Software Model Checking:

Searching for Computations in the Abstract or the Concrete

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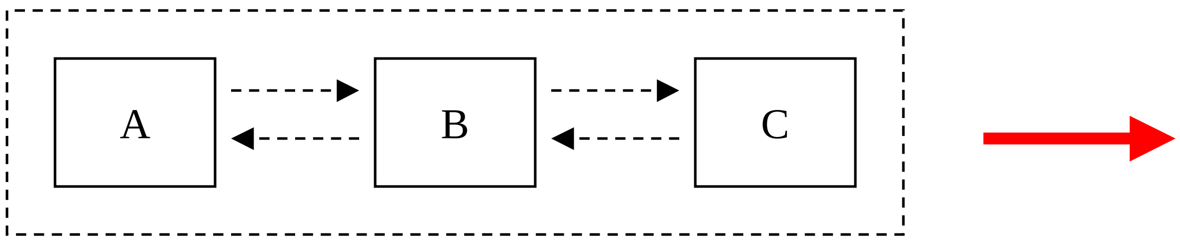
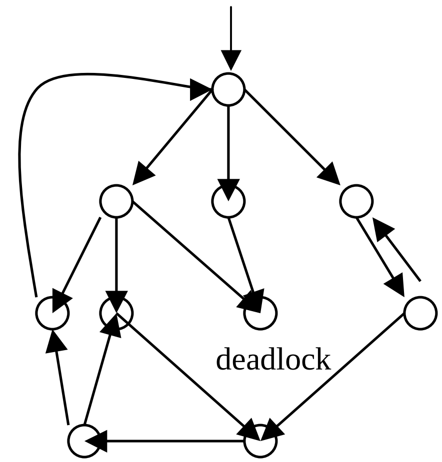
Overview

- Goal: an overview of software model checking
  - Past and current efforts
  - Future trends
- A discussion of the forces in play
  - Validation versus Falsification
  - Static (abstract) versus Dynamic (concrete) Analysis, and their integration
  - See paper in IFM'2005 Proc. for more (co-authored with Nils Klarlund)
- Disclaimer:
  - a personal view of where the field started and where it is currently going
  - emphasis on technical ideas, not references
  - emphasis on what influenced the speaker, not a fully exhaustive survey

“Model Checking”



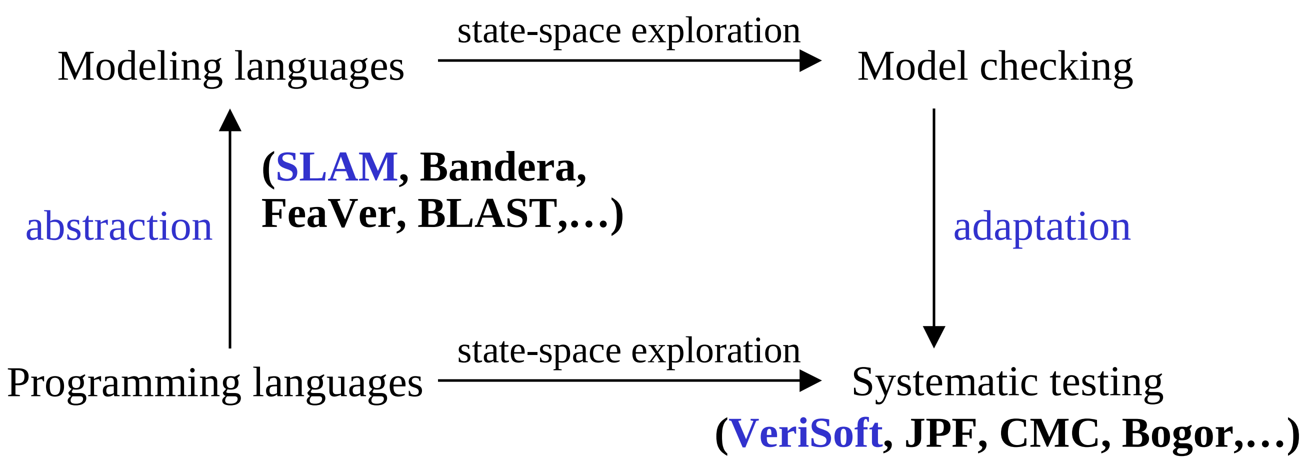
Each component is modeled by a FSM.



- Model Checking = systematic state-space exploration = exhaustive testing
- “Model Checking” = “check whether the system satisfies a temporal-logic formula”
  - Example: G(p->Fq) is an LTL formula
- Simple yet effective technique for <u>finding bugs</u> in high-level hardware and software designs (examples: FormalCheck for Hardware, SPIN for Software, etc.)
- Once thoroughly checked, models can be compiled and used as the core of the implementation (examples: SDL, VFSM, etc.)

Model Checking of Software

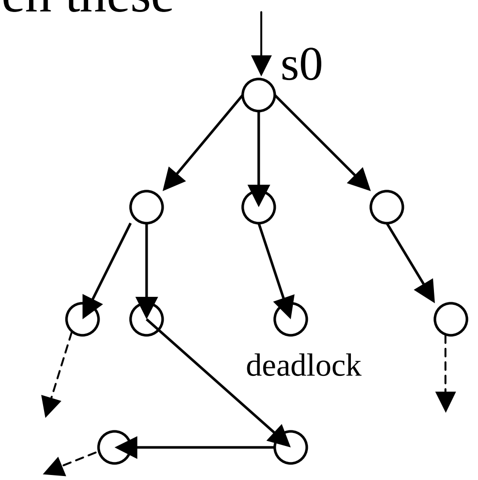
- Challenge: how to apply model checking to analyze **software**?
  - "Real" programming languages (e.g., C, C++, Java),
  - "Real" size (e.g., 100,000's lines of code).
- Two main approaches to software model checking:



Dynamic Approach: Systematic Testing (VeriSoft)

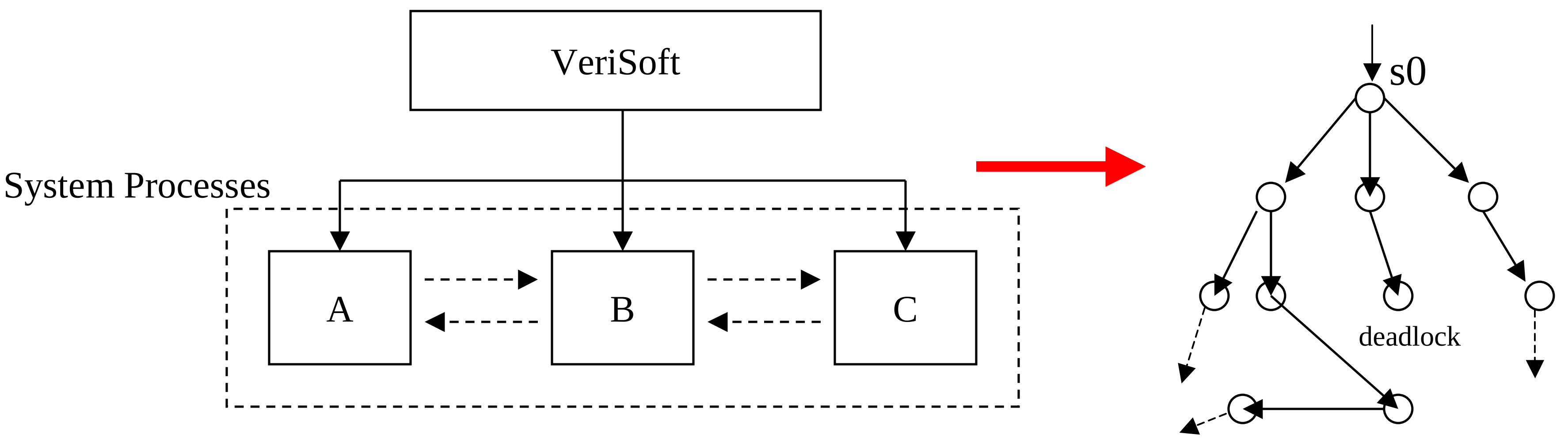
- State Space (Dynamic Semantics)= "product of (Unix) processes"
  - Processes communicate by executing operations on com. objects
  - Operations on com. objects are visible, other operations are invisible
  - Only executions of visible operations may be blocking
  - The system is in a global state when the next operation of each process is visible
  - State Space = set of global states + transitions between these

THEOREM: Deadlocks and assertion violations are preserved in the "state space" as defined above



