Software Verification: An Evolution-Centric Perspective

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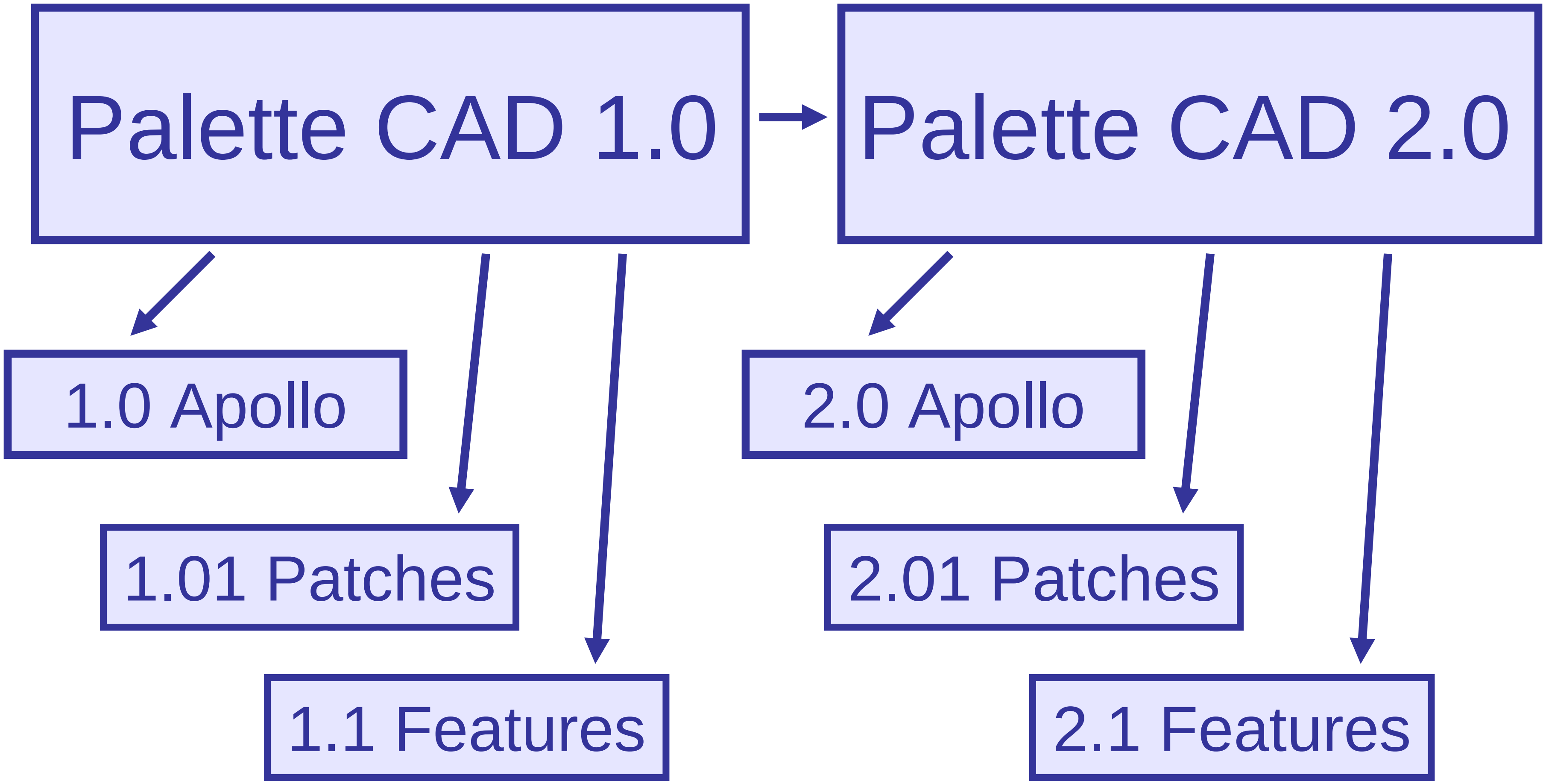
and Boeing Commercial Aircraft Group

Evolving Software



An Evolution-Centric Perspective on Software Verification

- Focus on evolution first
- Harness evolution
- Design for incremental validation

Overview of Presentation

- Evolving software
- Regression test selection
  - Dejavu algorithm
  - Analytical and empirical evaluation
- Regression model checking
  - Algorithm
  - Empirical evaluation
- Ongoing and Future Work

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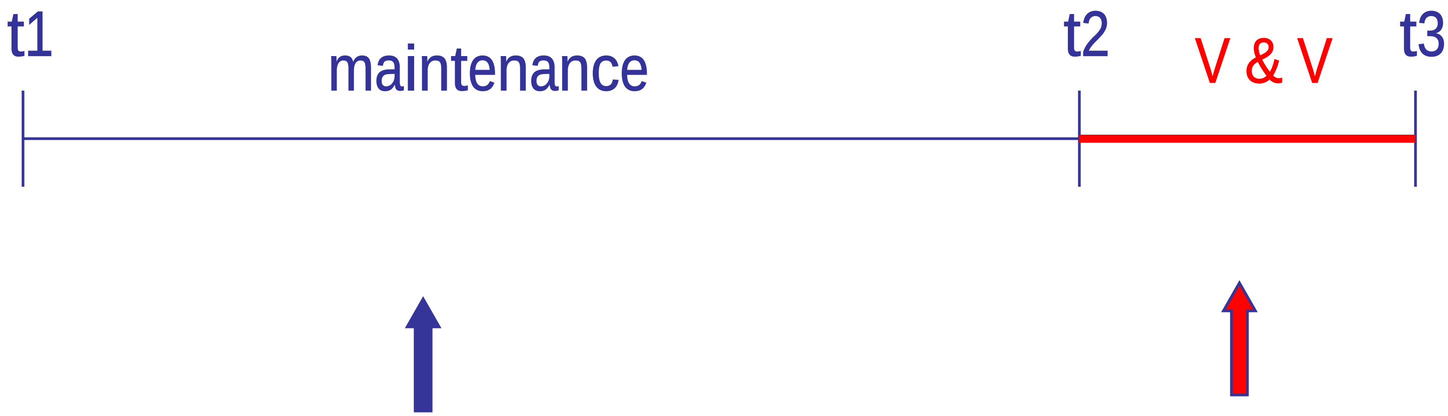
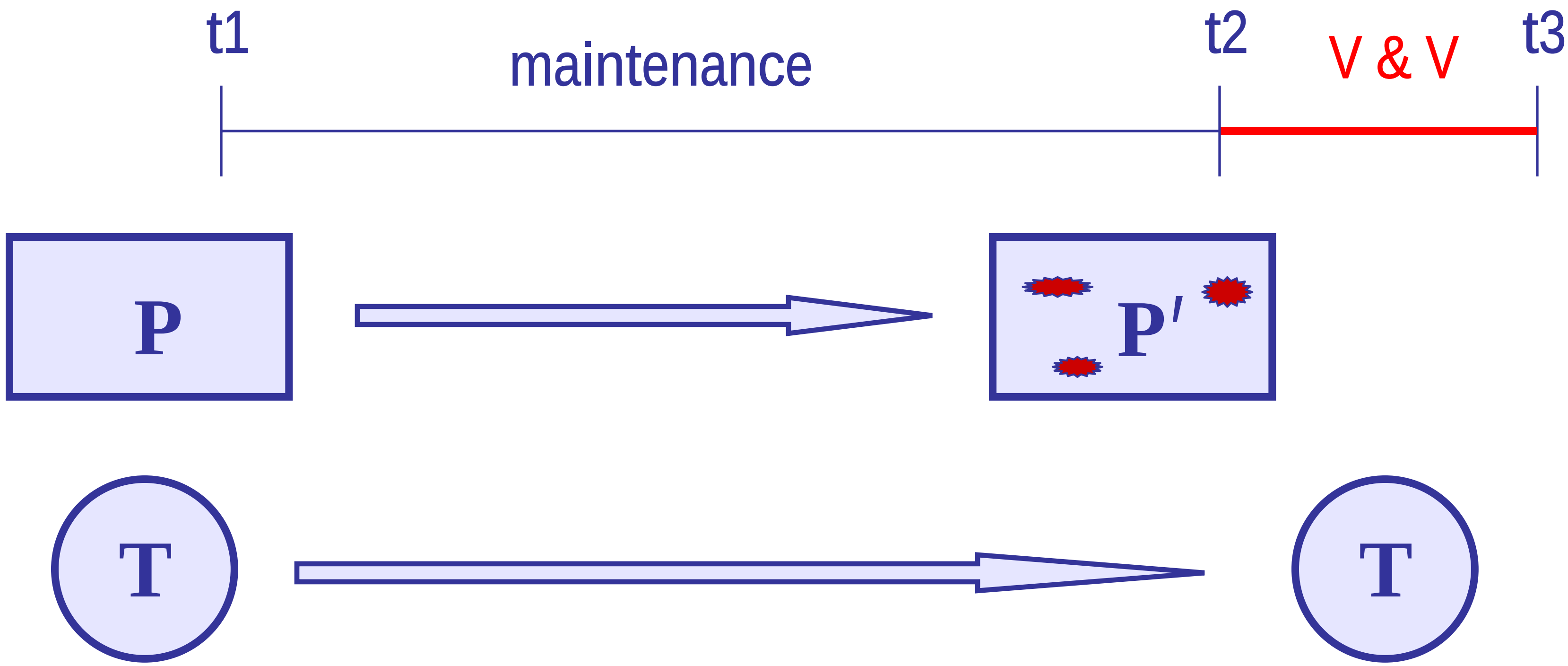
Evolving Software:
A Basic Process Model



