Introduction to Static Analysis for Assurance

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Overview

- What is static analysis?
- Examples of some techniques
- Tradeoffs
- Commercial static analyzers
- Use in Assurance

What Does This Program Do?

- Context: we have developed a program and want some evidence about what it does and doesn't do
- I'll call it a program, even though it's probably an embedded system with multiple software components
  - That makes use of systems software and libraries
  - And interacts with hardware

  We'll come to these complexities later
- Evidence is a pretty strong notion: intended for assurance
  - Never does certain things
    - ⋆ e.g., a runtime exception
  - Always does a certain thing
    - ⋆ e.g., delivers a good value to the actuator

  Weaker notions can be useful for bug finding

Evidence About Program Behavior

- One approach is testing
- We generate many tests and observe the program in execution
  - We are looking at the real thing—that's good
  - But how can we get evidence for always and never?
  - Usually some notion of coverage, but it falls short of evidence
- Let's look at an example

The Bug That Stopped The Zunes

Real time clock sets `days` to number of days since 1 Jan 1980

```
year = ORIGINYEAR; /* = 1980 */

while (days > 365) {
    if (IsLeapYear(year)) {
        if (days > 366) {
            days -= 366;
            year += 1;
        } else... loops forever on last day of a leap year
    } else {
        days -= 365;
        year += 1;
    }
}
```

Coverage-based testing will find this

A Hasty Fix

```
while (days > 365) {
    if (IsLeapYear(year)) {
        if (days > 365) {
            days -= 366;
            year += 1;
        }
    } else {
        days -= 365;
        year += 1;
    }
}
```

- Fixes the loop but now `days` can end up as zero
- Coverage-based testing might not find this
- Boundary condition testing would
- But I think the point is clear. . .

The Problem With Testing

- Is that it only samples the set of possible behaviors
- And unlike physical systems (where many engineers gained their experience), software systems are discontinuous
- There is no sound basis for extrapolating from tested to untested cases
- So we need to consider all possible cases. . . how is this possible?
- It's possible with symbolic methods
- Cf. $x^2 - y^2 = (x - y)(x + y)$ vs. `5*5-3*3 = (5-3)*(5+3)`
- Static Analysis is about totally automated ways to do this

The Zune Example Again

```
[days > 0]
while (days > 365) {        [days > 365]
    if (*)) {
        if (days > 365) {   [days > 365]
            days -= 366;    [days >= 0]
            year += 1;
        }
    } else {                [days > 365]
        days -= 365;        [days > 0]
        year += 1;
    }
}
[days >= 0 and days <= 365]
```

Approximations

- We were lucky that we could do the previous example with full symbolic arithmetic
- Usually, the formulas get bigger and bigger as we accumulate information from loop iterations (we'll see an example later)
- So it's common to approximate or abstract information to try and keep the formulas manageable
- Here, instead of the natural numbers 0, 1, 2, . . . , we could use
  - `zero, small, big`
  - Where `big` abstracts everything bigger than 365, `small` is everything from 1 to 365, and `zero` is 0
  - Arithmetic becomes nondeterministic
    - ⋆ e.g., `small+small` = `small | big`

The Zune Example Abstracted

```
[days = small | big]
while (days = big) {         [days = big]
    if (*)) {
        if (days = big ) {   [days = big ]
            days -= big;     [days = big | small | zero]
            year += 1;
        }
    } else {                 [days = big]
        days -= small;       [days = big | small]
        year += 1;
    }
}
[days = small | zero]
```

The Zune Example Abstracted Again

Suppose we abstracted to {negative, zero, positive}

```
[days = positive]
while (days = positive) {          [days = positive]
    if (*)) {
        if (days = positive ) {    [days = positive ]
            days -= positive;      [days = negative | zero | positive]
            year += 1;
        }
    } else {                       [days = positive]
        days -= positive;          [days = negative | zero | positive]
        year += 1;
}   }
[days = negative | zero]
```