VeriSoft

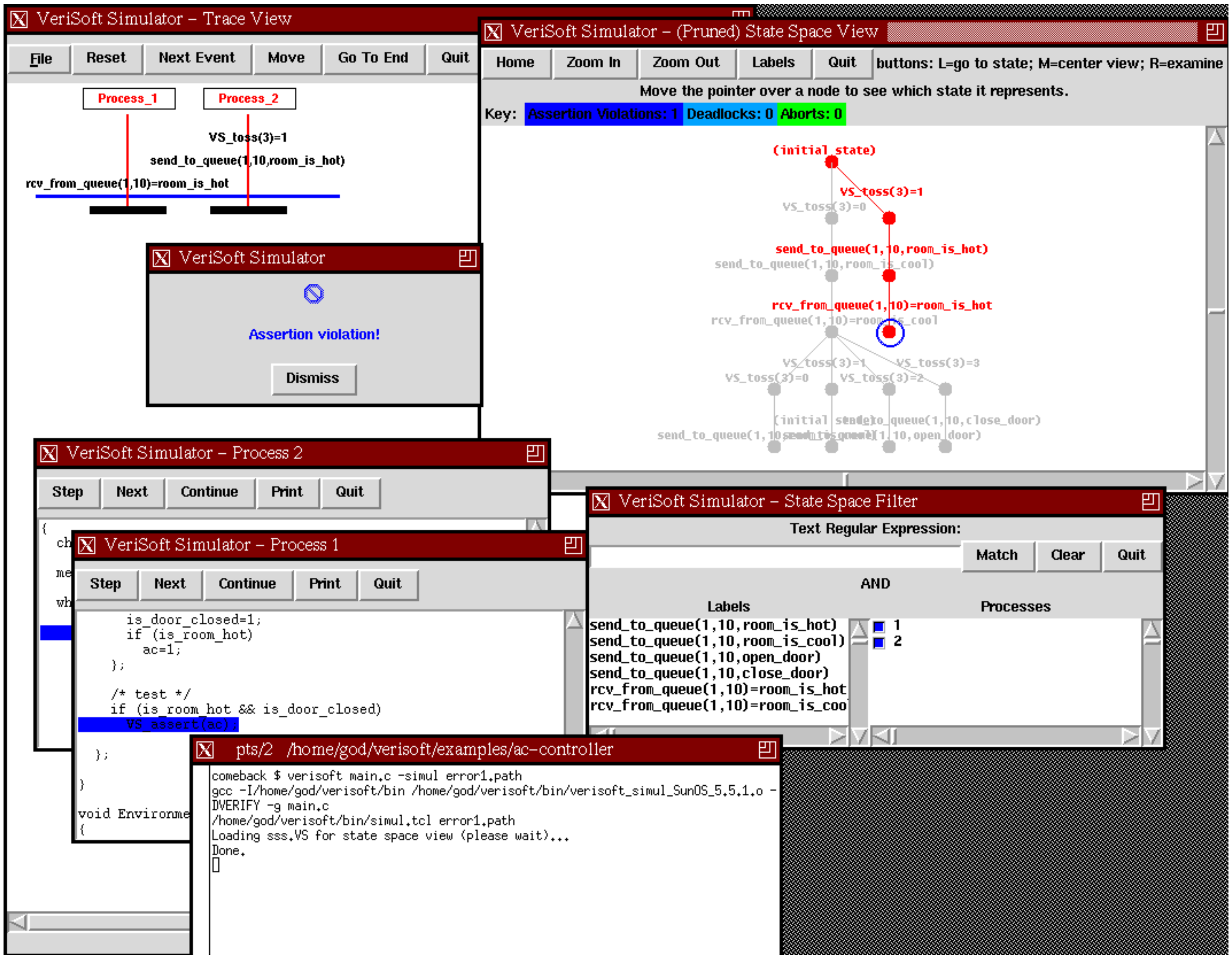
- Controls and observes the execution of concurrent processes of the system under test by intercepting system calls (communication, assertion violations, etc.)
- Systematically drives the system along all the paths (= scenarios) in its state space (= automatically generate, execute and evaluate many scenarios)
- From a given initial state, one can always guarantee a <u>complete coverage</u> of the state space <u>up to some depth</u>
- Note: analyzes “closed systems”; requires test driver(s) possibly using “VS_toss(n)”



VeriSoft State-Space Search

- Automatically searches for: (safety properties only!)
  - deadlocks,
  - assertion violations,
  - divergences (a process does not communicate with the rest of the system during more than x seconds),
  - livelocks (a process is blocked during x successive transitions)
- A scenario (=path in state space) is reported for each error found
- Scenarios can be replayed interactively using the VeriSoft simulator (driving existing debuggers)

The VeriSoft Simulator



VeriSoft - Summary

- VeriSoft is the first software model checker for general-purpose programming languages such as C and C++ [POPL97,Godefroid]
- Two key features distinguish VeriSoft from other model checkers
  - Does not require the use of any specific modeling/programming language
  - Performs a state-less search; use of partial-order reduction is key to make this approach tractable in the presence of concurrency
- In practice, the search is typically incomplete
  - From a given initial state, VeriSoft can always guarantee a complete coverage of the state space up to some depth
- Subsequent related tools: JPF (NASA; Java, stateful via instrumented JVM), CMC (Stanford; C, stateful, symmetry reduction), Bogor (Kansas U.), etc.

VeriSoft Users and Applications

- Development of research prototype started in 1996
- VeriSoft 2.0 available outside Lucent since January 1999:
  - 100's of licenses in 25+ countries, in industry and academia
  - Free download at http://www.bell-labs.com/projects/verisoft
- Examples of applications in Lucent:
  - 4ESS Heart-Beat-Monitor unit testing and debugging (telephone switch maintenance) [ISSTA'98]
  - WaveStar 40G R4 integration testing (optical network management)
  - 7R/E PTS Feature Server unit and integration testing (voice/data signaling)
  - CDMA Cell-Site Call Processing Library testing (wireless call processing) [ICSE'2002]

Discussion (Strengths and Limitations)

- VeriSoft (like model checking) is not a panacea
  - Limited by state-explosion…
  - Requires some training and effort (to write test drivers, properties, etc.)
  - "Model Checking is a push-button technology" is a myth!
- Used properly, VeriSoft is very effective at finding bugs
  - Concurrent/reactive/real-time systems are hard to design, develop and test
  - Traditional testing is not adequate
  - "Model checking" (systematic testing) can rather easily expose new bugs
- These bugs would otherwise be found by the customer!
- So the real question is "How much ($) do you care about bugs?"

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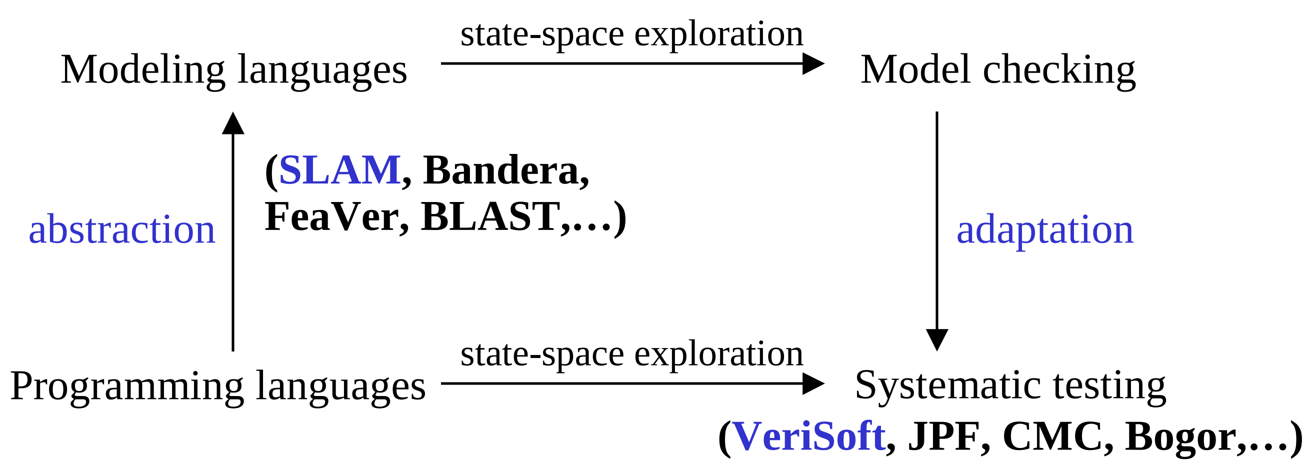


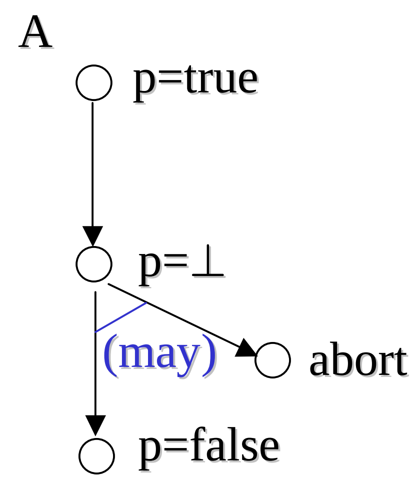
Static Approach: Automatic Abstraction (SLAM)