Preliminary period   Critical period

Evaluating Evolving Software with Regression Testing



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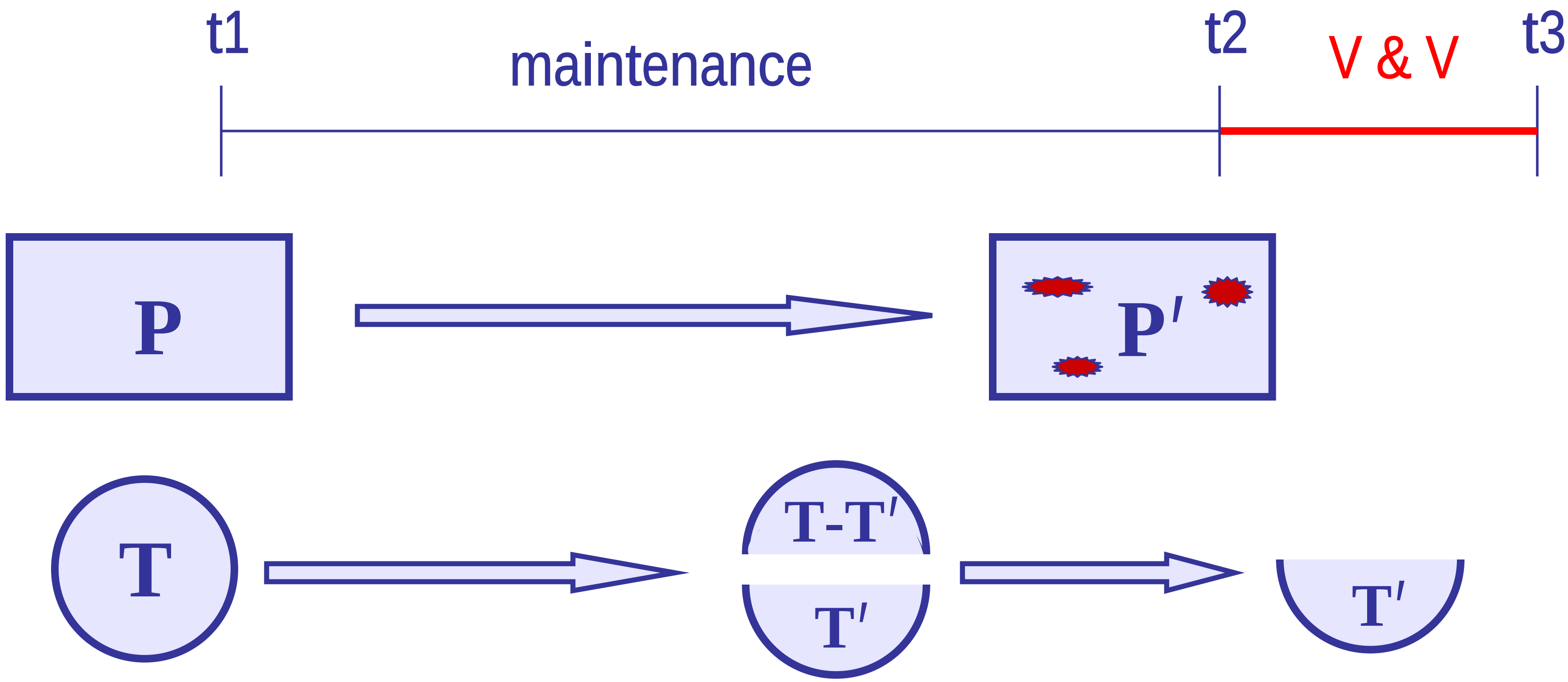
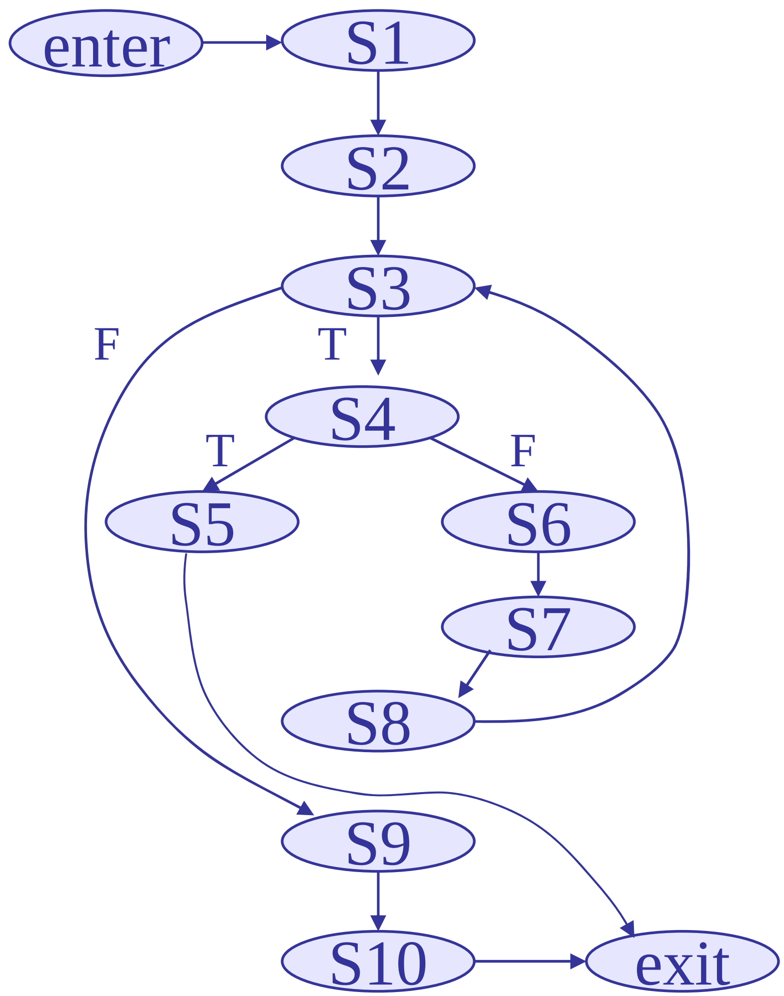
Regression Test Selection



Control Flow Graphs

Procedure Avg

```
S1   count = 0
S2   fread(fptr,n)
S3   while (not EOF) do
S4      if (n<0)
S5         return(error)
        else
S6         nums[count] = n
S7         count++
        endif
S8      fread(fptr,n)
     endwhile
S9   avg = mean(nums,count)
S10  return(avg)
```



Execution Traces

```
Procedure Avg
S1   count = 0
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```

test	input	output
t1	empty file	0

Execution Traces

Procedure Avg

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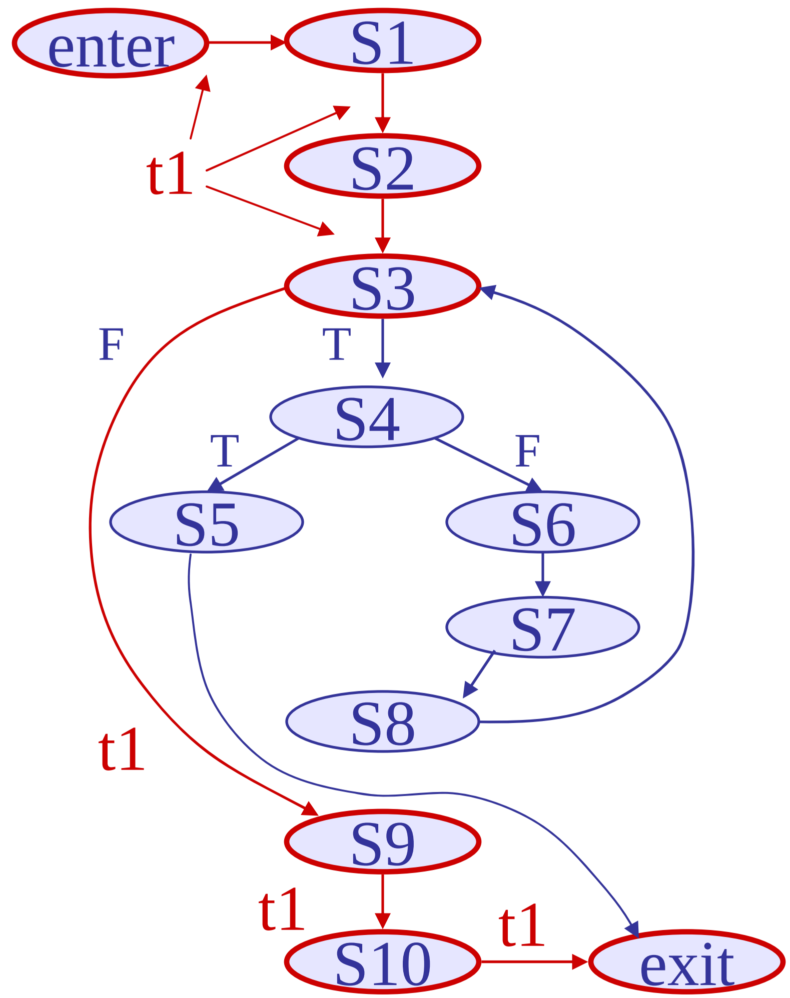
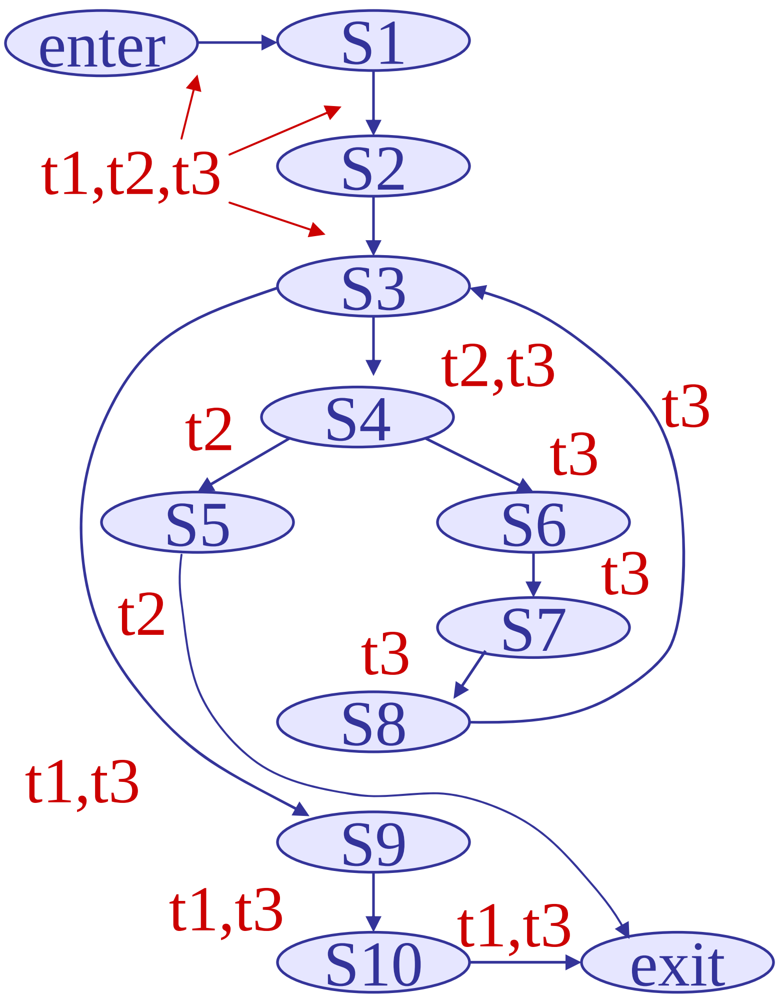


Test History Information

test	input	output
t1	empty file	0
t2	-1	error
t3	1 2 3	2



Program and Modified Version

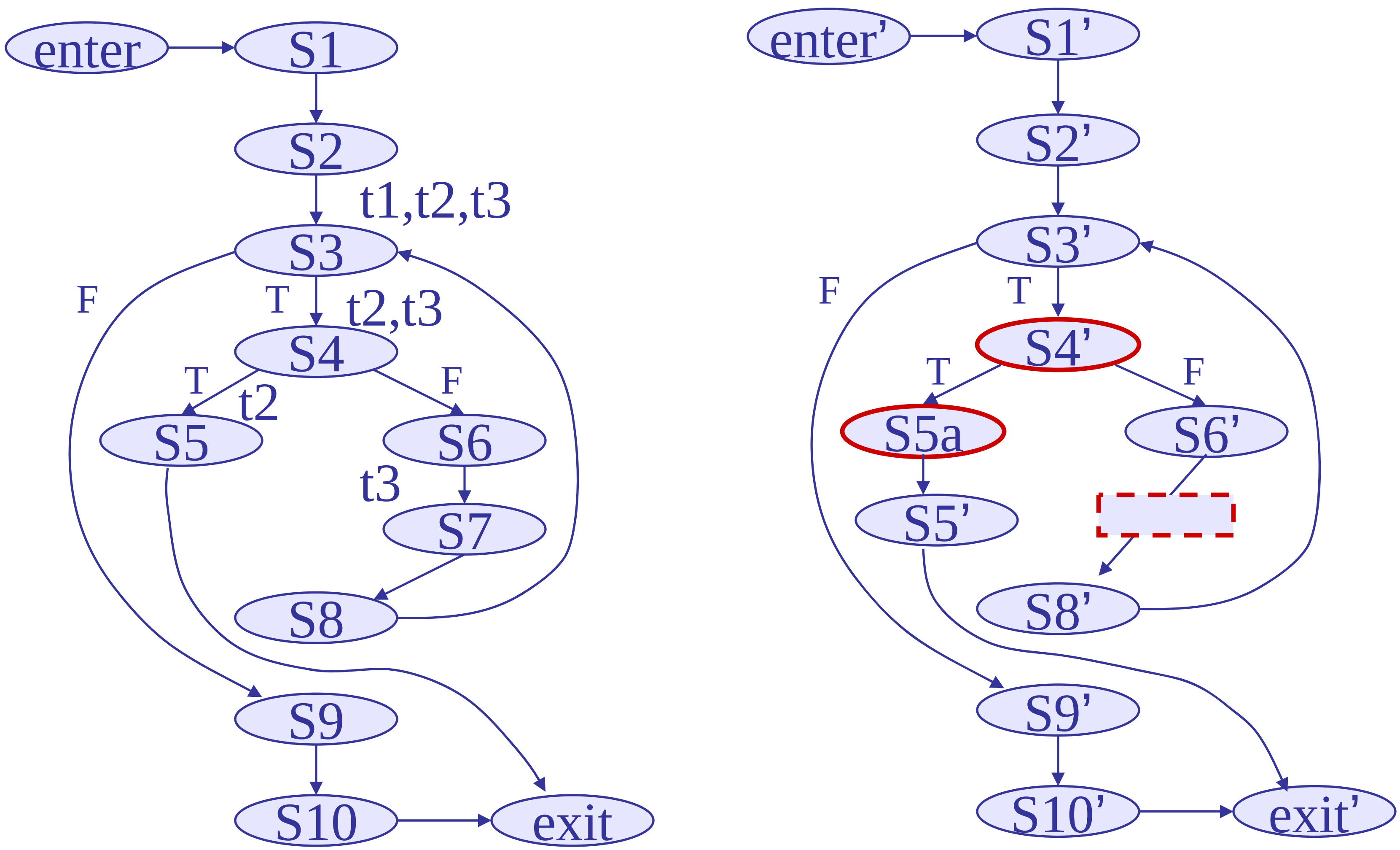
Procedure Avg

