Original | Upgrade | |
|---|---|---|---|
| Team04 | 11 | 5 | +6 |
| Team10 | 20 | 16 | +4 |
| Team17 | 15 | 9 | +6 |
| Team20 | 21 | 6 | +15 |
| Team26 | 17 | 13 | +4 |

## Deceptive GPS

| Team | Original | Upgrade | |
|---|---|---|---|
| Team04 | 12 | 9 | +3 |
| Team10 | 23 | 8 | +15 |
| Team17 | 15 | 9 | +6 |
| Team20 | 22 | 7 | +15 |
| Team26 | 16 | 13 | +3 |

# Original Team20

- Centralized Intelligence
- Queen Robot
  - Pools information from sensors and radio messages
  - Determines the best course of action
  - Issues commands to worker robots
- Worker Robot
  - Capable of completing several tasks
  - Always returns to base to await the next order

# Upgraded Team20

- Distributed Intelligence
- Queen Robot (unchanged)
- Worker Robot
  - Capable of deciding next task without queen
  - Might override queen's orders if beneficial

# Understanding the Improvement

Question:

What if the improvements are due to **when** the new controller invokes the new mode selector, not **what** the selector recommends?

Experiment:

- Ran same new controller with a random mode selector.
- Programs with random selector perform poorly.
- Program steering selectors make intelligent choices

# Comparison with Random Selector

## Hardware Failures

| Team | Original | Upgrade | | Random | |
|---|---|---|---|---|---|
| Team04 | 11 | 5 | +6 | 9 | +2 |
| Team10 | 20 | 16 | +4 | 21 | -1 |
| Team17 | 15 | 9 | +6 | 20 | -5 |
| Team20 | 21 | 6 | +15 | 23 | -2 |
| Team26 | 17 | 13 | +4 | 22 | -5 |

## Deceptive GPS

| Team | Original | Upgrade | | Random | |
|---|---|---|---|---|---|
| Team04 | 12 | 9 | +3 | 17 | -5 |
| Team10 | 23 | 8 | +15 | 18 | +5 |
| Team17 | 15 | 9 | +6 | 15 | 0 |
| Team20 | 22 | 7 | +15 | 21 | +1 |
| Team26 | 16 | 13 | +3 | 20 | -4 |

# Overall Averages

| Team | Upgrade | Random |
|---|---|---|
| Team04 | +4.0 | +0.7 |
| Team10 | +3.8 | +1.2 |
| Team17 | +4.2 | -1.5 |
| Team20 | +8.8 | -1.3 |
| Team26 | +1.0 | -3.7 |

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# Future Work

- Use other mode selection policies
  - Refine property weights with machine learning
  - Detect anomalies using models
- Try other modeling techniques
  - Model each transition, not just each mode
- Automatically suggest new modes

# Conclusion

- New mode selectors generalize original mode selector via machine learning
- Technique is domain independent
- Program steering can improve adaptability because upgraded teams perform:
  - As well or better in old environment
  - Better in new environments