- "Abstract-Check-Refine" Loop:
  1. Abstract: generate a (may) abstraction via static program analysis
     - Ex: predicate abstraction and boolean program
  2. Check: "model check" the abstraction
  3. Refine: map abstract error traces back to code, or refine the abstraction (e.g., by adding predicates); goto 1

```
Program P( ) {
  int x = 1;
  x = h(x);
  if (odd(x))
     abort(); // error!
  x = 0;
}
```

Predicate abstraction

p: "x is odd"



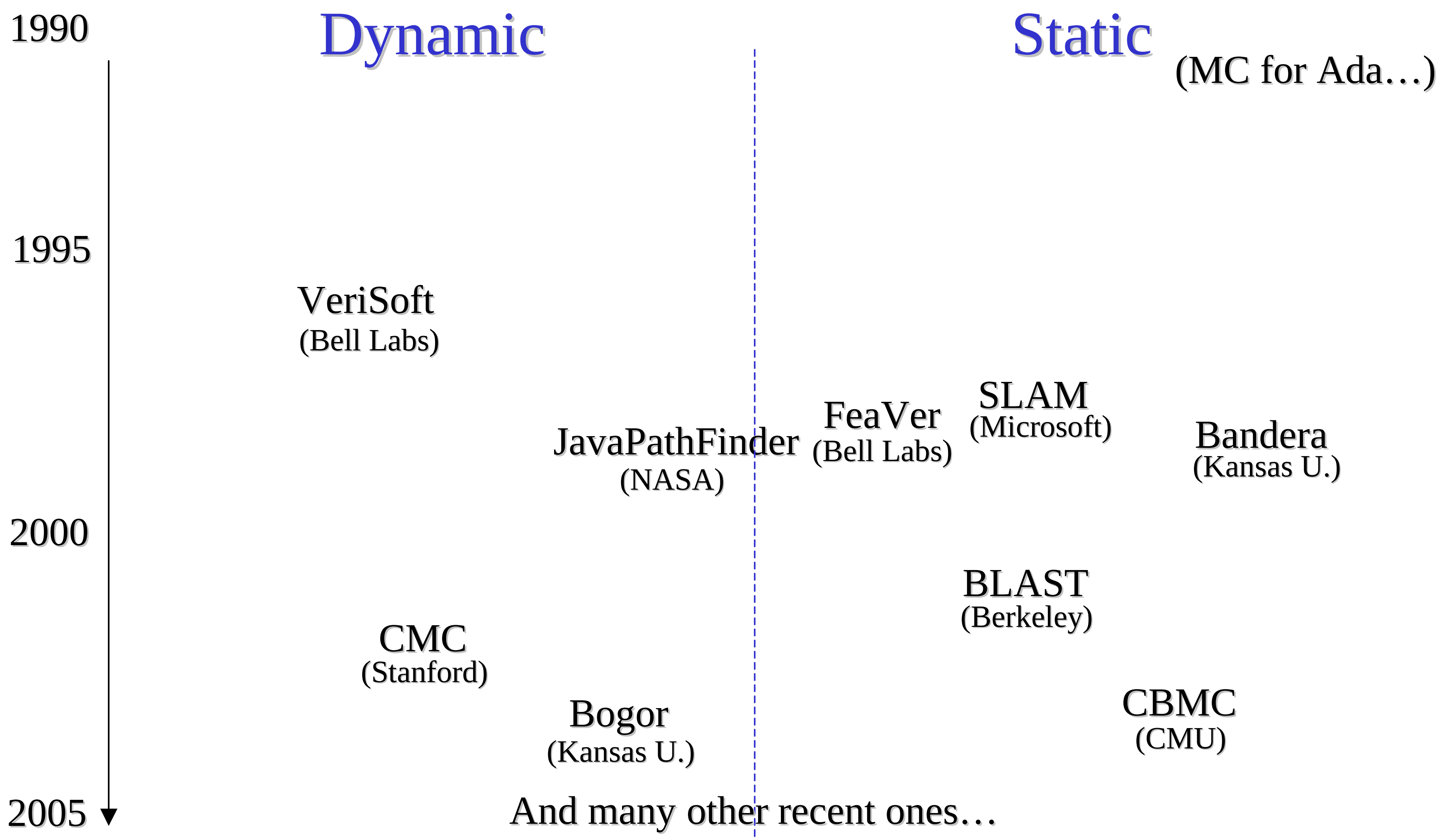
Main Ideas and Issues

1. Abstract: extract a “model” out of concrete program via static analysis
   - Which programming languages are supported? ((subset of) C, Java, Ada, Domain-Specific Language?)
   - Additional assumptions? (Pointers? Recursion? Concurrency?…)
   - What is the target modeling language? ((C)(E)FSMs, PDAs,…)
   - Can/must the abstraction process be guided by the user? How?
2. Model check the abstraction
   - What properties can be checked? (Safety? Liveness?,…)
   - How to model the environment? (Closed or open system ?…)
   - Which model-checking algorithm? (New algos for PDAs, use SAT solvers…)
   - Is the abstraction “conservative”? (I.e., is the static analysis “sound”?)
3. Map abstract counter-examples back to code, or refine the abstraction
   - Behaviors violating the property may have been introduced during Step 1
   - How to map scenarios leading to errors back to the code?
   - When an error trace is spurious, how to refine the abstraction?

Lots of Recent Work…

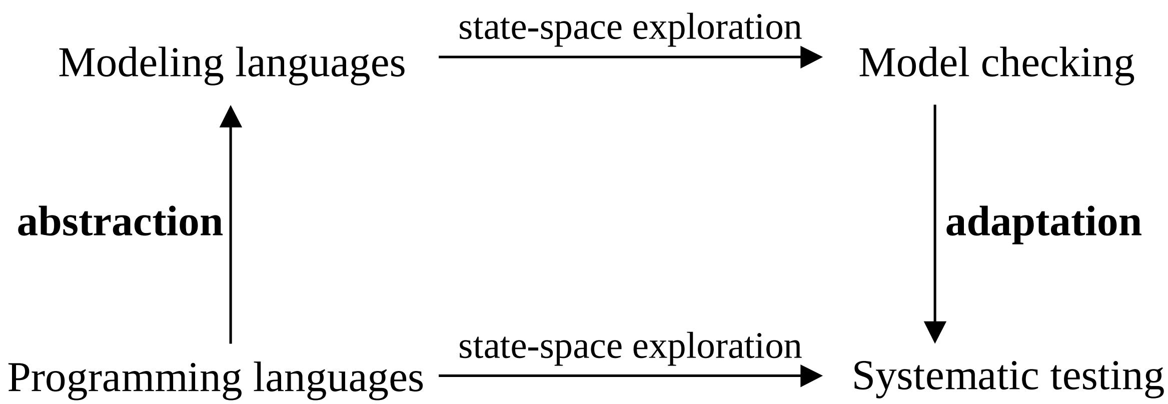
- Examples of tools:
  - SLAM (Microsoft): see previous slides; now part of Microsoft Windows device-driver development toolkit
  - Bandera (Kansas U.): Java to SPIN/SMV/* using user-guided abstraction mapping and slicing/abstract-interpretation/*
  - FeaVer (Bell Labs): C to SPIN using user-specified abstraction mapping
  - BLAST (Berkeley): similar to SLAM but "lazy abstraction refinement"
  - Etc! (+ Tools for static analysis of concurrent programs, Ada, etc.)
- Examples of frameworks: (automatic abstraction refinement)
  - [Graf,Saidi,…], [Clarke,Grumberg,Jha,…], [Ball,Rajamani,Podelski,…], [Dill,Das,…], [Khurshan,Namjoshi,…], [Dwyer,Pasareanu,Visser,…], [Bruns,Godefroid,Huth,Jagadeesan,Schmidt…], [Henzinger, Jhala, Majumdar,…], and many more!

Software Model Checking Tools (for C,C++,Java…)



Model Checking of Software

- Two <u>complementary</u> approaches to software model checking:



Automatic Abstraction (static analysis):
- Idea: parse code to generate an abstract model that can be analyzed using model checking
- No execution required but language dependent
- May produce spurious counterexamples (unsound bugs)
- Can prove correctness (complete) in theory (but not in practice…)

Systematic Testing (dynamic analysis):
- Idea: control the execution of multiple test-drivers/processes by intercepting systems calls
- Language independent but requires execution
- Counterexamples arise from code (sound bugs)
- Provide a complete state-space coverage up to some depth only (typically incomplete)

Model Checking of Sofware: What Next?