```
S1   count = 0
S2   fread(fptr,n)
S3   while (not EOF) do
S4      if (n<0)

S5         return(error)
        else
S6         nums[count] = n
S7         count++
        endif
S8      fread(fptr,n)
     endwhile
S9   avg = mean(nums,count)
S10  return(avg)
```

Procedure Avg′

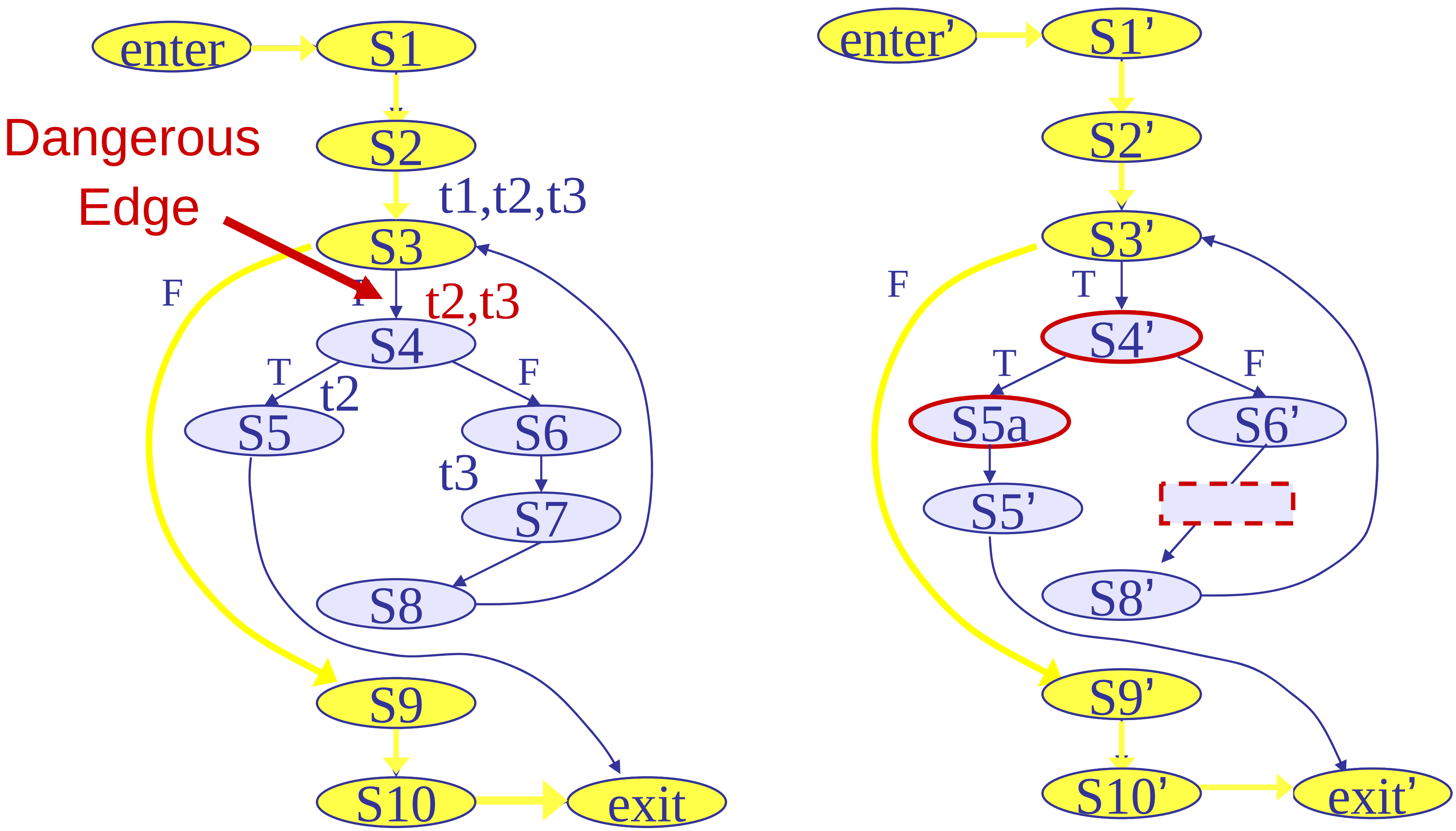
```
S1'  count = 0
S2'  fread(fptr,n)
S3'  while (not EOF) do
S4'     if (n<=0)
S5a        print("input error")
S5'        return(error)
        else
S6'        nums[count] = n