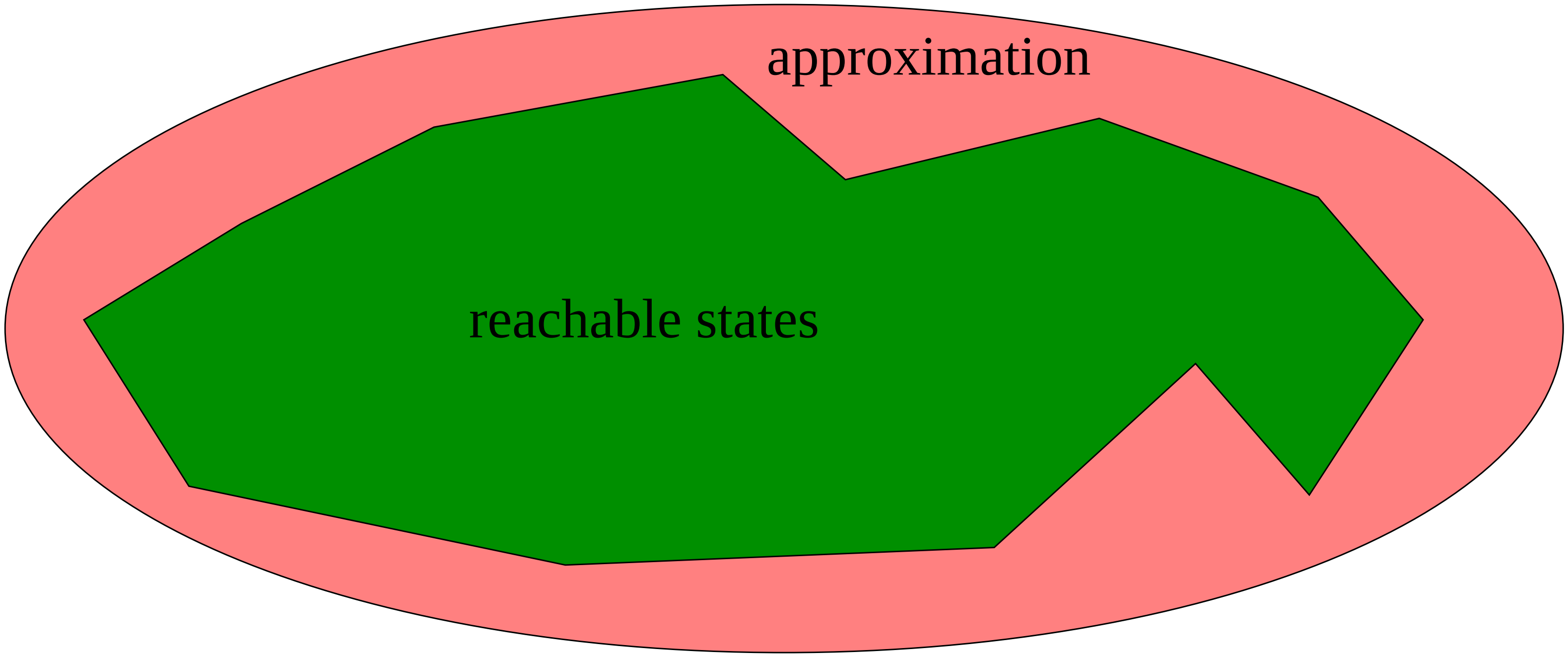
We've lost too much information: have a false alarm that `days` can go negative (pointer analysis is sometimes this crude)

We Have To Approximate, But There's A Price

- It's no accident that we sometimes lose precision
- Rice's Theorem says there are inherent limits on what can be accomplished by automated analysis of programs
  - Sound (miss no errors)
  - Complete (no false alarms)
  - Automatic
  - Allow arbitrary (unbounded) memory structures
  - Final results