- A new generation of software model checkers combining static and dynamic analysis is coming up…
- Motivation: take the best of both approaches (precision of dynamic analysis AND efficiency of static analysis)
- Example: DART (Directed Automated Random Testing)
  - See [PLDI'2005], joint work done at Bell Labs with Nils Klarlund and Koushik Sen (summer intern from UIUC)
  - Can be viewed as extending the VeriSoft approach to data nondeterminism (see also [PLDI'98, Colby-Godefroid-Jagadeesan] for an earlier attempt)
  - Uses static program analysis and symbolic execution techniques (including theorem proving) for systematic test-input generation and execution
  - Just one way to combine static and dynamic analysis for software model checking…

DART: Directed Automated Random Testing

1. Automated extraction of program interface from source code
2. Generation of test driver for random testing through the interface
3. Dynamic test generation to direct executions along alternative program paths

- Together: (1)+(2)+(3) = DART
- DART can detect program crashes and assertion violations
- Any program that compiles can be run and tested this way:

  No need to write any test driver or harness code!

- (Pre- and post-conditions can be added to generated test-driver)

Example (C code)

```
int double(int x) {
    return 2 * x;
}

void test_me(int x, int y) {
  int z = double(x);
  if (z==y) {
    if (y == x+10)
      abort(); /* error */
  }
}
```

→ (1) Interface extraction:
- parameters of top-level function
- external variables
- return values of external functions

→ (2) Generation of test driver for random testing:

```
main(){
    int tmp1 = randomInt();
    int tmp2 = randomInt();
    test_me(tmp1,tmp2);
}
```

→ Closed (self-executable) program that can be run

Problem: probability of reaching abort() is extremely low!

DART Step (3): Directed Search

```
main(){
    int t1 = randomInt();
    int t2 = randomInt();
    test_me(t1,t2);
}
int double(int x) {return 2 * x; }

void test_me(int x, int y) {
  int z = double(x);
  if (z==y) {
    if (y == x+10)
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}
```

Concrete Execution	Symbolic Execution	Path Constraint
x = 36, y = 99	create symbolic variables x, y	

DART Step (3): Directed Search

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main(){
      int t1 = randomInt();
      int t2 = randomInt();
      test_me(t1,t2);
}
int double(int x) {return 2 * x; }

void test_me(int x, int y) {
  int z = double(x);
  if (z==y) {
      if (y == x+10)
          abort(); /* error */
  }
}
```

Concrete Execution

x = 36, y = 99,
z = 72

Symbolic Execution

create symbolic variables x, y

z = 2 * x

Path Constraint

DART Step (3): Directed Search

```
main(){
     int t1 = randomInt();
     int t2 = randomInt();
     test_me(t1,t2);
}
int double(int x) {return 2 * x; }

void test_me(int x, int y) {
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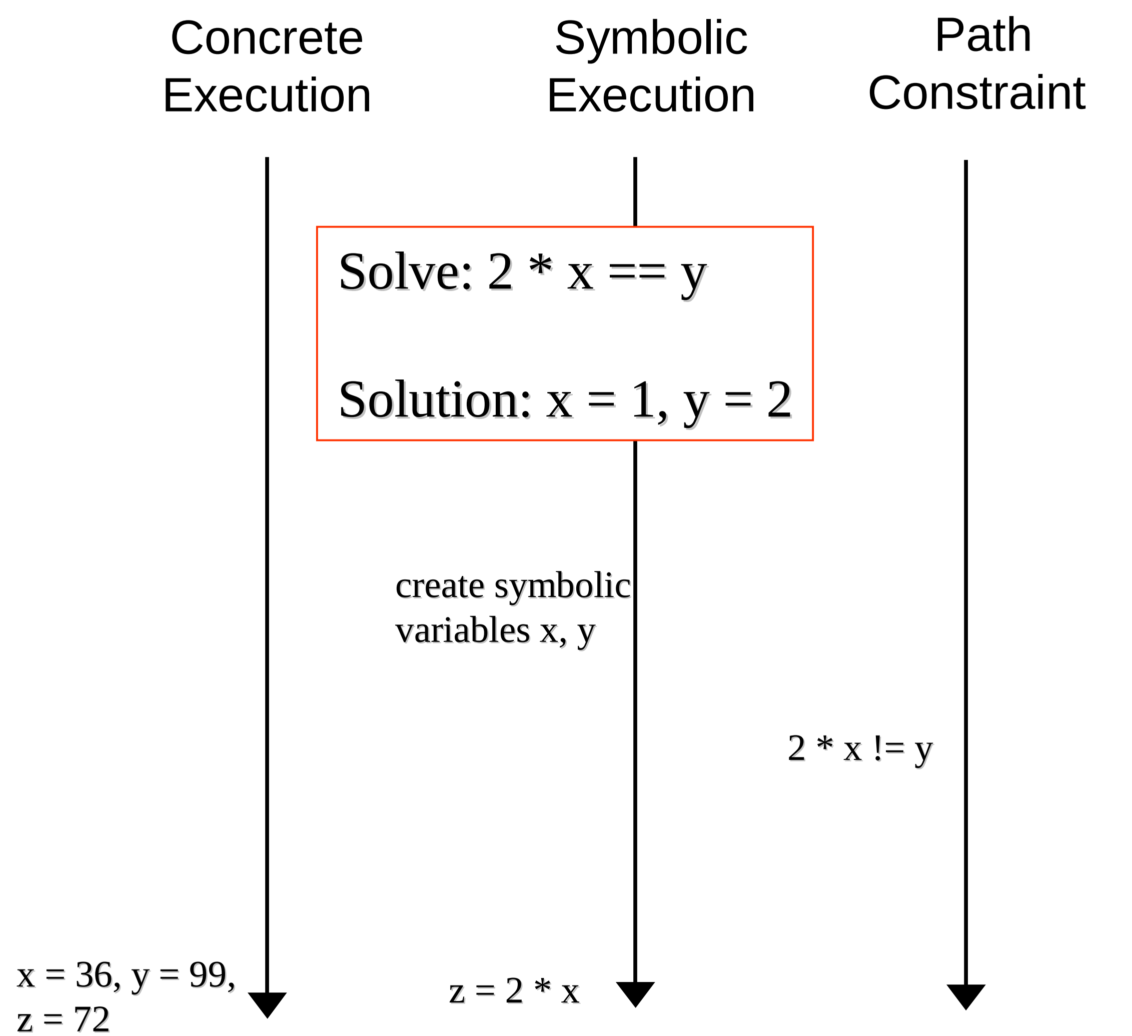

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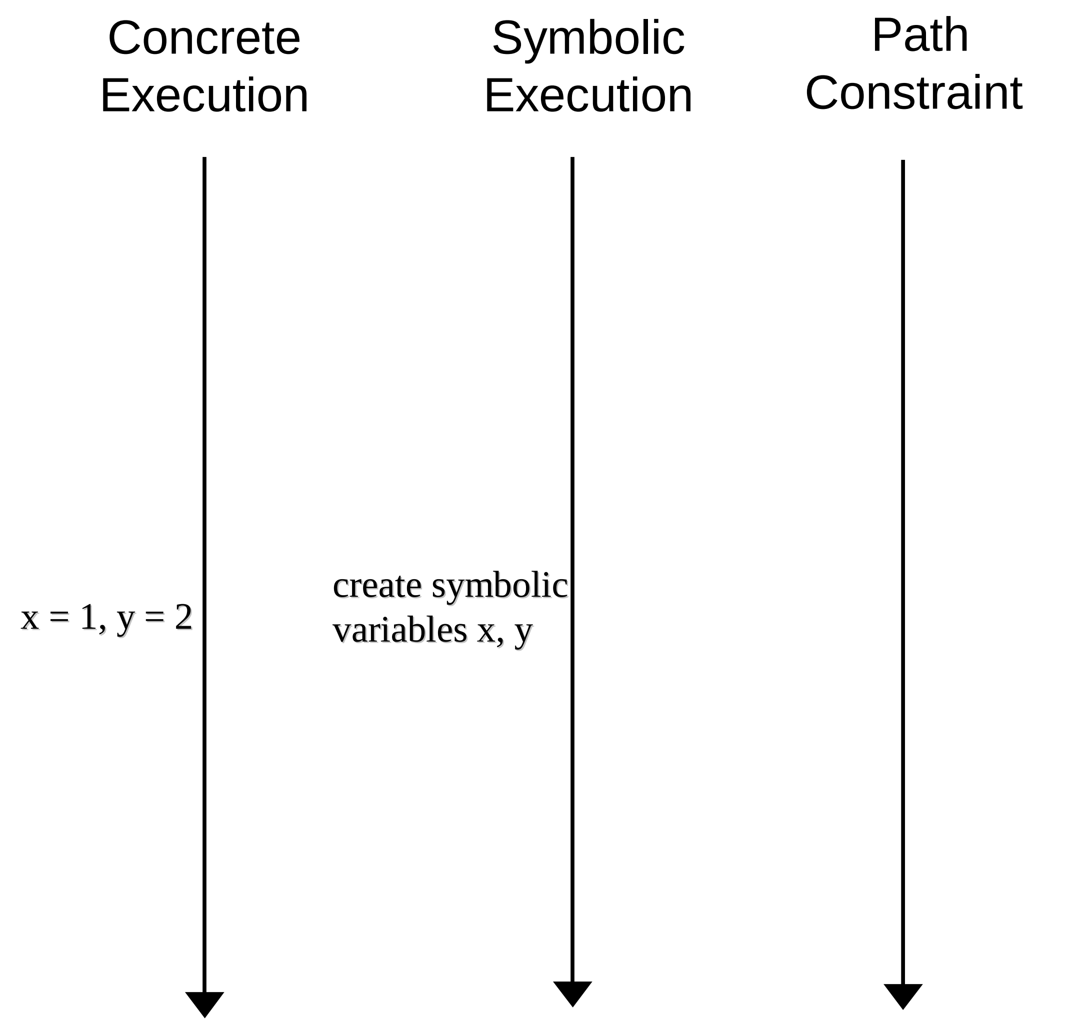