        endif
S8'     fread(fptr,n)
     endwhile
S9'  avg = mean(nums,count)
S10' return(avg)
```

CFG and Modified CFG



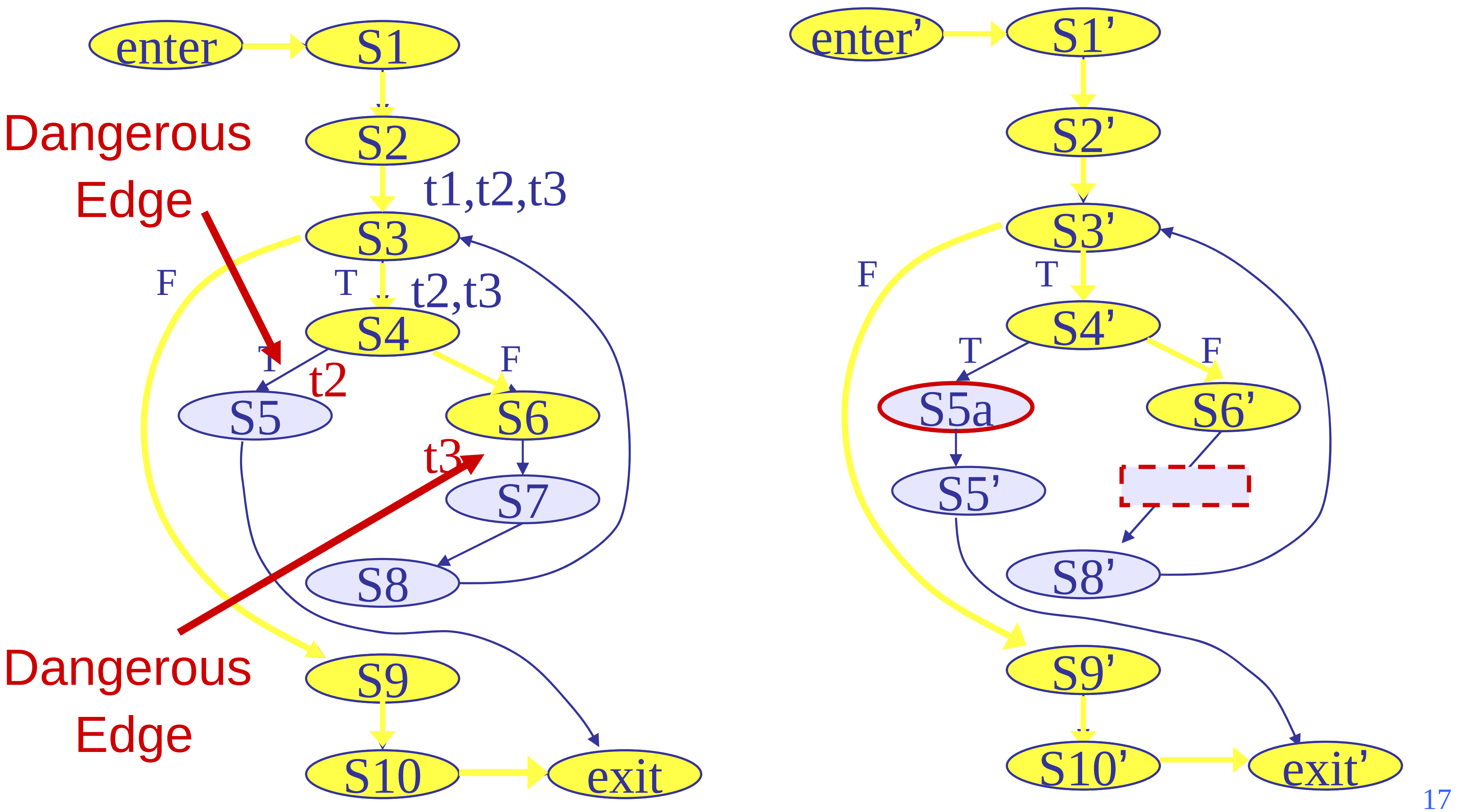
Example 1

T' = {t2, t3}



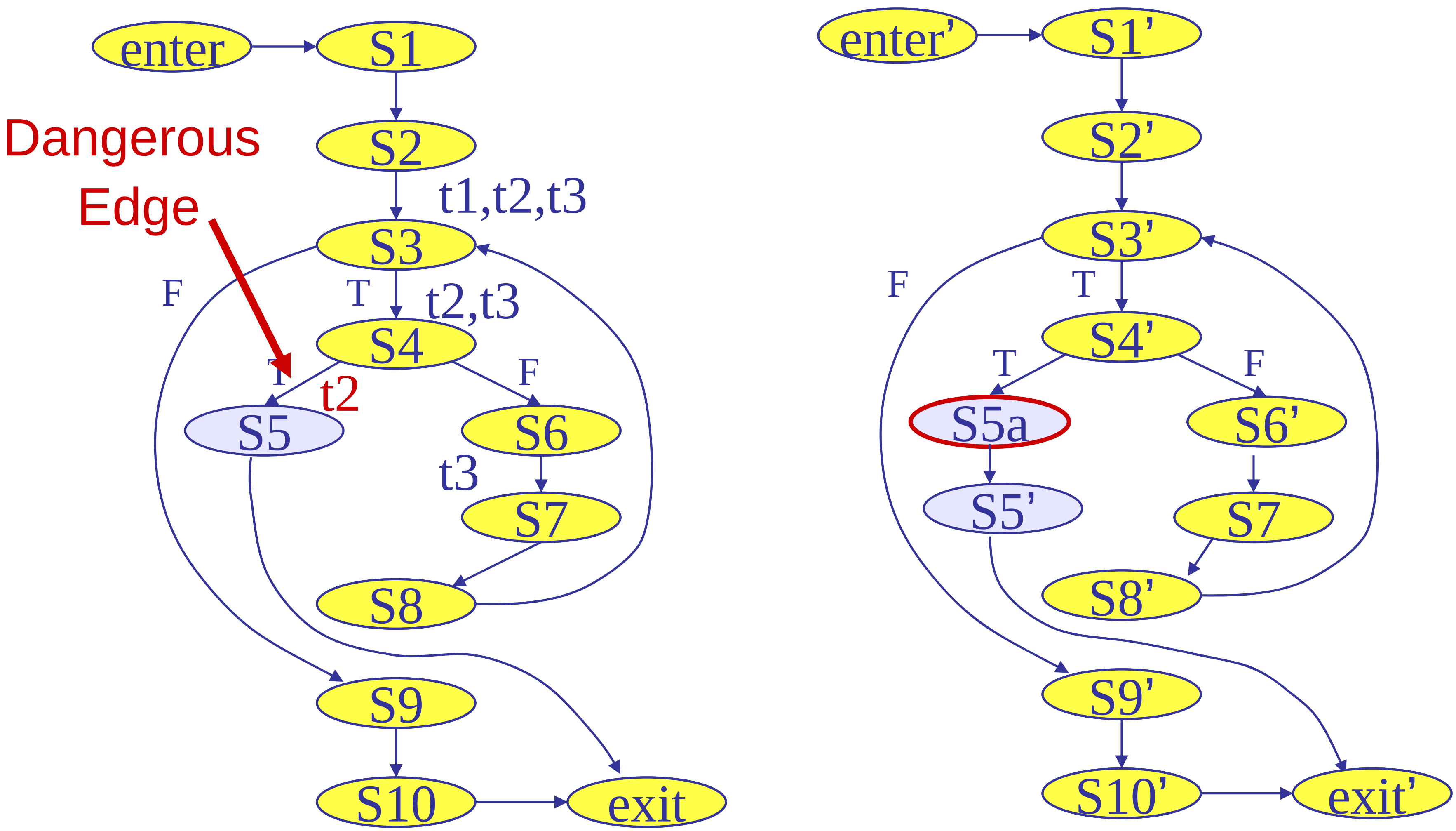
Example 2

T' = {t2, t3}



Example 3

T’ = {t2}



Algorithm Dejavu

Input: P, P', T   Output: T'

1. Build CFGs G and G' for P and P'
2. Compare(G.EntryNode,G'.EntryNode)

3. Compare(N,N')
4.   mark N "N'-visited"
5.   for each pair of successors C and C' of N and N'
6.   on equivalently labeled edges do
7.   if C is not marked "C'-visited"
8.   if C and C' are not lexically identical
9. $T' = T' \cup$ TestsOnEdge(N,C,T)
10.   else
11.   Compare(C,C')

Interprocedural Methodologies

1. Compare all pairs of procedures
2. Create & walk interprocedural representation
3. Compare all pairs of procedures identified by configuration management system

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Algorithm Efficiency

CFG construction: linear in program size

Graph walk (graph sizes n, n'; test set size t):

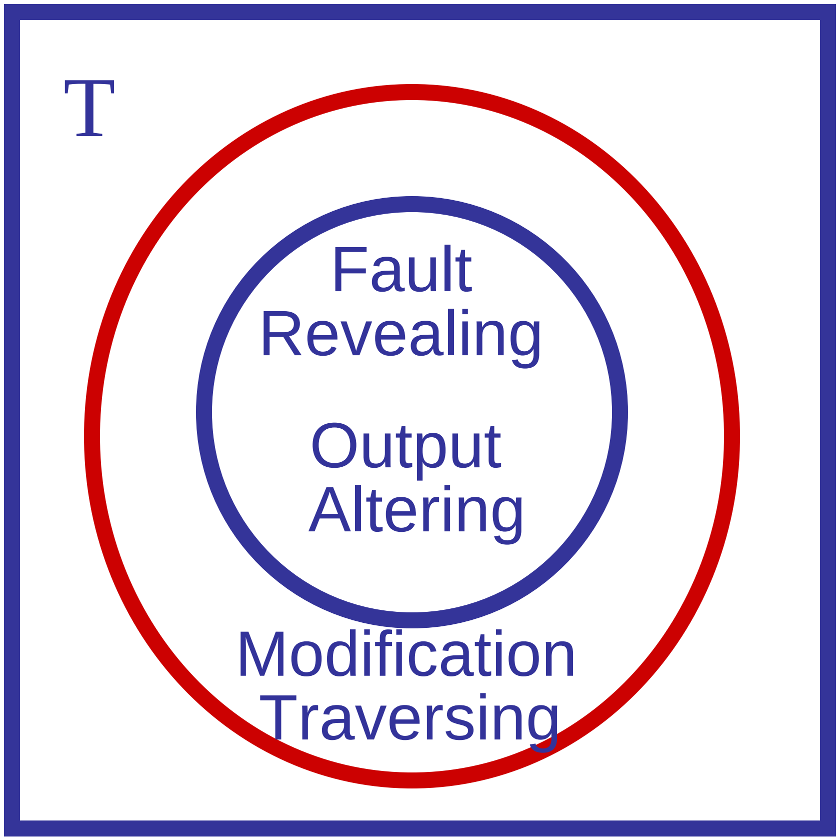
$O(t * n * n')$

(with *multiply-visited nodes*)

$O(t * \min(n,n'))$

(with no *multiply-visited nodes*)

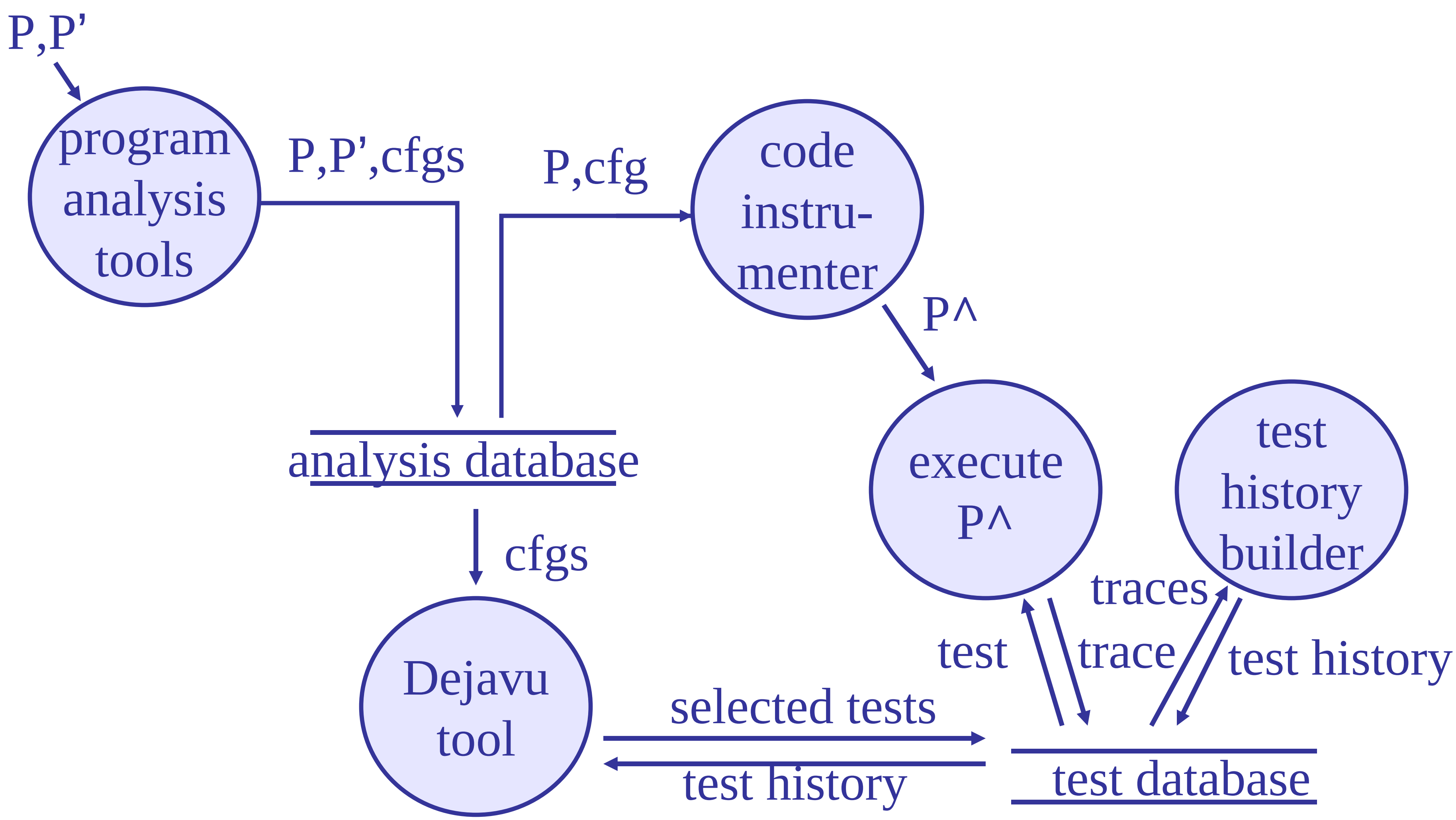
Precision and Safety



Conditions:

1. P was correct for all tests in T
2. T contains no obsolete tests
3. Controlled regression testing

Regression Test Selection System

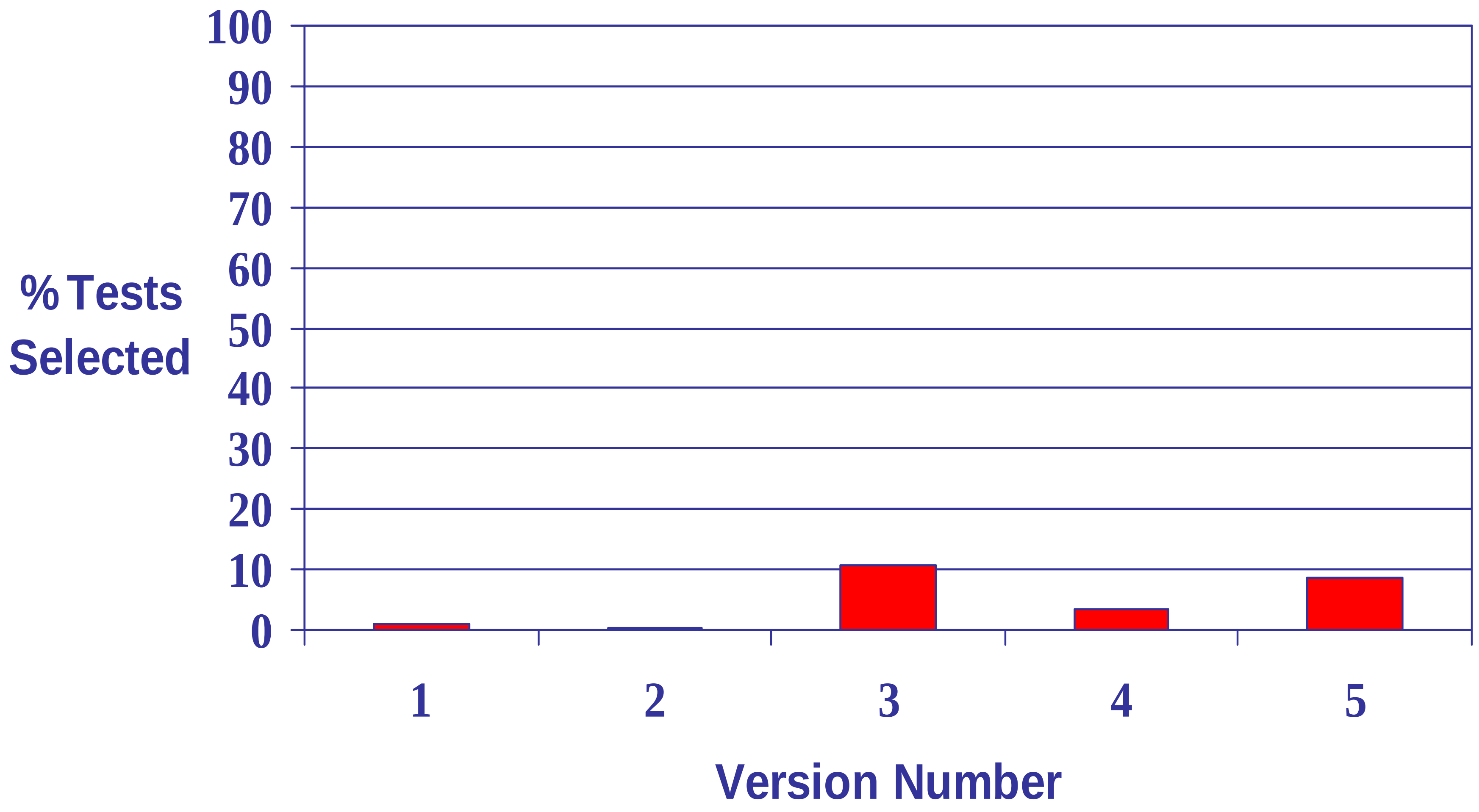


Study 1: Empire

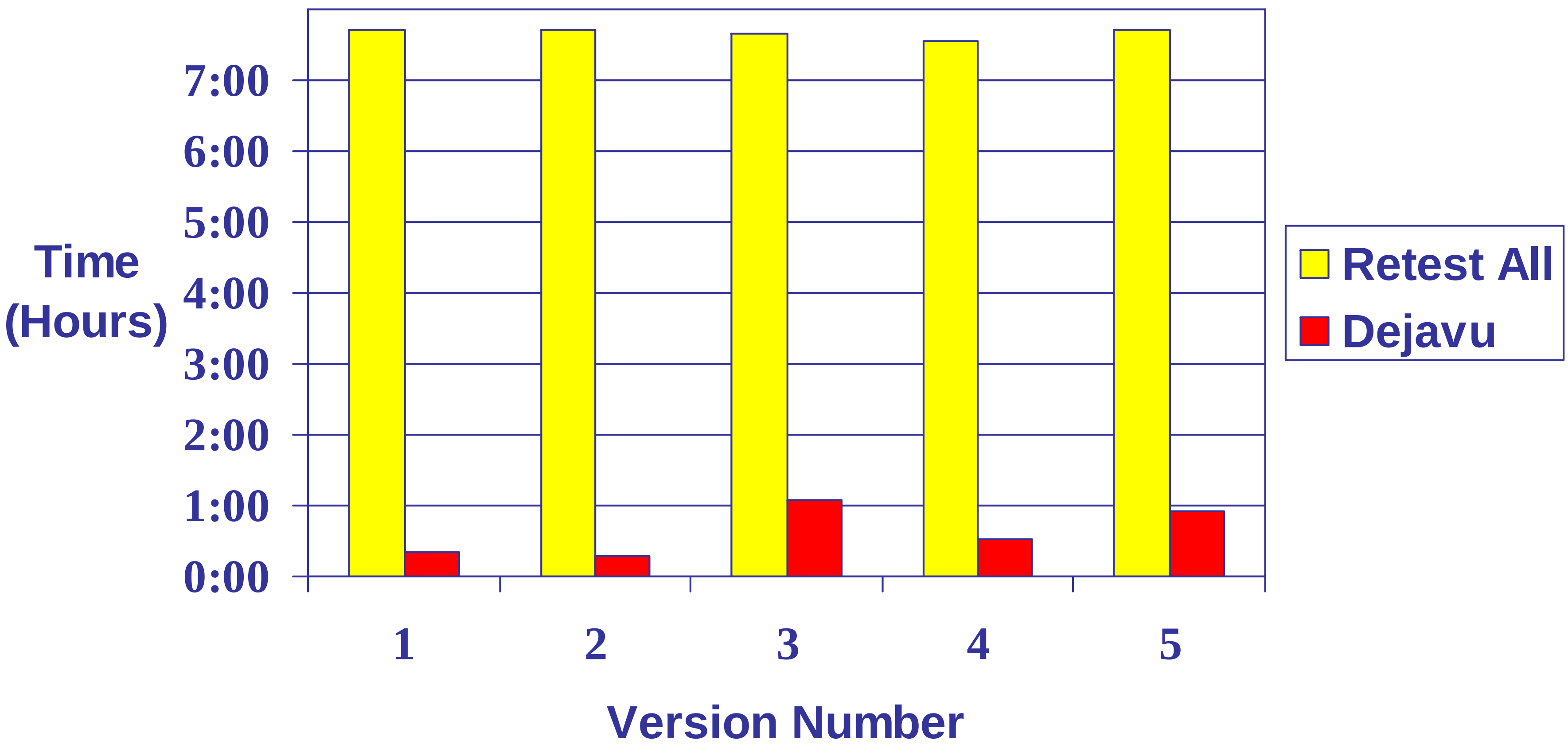
Program	Procs	LOC	Vers	Tests
server	766	49316	5	1033

Version	Functions Modified	LOC Modified
1	3	114
2	2	55
3	11	726
4	11	62
5	42	221

Study 1: Test Selection Percentages



Study 1:
Cost Effectiveness

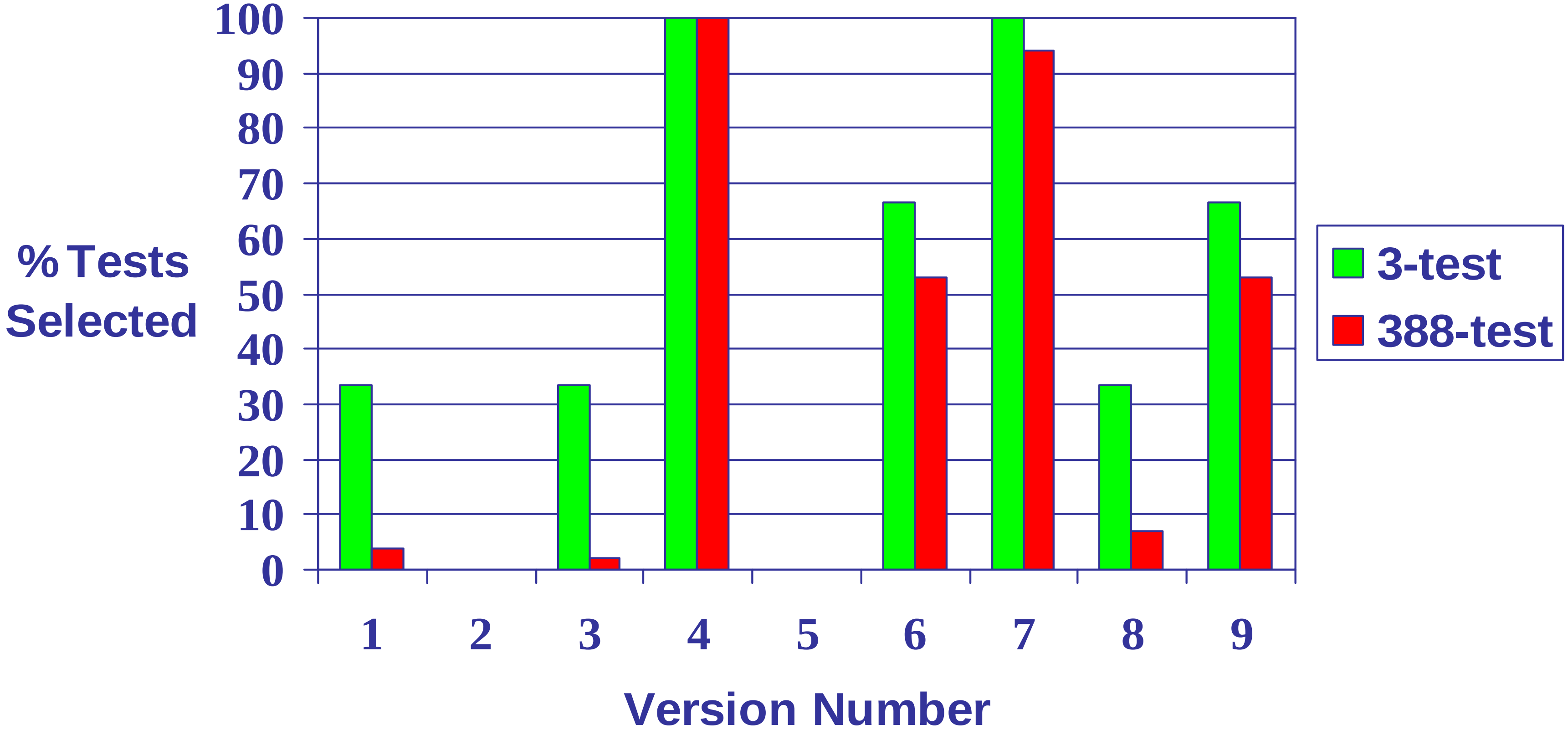


Study 2:
Windows NT Calculator

Program	Funcs	LOCs	Vers	Tests
calculator	27	2145	9	3/388

Version	Functions Modified	LOCs Modified
1	1	1
2	2	12
3	1	1
4	12	264
5	1	3
6	3	4
7	3	245
8	2	15
9	2	44

Study 2:
Test Selection Percentages



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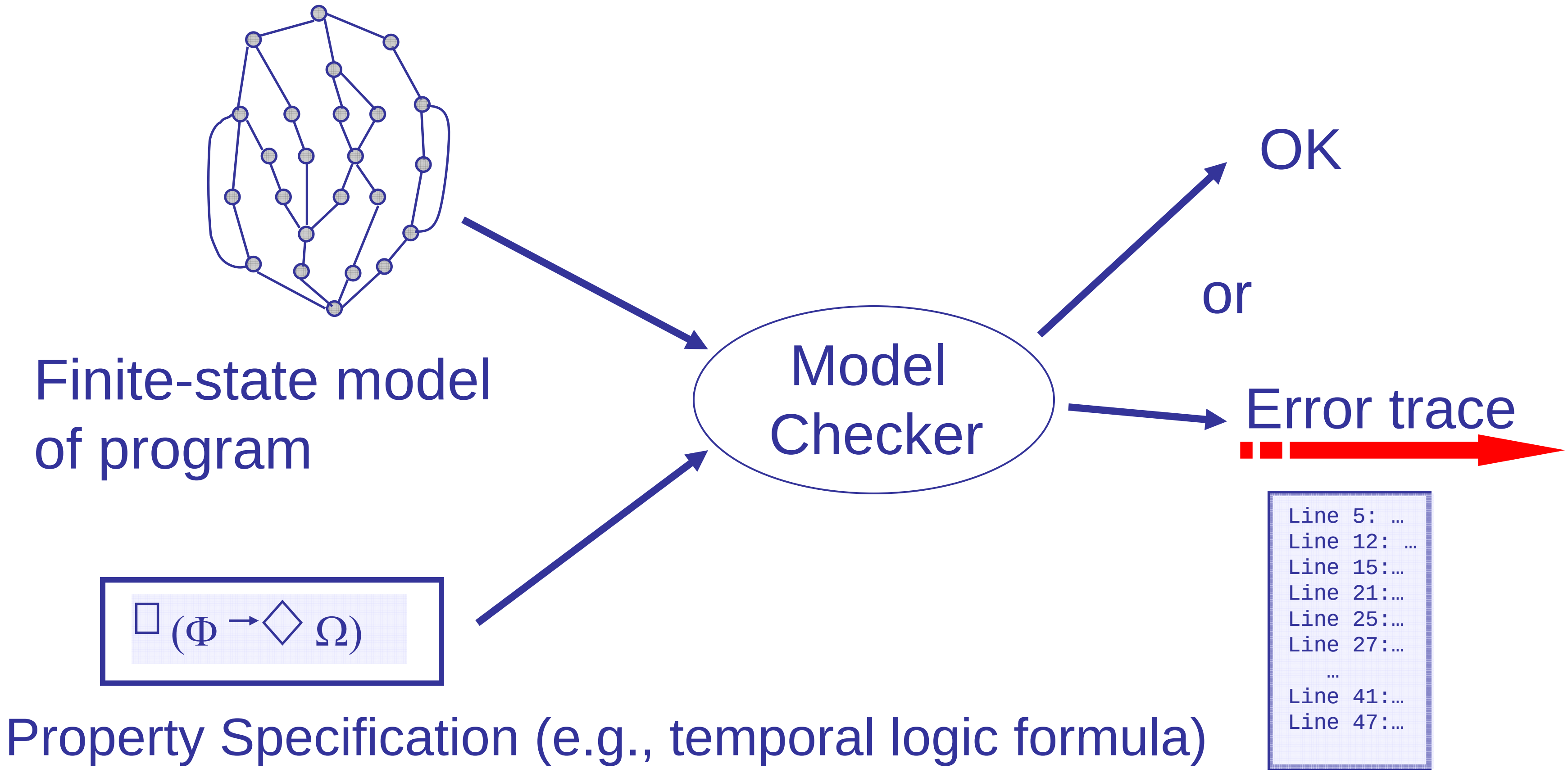
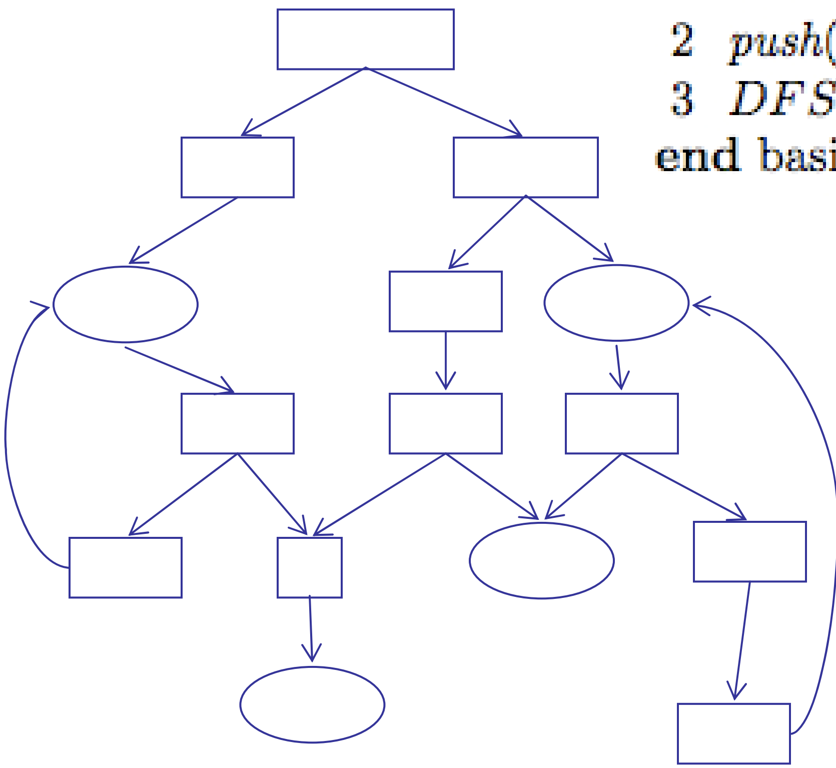
Model Checking



Basic DFS Approach



basicDFS()
  $seen := \{s_0\}$
  $push(stack, s_0)$
  $DFS(s_0)$
end basicDFS()

DFS(s)
  for $\alpha \in enabled(s)$ **do**
    $s' := \alpha(s)$
    if $error(s')$ **then**
      $ce := stack$
      exit
    if $s' \notin seen$ **then**
      $seen := seen \cup \{s'\}$
      $push(stack, s')$
      $DFS(s')$
      $pop(stack)$
  endfor
end DFS()

Why use Model Checking?

- Automatically check, e.g.,
  - invariants, safety & liveness properties
  - absence of dead-lock and live-lock,
  - complex event sequencing properties,

> “Between the key being inserted and the key being removed, the ignition can be activated at most twice.”