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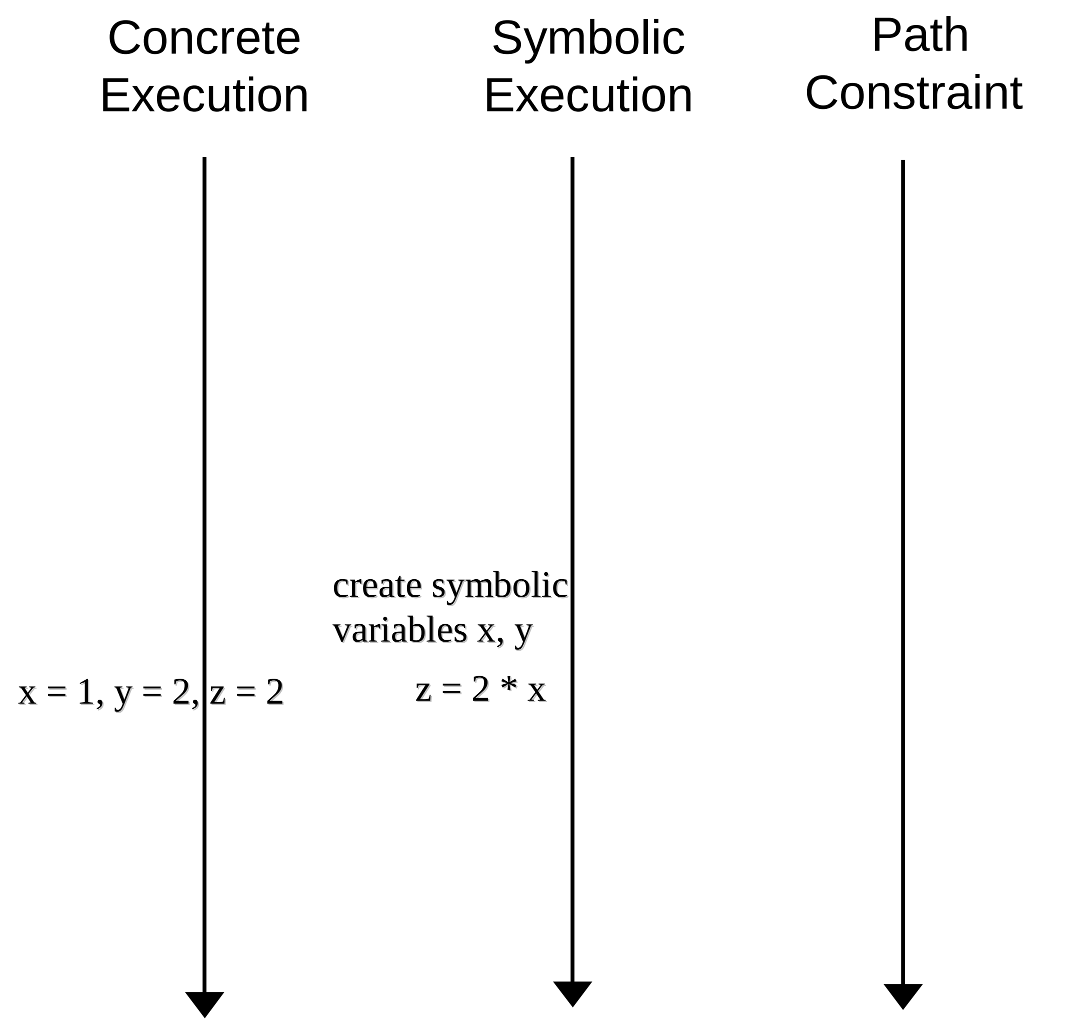

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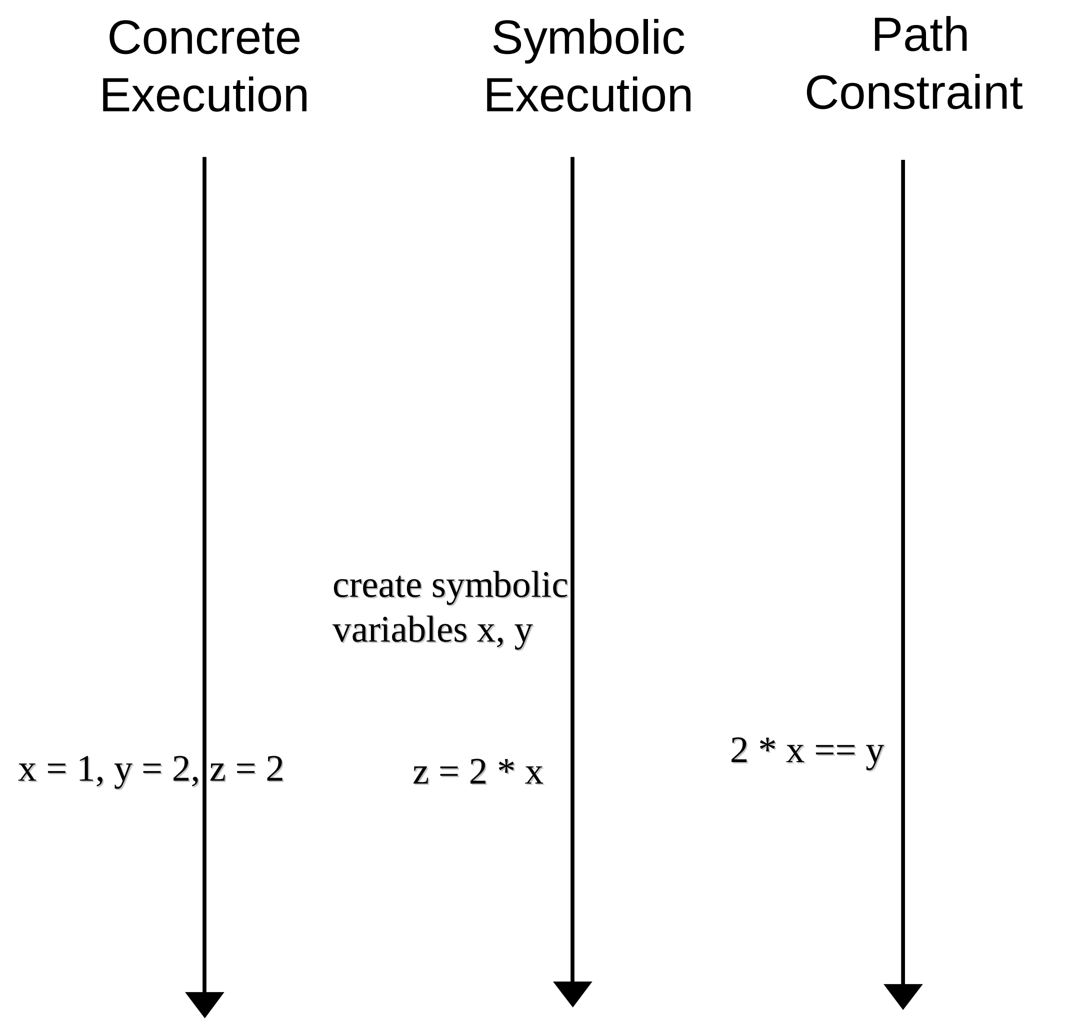