- In contrast to testing, model checking gives complete coverage by exhaustively exploring all paths in a system

What Makes Model Checking Difficult to Apply in Practice?

- Model construction
- Property specification
- State explosion
- Output interpretation

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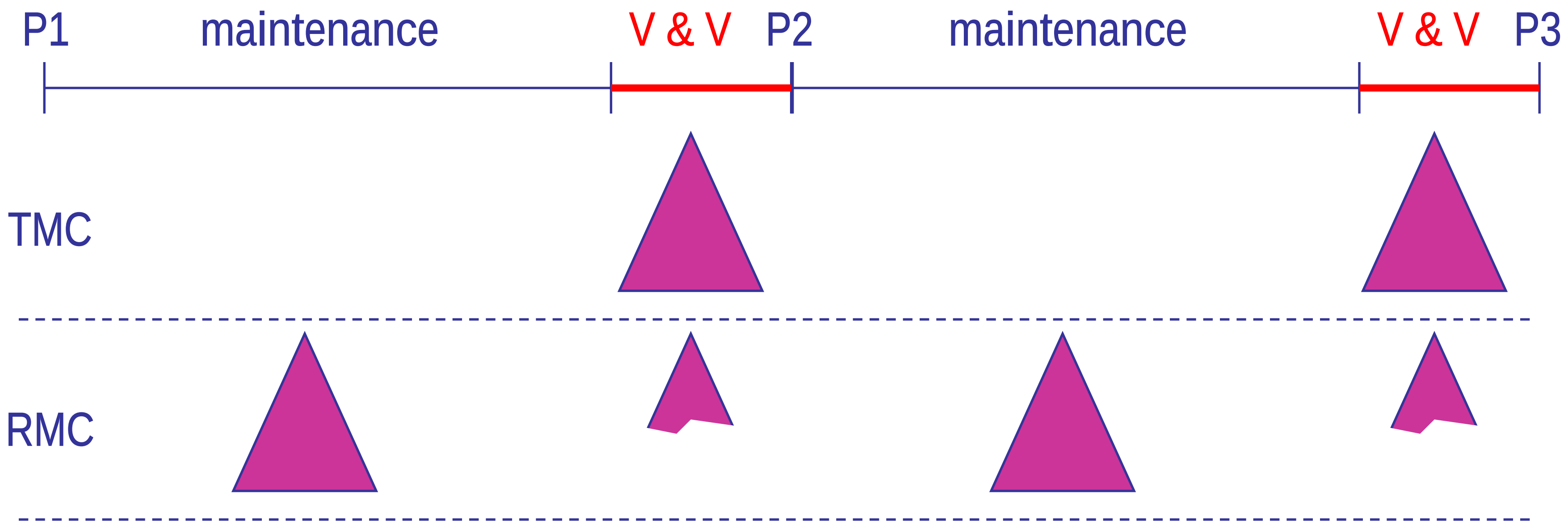
- Model construction
- Property specification
- State explosion
- Output interpretation
- System evolution

Regression Model Checking



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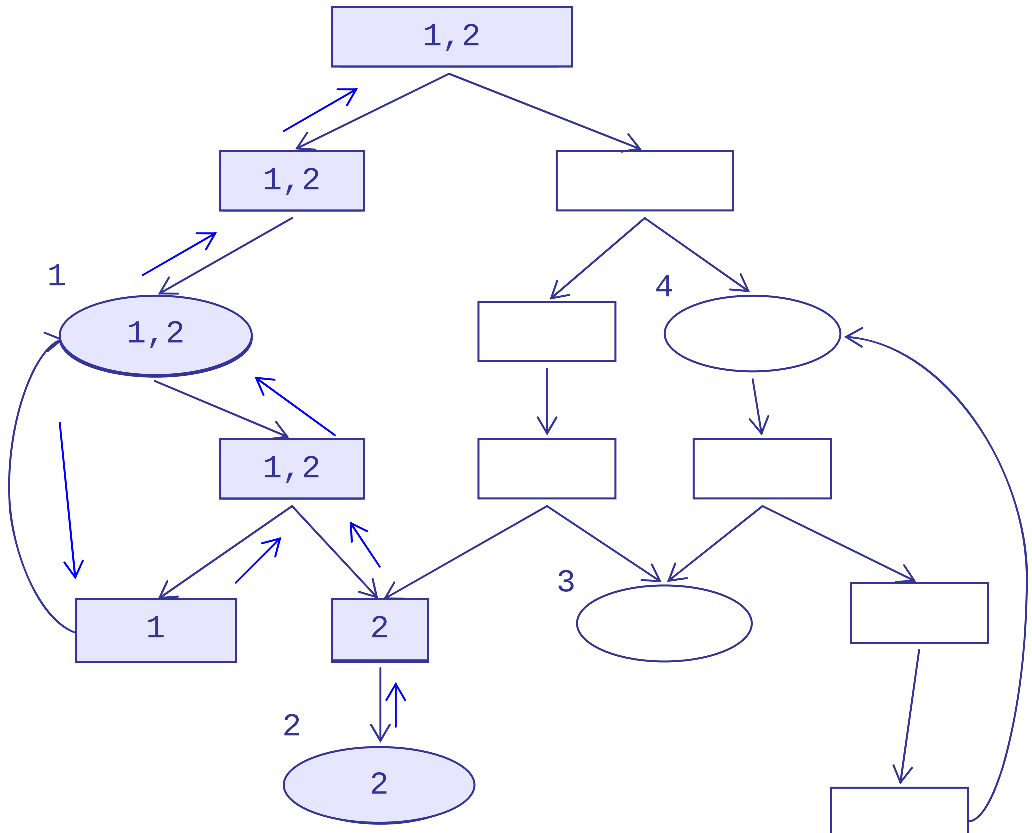
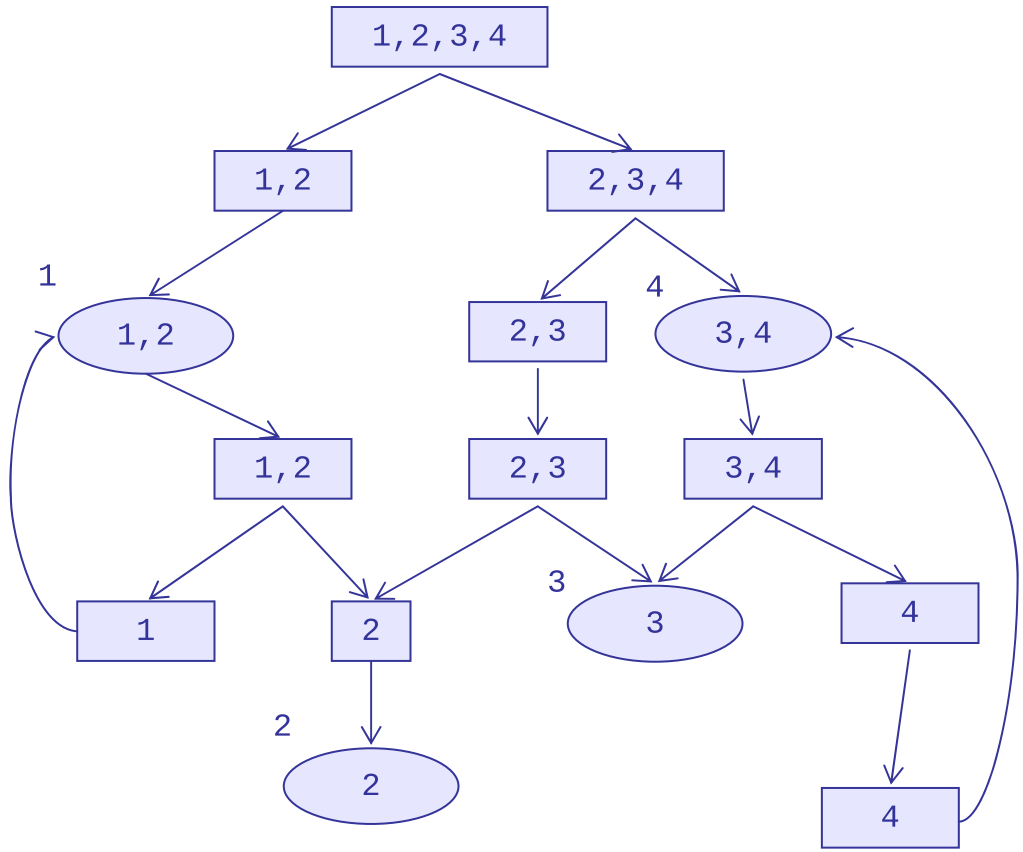
Regression Model Checking (RMC) Process

1) A *recording phase* of RMC (recordingRMC) gathers data while model checking P in the preliminary period
2) Dejavu computes the dangerous elements with respect to P and P'
3) A *pruning phase* of RMC (pruningRMC) determines which sub-state spaces in P' are safe and prunes them in the critical period, performing model checking only where needed
4) RMC preserves property checking relative to a traditional model check

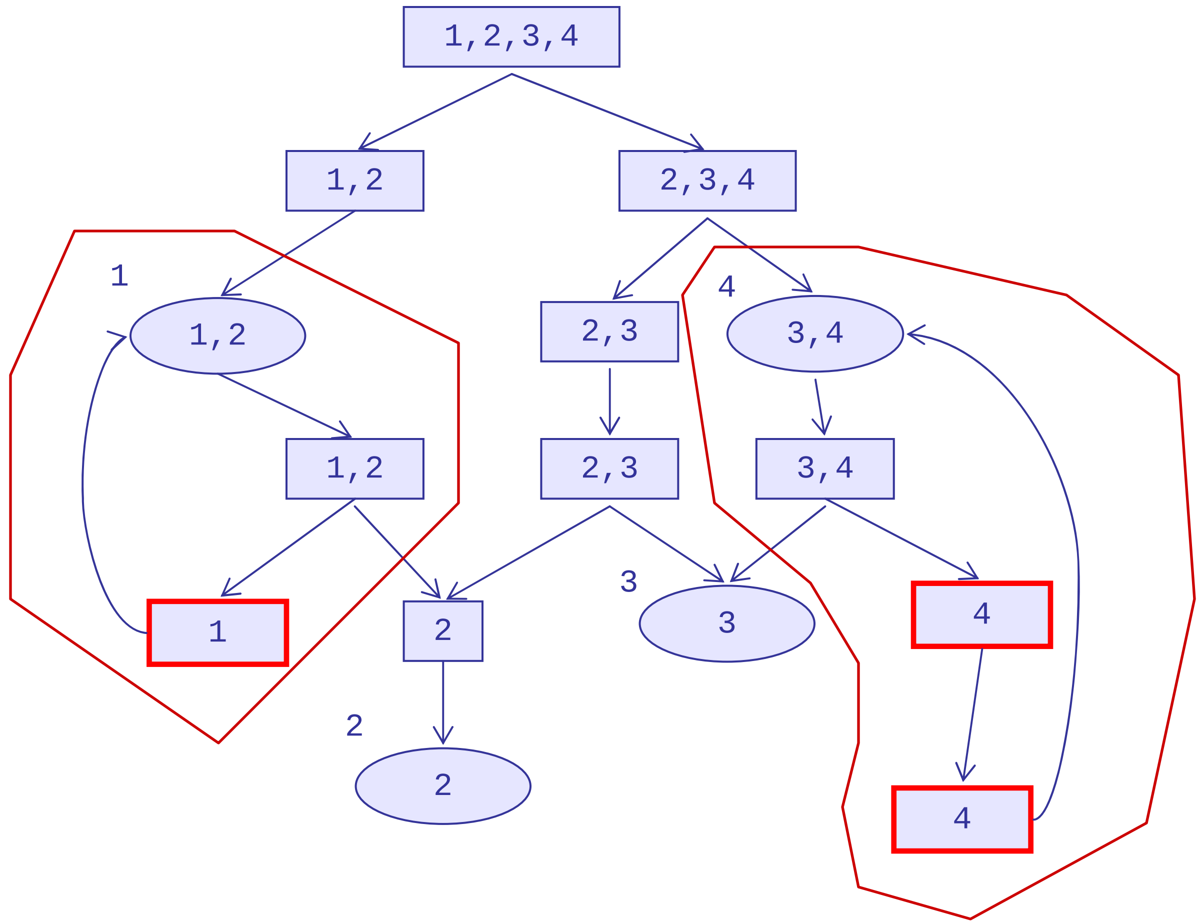
RecordingRMC



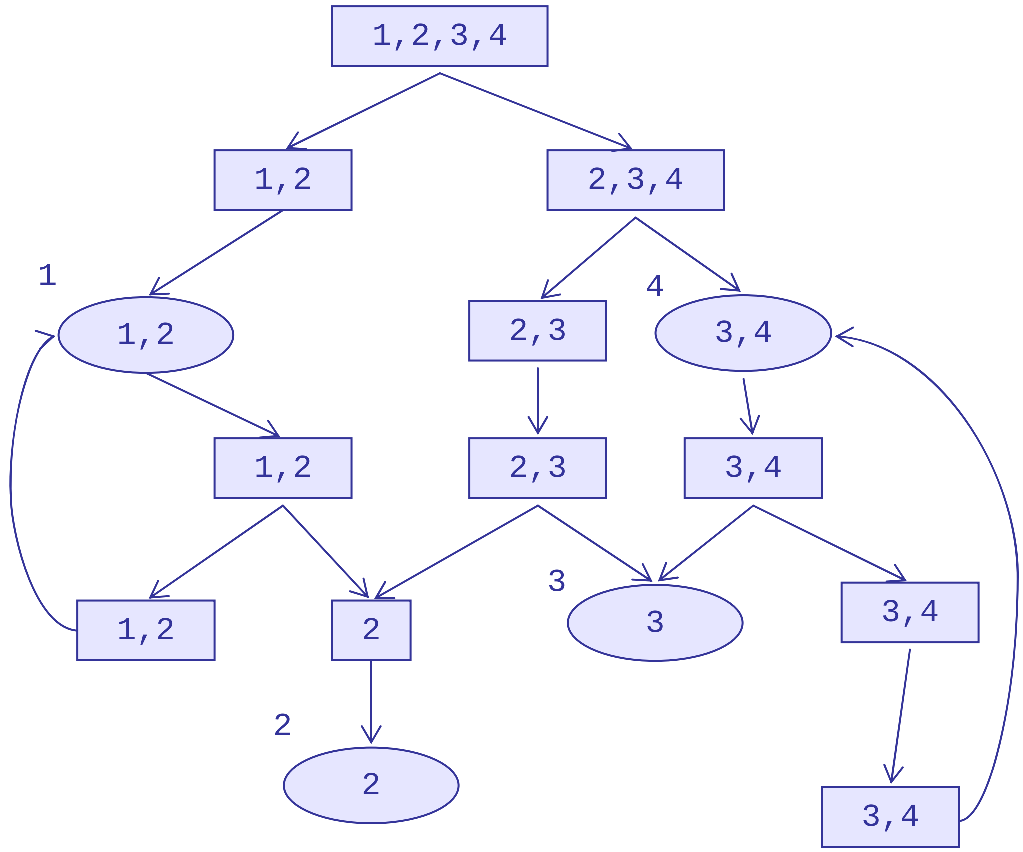
RecordingRMC



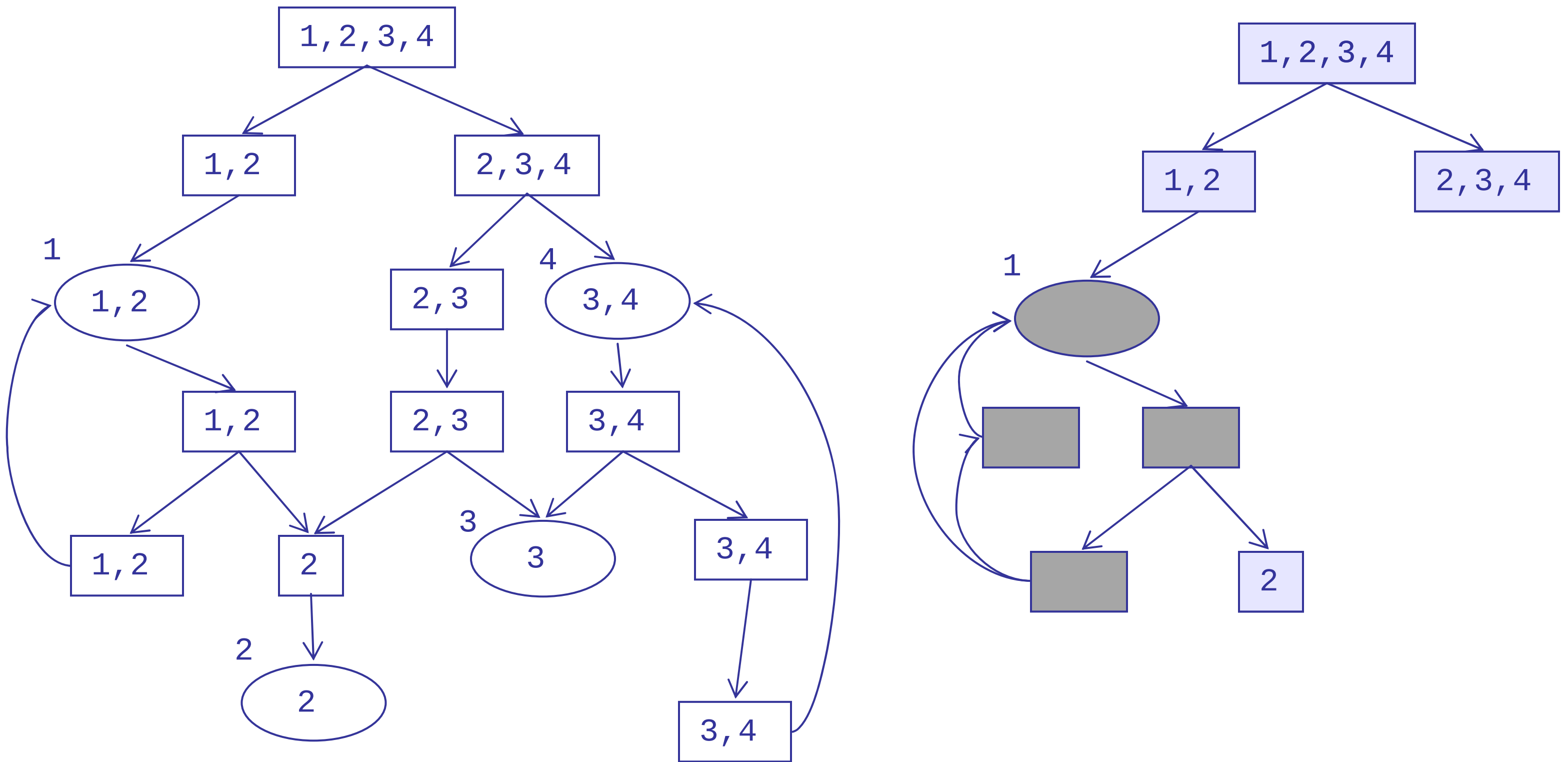
RecordingRMC



RecordingRMC

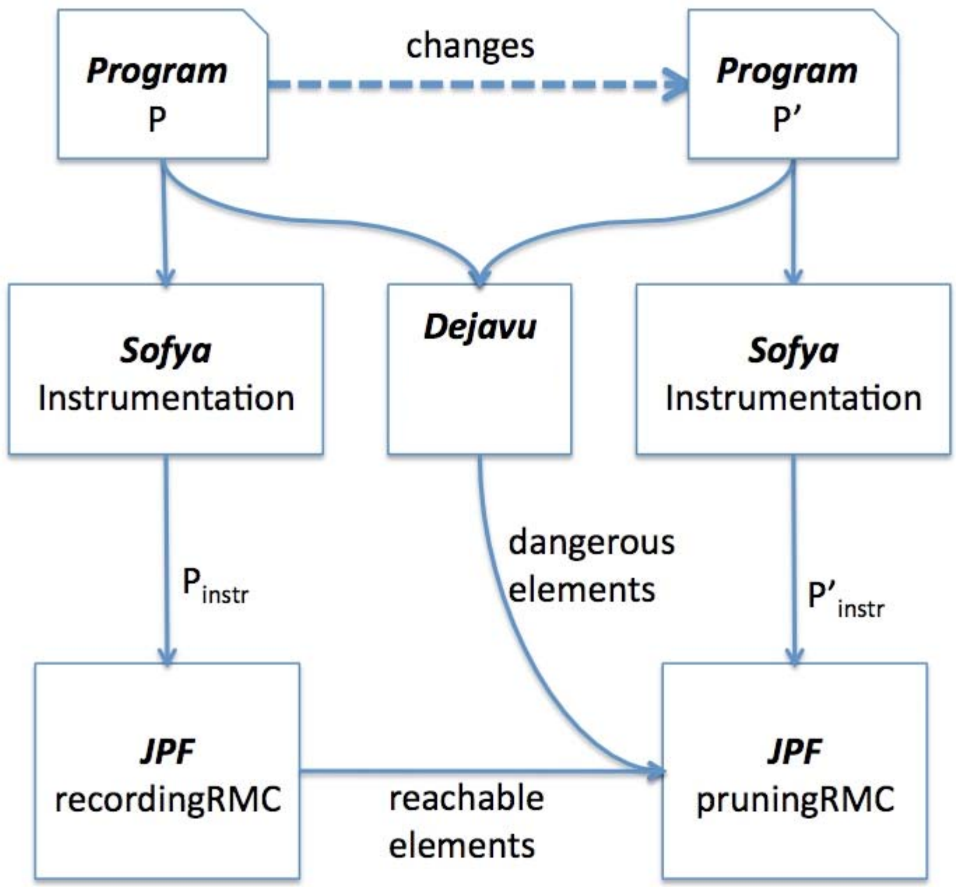


PruningRMC



Dangerous elements = {1}

RMC Implementation



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Research Question