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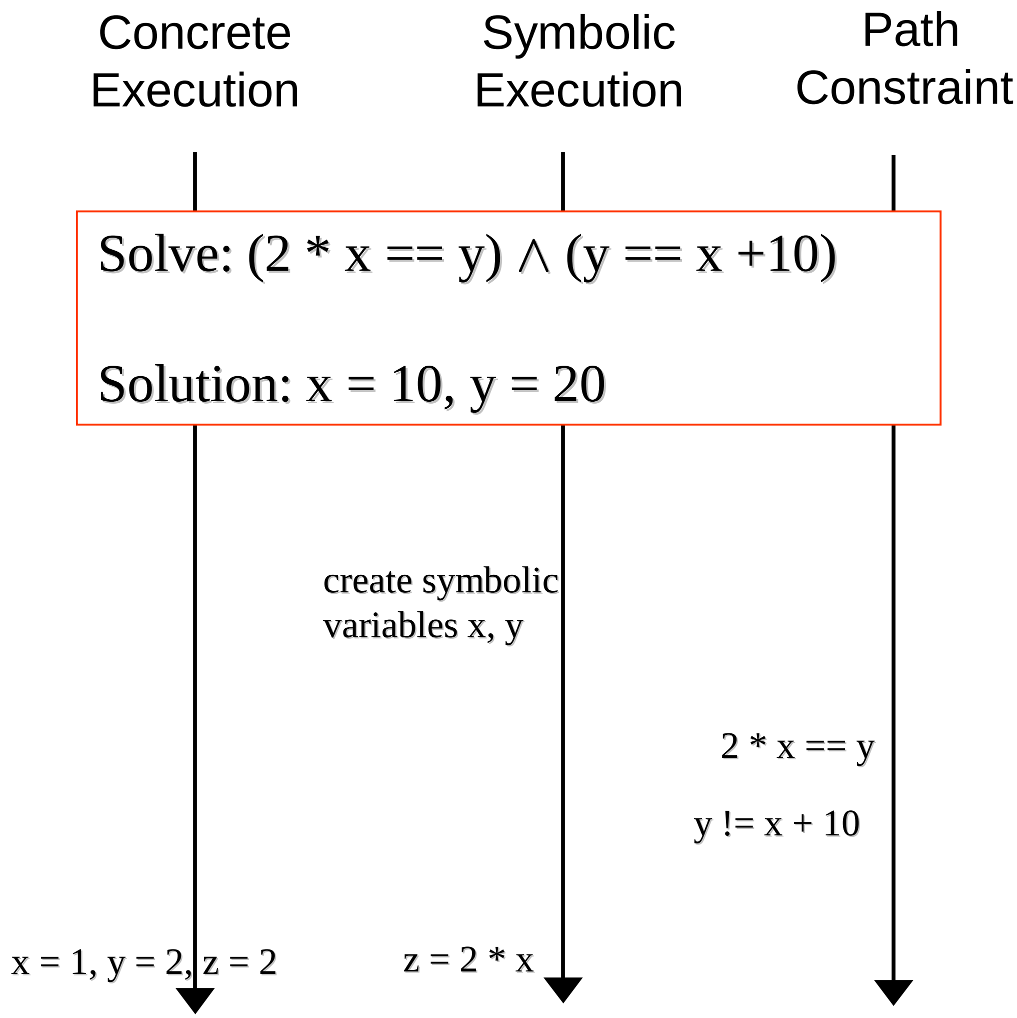

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      if (y == x+10)
          abort(); /* error */
  }
}
```

Concrete Execution	Symbolic Execution	Path Constraint
x = 10, y = 20	create symbolic variables x, y	

DART Step (3): Directed Search

```
main(){
    int t1 = randomInt();
    int t2 = randomInt();
    test_me(t1,t2);
}
int double(int x) {return 2 * x; }

void test_me(int x, int y) {
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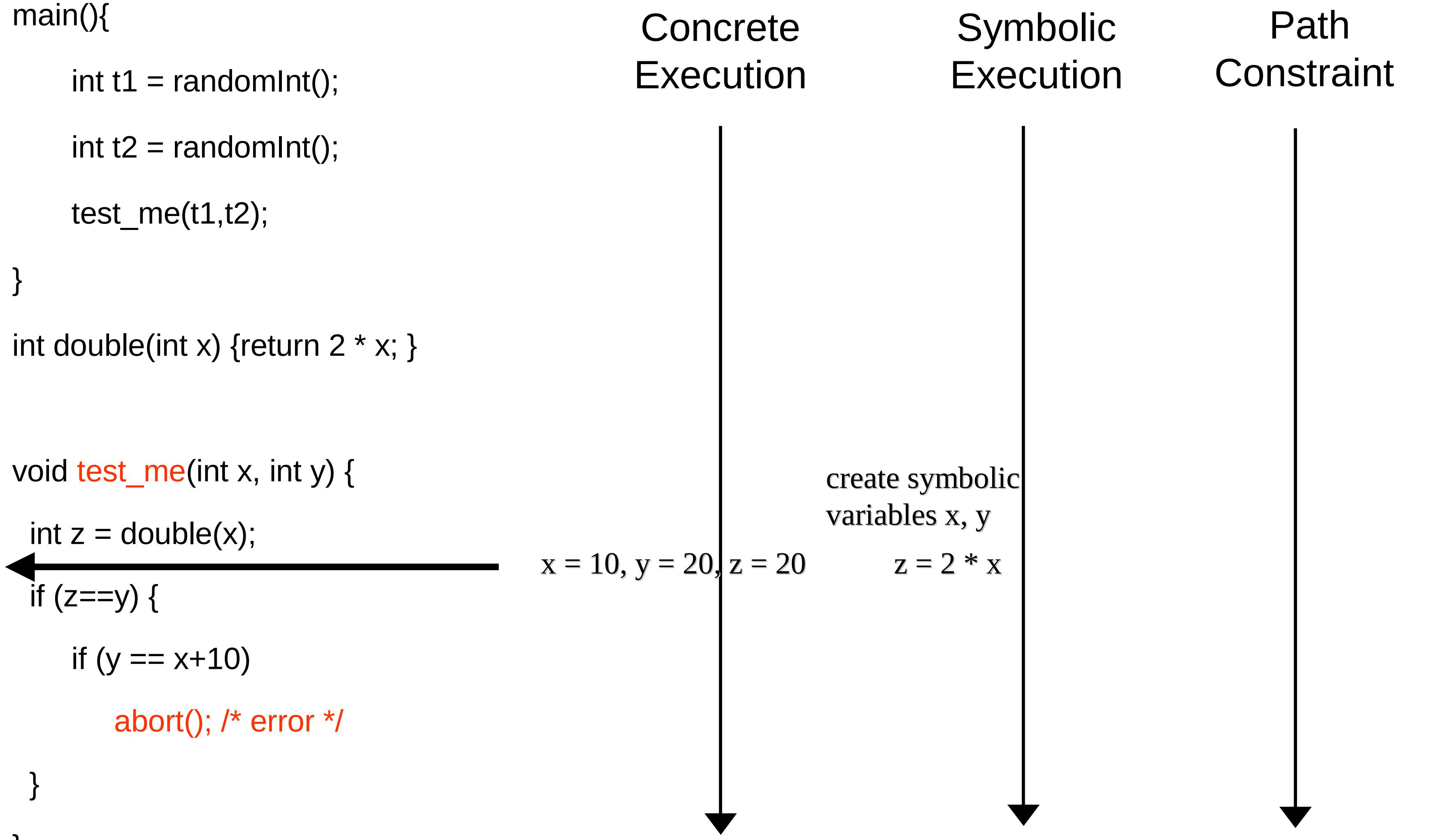