RQ1: How does RMC compare in the critical period to TMC

RQ2: How does RMC compare overall to TMC

Objects

Object	*Error*	*Thd*	*Cls*	*Meth*	*LOC*	*Vers*
Daisy	AssertionViolation	3	21	106	744	13
Elevator	ArrayException	4	12	96	934	29
Alarmclock	NullPtrException	3	6	20	125	13
RaxExtended	AssertionViolation	6	11	23	127	9
ReplicatedWorkers	Deadlock	6	14	50	304	25

Variables

- Independent variables:
  - RMC and TMC (default mode of JPF)

Variables

- Independent variables:
  - RMC and TMC (default mode of JPF)
- Dependent variables:
  - execution time (ET_{TMC}, ET_{RMC})
  - memory usage (MU_{TMC}, MU_{RMC})

Obtaining Versions - Choices

1. Actual versions
2. Versions created by people with enough related experience to modify the program
3. Versions created by simulating changes at beginnings of methods

Threats to Validity

- External Validity
  - representativeness of object programs
  - representativeness of versions
- Internal Validity
  - faults in implementation of algorithms
  - faults in tools
- Construct Validity
  - metrics we have chosen

Time / Memory Cost Ratios

Program	TMC / RMC-Cri	TMC / RMC
Daisy	5.0 3.0	0.97 1.09
Elevator	43.4 1.6	1.57 0.36
AlarmClock	1.2 1.3	0.99 1.14
RaxExtnded	79.6 2.1	1.56 0.75
ReplWorkers	43.5 1.0	1.47 0.24

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RMC-Cri consistently faster than TMC; in three cases substantially

TMC uses between 1.1 and 3.0 times more memory than RMC-Cri