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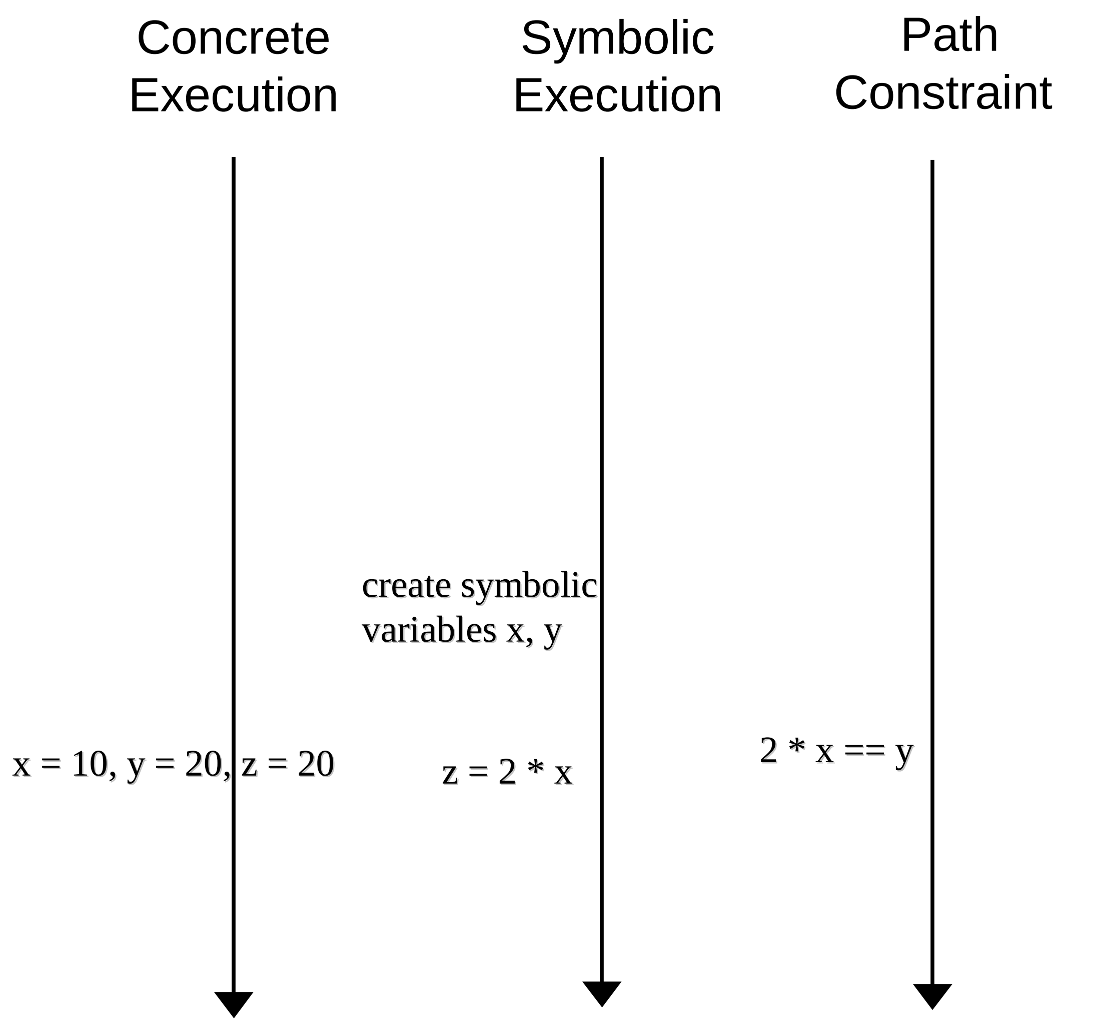

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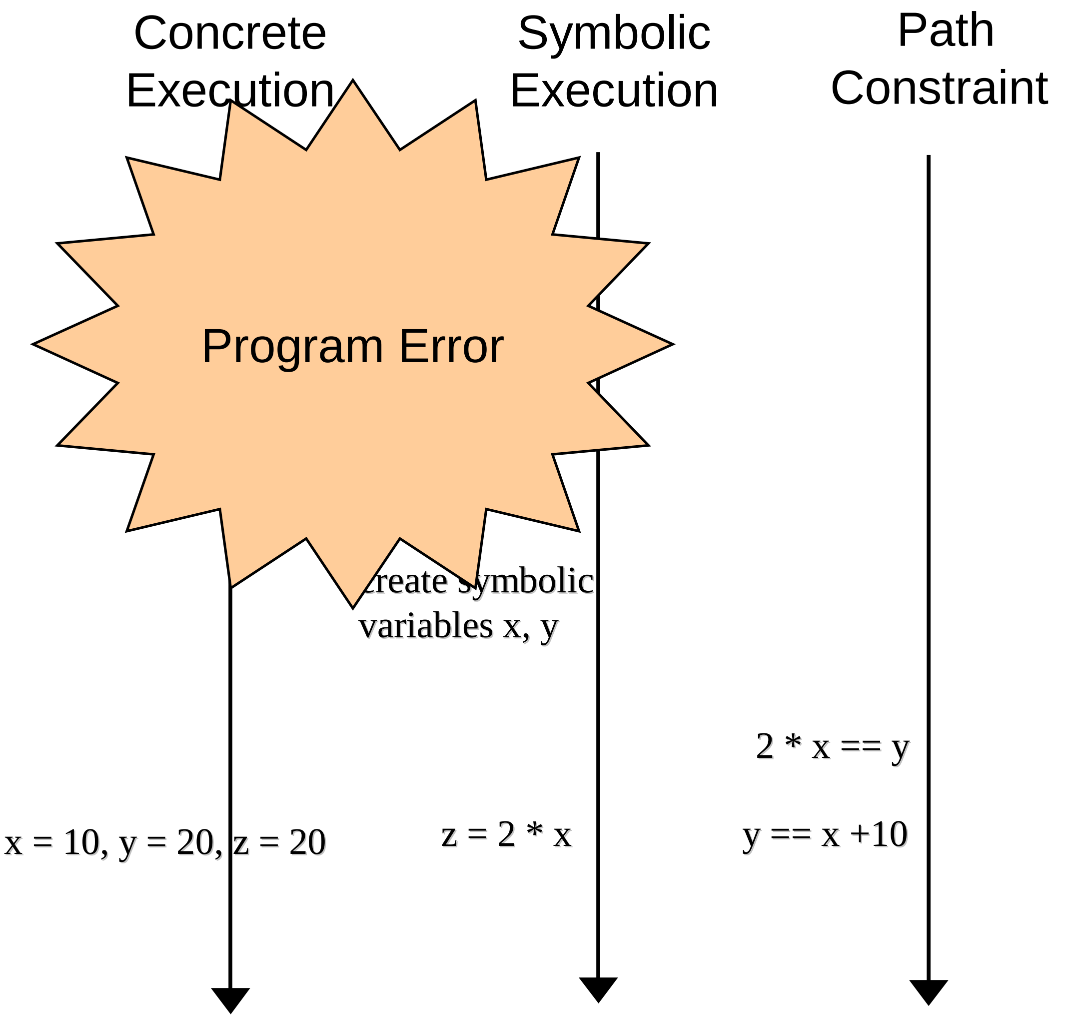


Directed Search: Summary

- Dynamic test generation to direct executions along alternative program paths
  - collect symbolic constraints at branch points (whenever possible)
  - negate one constraint at a branch point to take other branch (say b)
  - call constraint solver with new path constraint to generate new test inputs
  - next execution driven by these new test inputs to take alternative branch b
  - check with dynamic instrumentation that branch b is indeed taken
- Repeat this process until all execution paths are covered
  - May never terminate!
- Significantly improves code coverage vs. pure random testing

Novelty: Simultaneous Concrete & Symbolic Executions

```
void foo(int x,int y){
    int z = x*x*x; /* could be z = h(x) */
    if (z == y) {
        abort(); /* error */
    }
}
```

- Assume we can reason about linear constraints only
- Initially x = 3 and y = 7 (randomly generated)
- Concrete z = 27, but symbolic z = x*x*x
  - Cannot handle symbolic value of z!
  - Stuck?

Novelty: Simultaneous Concrete & Symbolic Executions

```
void foo(int x,int y){
    int z = x*x*x; /* could be z = h(x) */
    if (z == y) {
        abort(); /* error */
    }
}
```

Replace symbolic expression by concrete value when symbolic expression becomes unmanageable (e.g. non-linear)

NOTE: whenever symbolic execution is stuck, static analysis becomes imprecise!

- Assume we can reason about linear constraints only
- Initially x = 3 and y = 7 (randomly generated)
- Concrete z = 27, but symbolic z = x*x*x
  - Cannot handle symbolic value of z!
  - Stuck?
  - NO! Use concrete value z = 27 and proceed…
- Take else branch with constraint 27 != y
- Solve 27 = y to take then branch
- Execute next run with x = 3 and y = 27
- DART finds the error!

Comparison with Static Analysis

```
1  foobar(int x, int y){
2    if (x*x*x > 0){
3       if (x>0 && y==10){
4           abort(); /* error */
5       }
6    } else {
7       if (x>0 && y==20){
8           abort(); /* error */
9       }
10   }
11 }
```

- Symbolic execution is stuck at line 2…
- Static analysis tools will conclude that both aborts may be reachable
  - "Sound" tools will report both, and thus one false alarm
  - "Unsound" tools will report "no bug found", and miss a bug
- Static-analysis-based test generation techniques are also helpless here…
- In contrast, DART finds the only error (line 4) with high probability
- Unlike static analysis, all bugs reported by DART are guaranteed to be sound

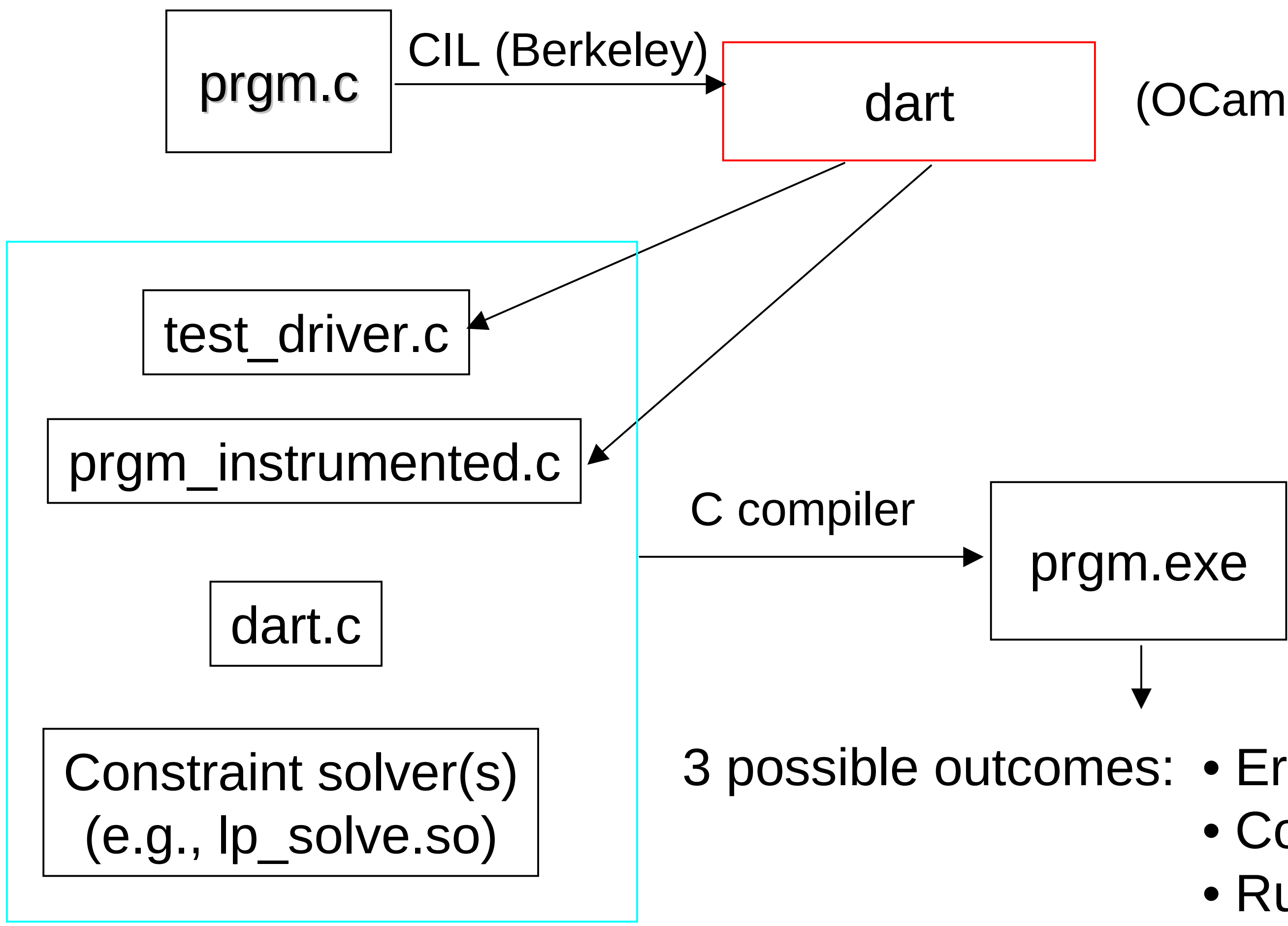
Other Advantages of Dynamic Analysis

```
struct foo { int i; char c; }

bar (struct foo *a) {
    if (a->c == 0) {
        *((char *)a + sizeof(int)) = 1;
        if (a->c != 0) {
            abort();
        }
    }
}
```

- Dealing with dynamic data is easier with concrete executions
- Due to limitations of alias analysis, static analysis tools cannot determine whether “a->c” has been rewritten
  - “the abort may be reachable”
- In contrast, DART finds the error easily (by solving the linear constraint a->c == 0)
- In summary, all bugs reported by DART are guaranteed to be sound!
- But DART may not terminate…

DART for C: Implementation Details



3 possible outcomes:
- Error found
- Complete coverage
- Run forever…

Experiments: NS Authentication Protocol

- Tested a C implementation of a security protocol (Needham-Schroeder) with a known attack
  - About 400 lines of C code; experiments on a Linux 800Mz P-III machine
  - DART takes 57 seconds (9,926 runs) to discover a full attack, with a realistic (Dolev-Yao) intruder model
  - In contrast, VeriSoft could not find this attack in 24 hours (albeit with a different, concurrent and nondeterministic, Dolev-Yao intruder model)
  - Also, the static software model checker BLAST reports a spurious error after 6 minutes of search (due to imprecision of current alias analysis used), and does not find the attack
- DART found a new bug in this C implementation of Lowe's fix to the NS protocol (bug confirmed by the code's author)

A Larger Application: oSIP

- Open Source SIP library (Session Initiation Protocol)
  - 30,000 lines of C code (version 2.0.9), 600 externally visible functions
- Results:
  - DART crashed 65% of the externally visible functions within 1000 runs
  - Most of these due to missing(?) NULL-checks for pointers…
  - Analysis of results for oSIP parser revealed a simple attack to crash it!

Attack: send a packet of size 2.5 MB (cygwin) with no 0 or "|" character

oSIP version 2.0.9 (August 2004)

```
Int osip_message_parse (osip_message_t * sip,
                        const char *buf)
{ [ … ]
  char *tmp;
  tmp = alloca (strlen (buf) + 2);
  osip_strncpy (tmp, buf, strlen (buf));
  osip_util_replace_all_lws (tmp);
[ etc. ]
```

alloca fails and returns NULL

crash!

oSIP version 2.2.0 (December 2004)

```
Int osip_message_parse (osip_message_t * sip,
                        const char *buf, size_t length)
{ [ … ]
  char *tmp;
  tmp = osip_malloc (length + 2);
  if (tmp==NULL) { [… print error msg and return –1; ] }
  osip_strncpy (tmp, buf, length);
  osip_util_replace_all_lws (tmp);
  [ etc. ]
```

Related Work

- Static analysis and automatic test generation based on static analysis: limited by symbolic execution technology (see previous discussion)

- Random testing (fuzz tools, etc.): poor coverage

- Dynamic test generation (Korel, Gupta-Mathur-Soffa, etc.)
  - Attempt to exercise a specific program path
  - DART attempts to cover all executable program paths instead (like model checking)
  - Also, DART handles function calls, unknown functions, exploits simultaneous concrete and symbolic executions, is sometimes complete (verification) and has run-time checks to detect incompleteness;
    DART has been implemented for C and applied to large examples

- The DART approach (idea, formalization, tool architecture) is independent of specific constraint types or solvers; those params define DART implementations
  - Ex: DART implementation with pointer in-/equality constraints [Sen et al., FSE'05]

- Independent, closely related work on directed search [Cadar-Engler, SPIN'05]

Future Work: Short Term (See IFM'05 Paper)

- Faster constraint solvers
  - Ex: DART on NS with conjunctions only (1) or with disjunctions (2)

depth	error?	Implementation 1	Implementation 2
1	no	5 runs (<1 second)	4 runs (<1 second)
2	no	85 runs (<1 second)	30 runs (<1 second)
3	no	6,260 runs (22 seconds)	554 runs (<1 second)
4	yes	328,459 runs (18 minutes)	9,926 runs (57 seconds)

- More constraint types and decision procedures
  - for pointers, arrays, strings, bit-vectors, etc. (default: random testing)
- Concurrency
  - Scheduling nondeterminism is orthogonal to input data nondeterminism
  - Use partial-order reduction for concurrency (multi-threaded/process)

Future Work: Longer Term (See IFM’05 Paper)

- Combining further static and dynamic software model checking
  - Ex: use program slicing to focus dynamic search towards specific code
  - Ex: use DART as a subroutine to test path feasibility inside static SW MC
- Specifying preconditions (and postconditions)
  - Either using tool-friendly annotations (logic) or input-filtering code
  - How to interpret code as precisely as if specified directly into logic?
  - We need “constraint inference” capabilities…
- Scalability
  - Ex: like static analysis, testing could also be done compositionally
    - When testing f(g(x)), g() could be summarized when testing f(), using pre/post condition constraints as done for interprocedural static analysis

Conclusions

- Past: two complementary approaches to software model checking
  - Dynamic Approach: Systematic Testing (Ex: VeriSoft)
  - Static Approach: Automatic Abstraction (Ex: SLAM)
- Future: combine both approaches (Ex: DART)
  - DART = Directed Automated Random Testing
  - No manually-generated test driver required (fully automated)
    - As automated as static analysis but with higher precision
    - Starting point for testing process
  - No false alarms but may not terminate
  - Smarter than pure random testing (with directed search)
  - Can work around limitations of symbolic execution technology
    - Symbolic execution is an adjunct to concrete execution
    - Randomization helps where automated reasoning is difficult
- Still plenty of work to do before “software model checking for the masses” !