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ReplWorkers	43.5 1.0	1.47 0.24

RMC is faster than TMC in 3 of 5 cases, and not much slower in 2 others

RMC uses more memory than TMC in 3 of 5 cases, and a bit less in 2 others

Summary

- In the critical period, RMC requires less time than TMC, and less memory
- Savings increase with costs of analysis
- Overall, RMC can also provide savings in time compared to TMC, but it does this through increased memory usage

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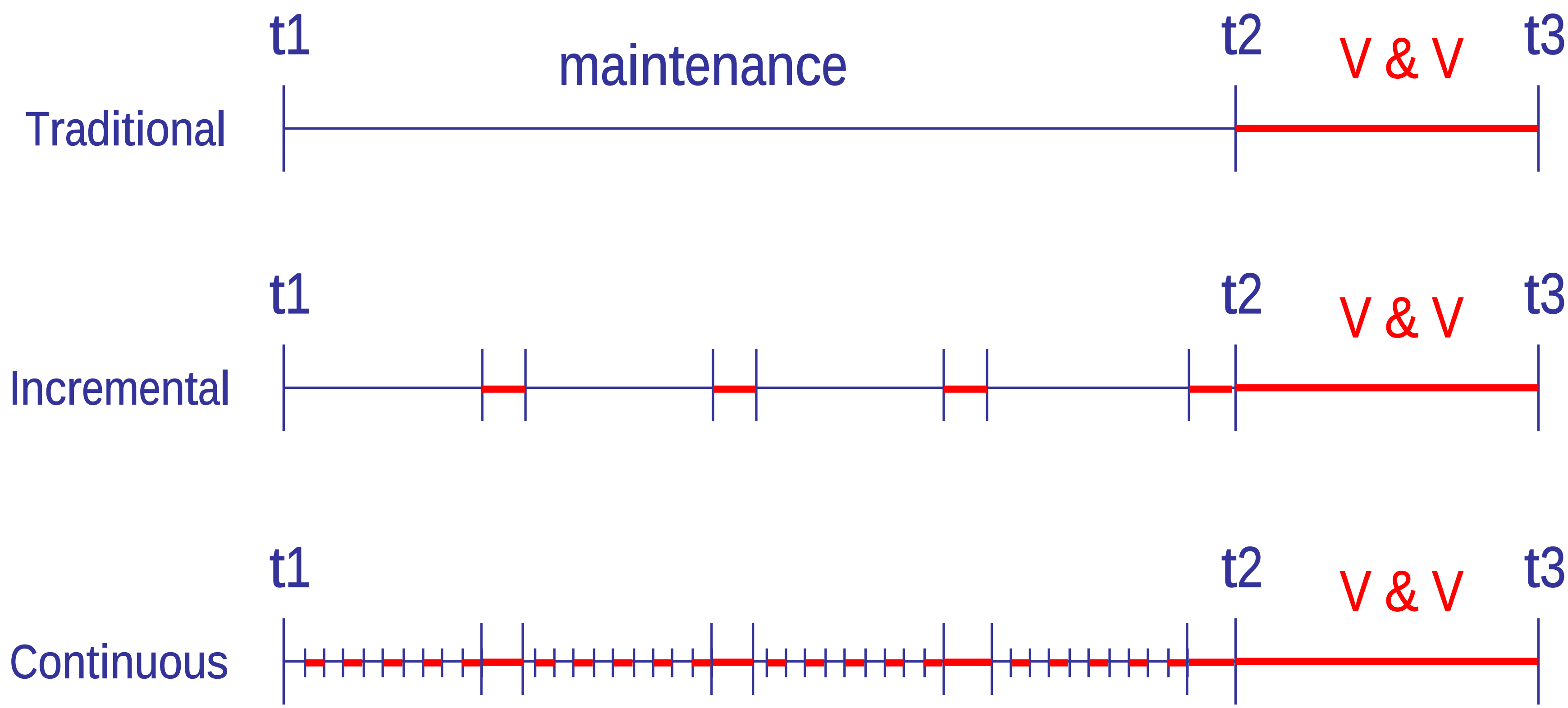
Ongoing and Future Work: Regression Testing

- Test case prioritization and test augmentation
- Economic models for evaluating costs/benefits
- Configurable systems and product lines
- Regression testing real-time embedded systems
- Testing under different process models

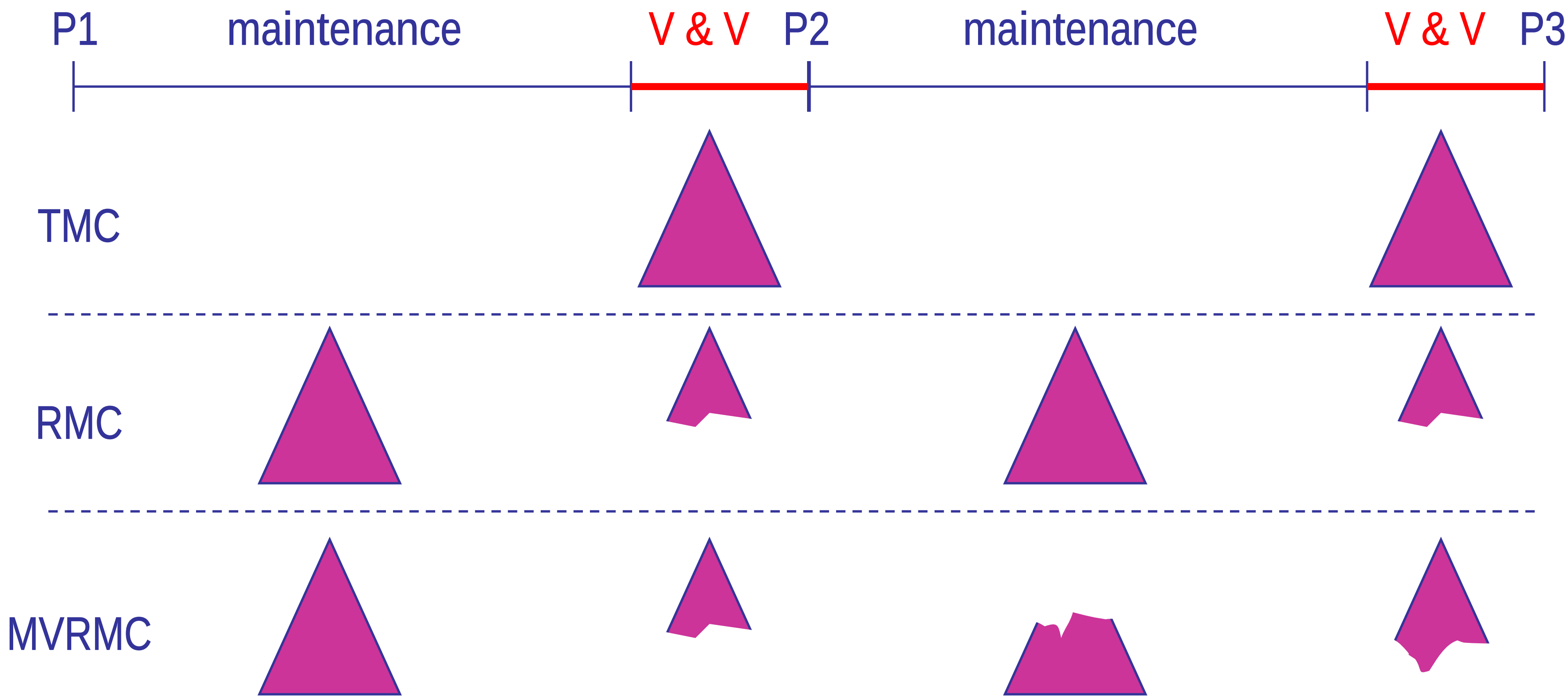
Ongoing and Future Work: Regression Model Checking

- Reduce memory costs by using coarser coverage elements or dominator analysis
- RMC is sensitive to the structure of program states; sub-setting program states may help
- Systems move through successions of releases; RMC ignores this, a multi-version RMC approach could be more cost-effective

More Process Models



Adapting to Other Processes



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Acknowledgments

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