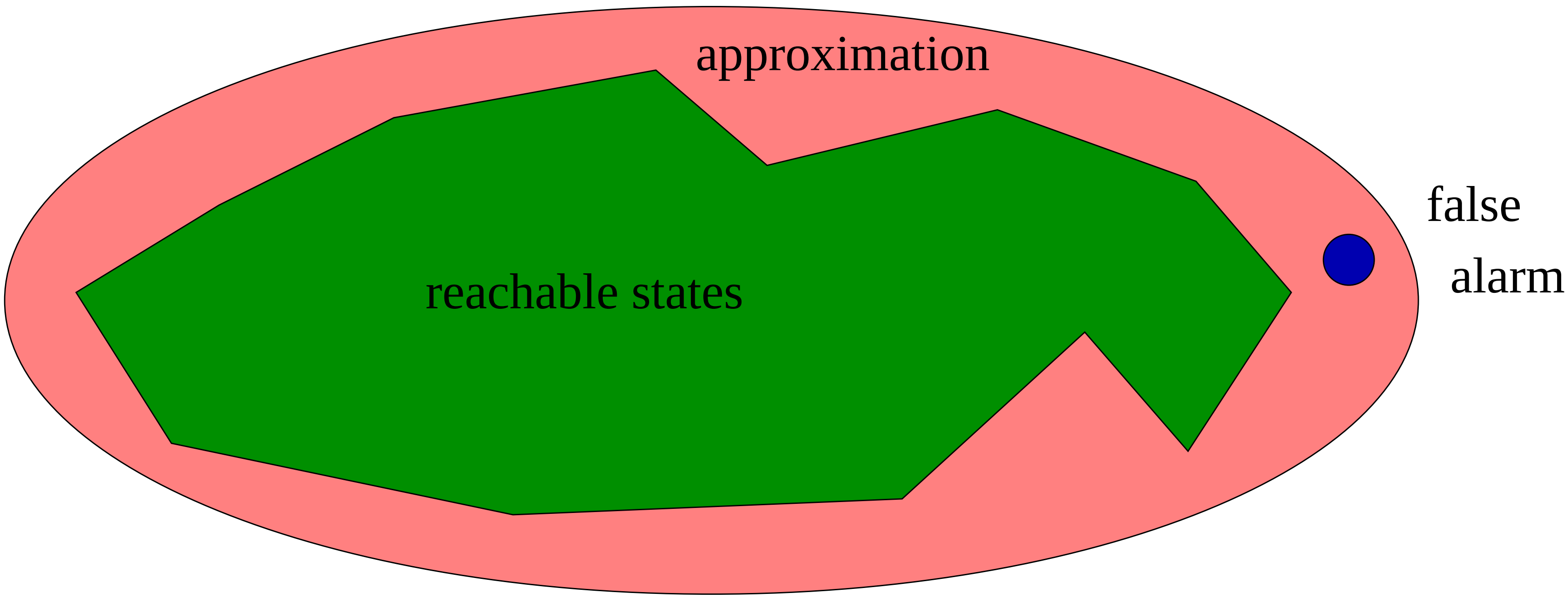
  Choose at most 4 of the 5

Approximations



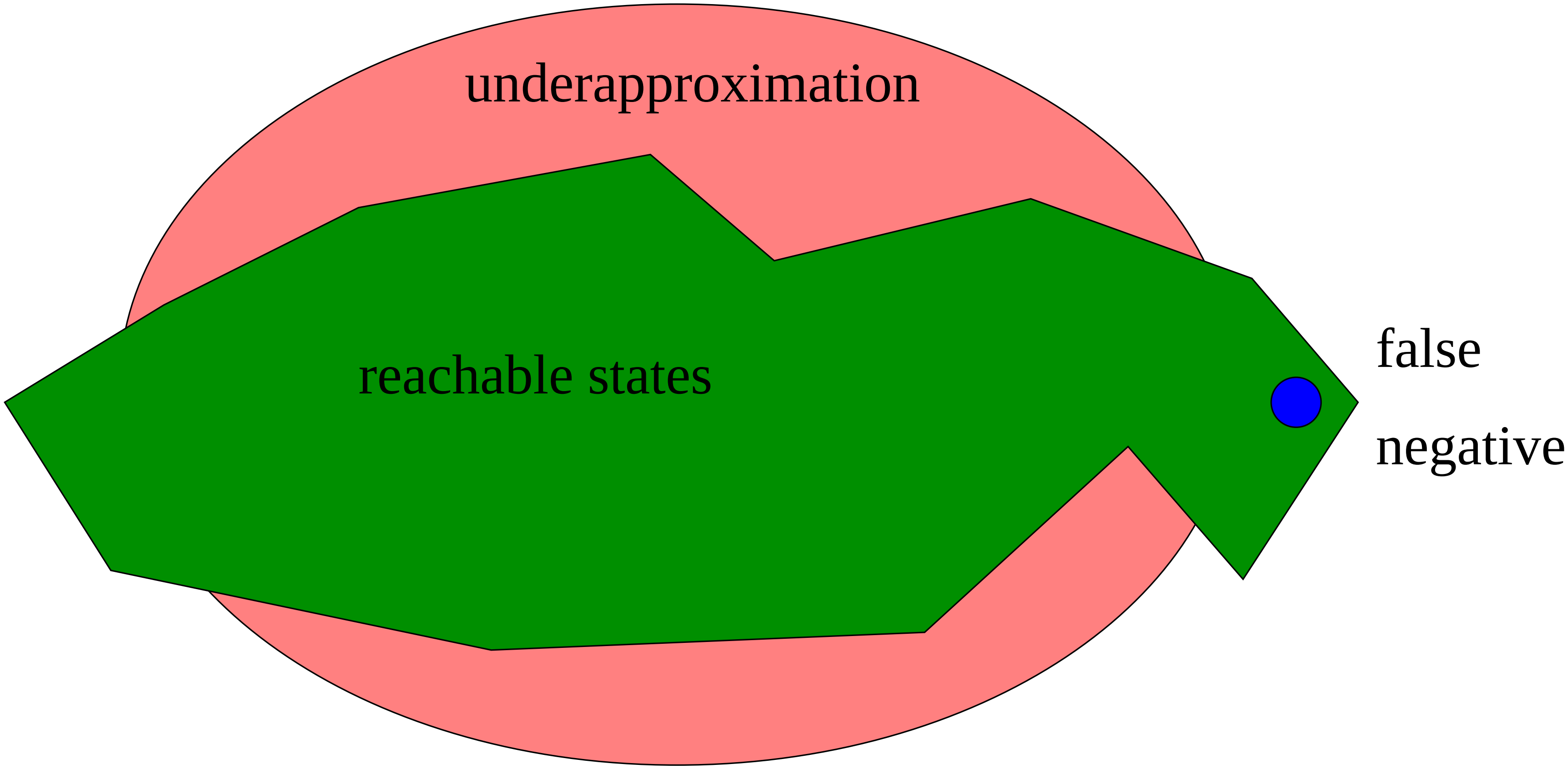
Sound approximations include all the behaviors and reachable states of the real system, but are easier to compute

But Sound Approximations Come with a Price



May flag an error that is unreachable in the real system: a false positive, or false alarm

Unsound Approximations Come with a Price, Too



Can miss real errors: a false negative

Predicate Abstraction

- The Zune example used data abstraction
    - A kind of abstract interpretation
- Replaces variables of complex data types by simpler (often finite) ones
    - e.g., integers replaced by {`negative`, `zero`, `positive`}
- But sometimes this doesn't work
    - Just replaces individual variables
    - Often its the relationship between variables that matters
- Predicate abstraction replaces some relationships (predicates) by Boolean variables

Another Example

```
start with r unlocked
do {
  lock(r)
  old = new
  if (*) {
    unlock(r)
    new++
  }
}
while old != new
want r to be locked at this point
unlock(r)
```

Abstracted Example

The significant relationship seems to be `old == new`

Replace this by `eq`, throw away `old` and `new`

```
[!locked]
do {
  lock(r)       [locked]
  eq = true     [locked, eq]
  if (*) {
    unlock(r)   [!locked, eq]
    eq = false [!locked, !eq]
  }
}  [locked, eq] or [!locked, !eq]
while not eq
[locked, eq]
unlock(r)
```

Yet Another Example

```
z := n; x := 0; y := 0;
while (z > 0) {
  if (*) {
     x := x+1;
     z := z-1;
  } else {
     y := y+1;
     z := z-1;
  }
}
want y!= 0, given x != z, n > 0
```

- The invariant needed is `x + y + z = n`
- But neither this nor its fragments appear in the program or the desired property

Let's Just Go Ahead

First time into the loop

```
[n > 0]

z := n; x := 0; y := 0;

while (z > 0) {    [x = 0, y = 0, z = n]

  if (*) {

     x := x+1;

     z := z-1;     [x = 1, y = 0, z = n-1]

  } else {

     y := y+1;

     z := z-1;     [x = 0, y = 1, z = n-1]

  } [x = 1, y = 0, z = n-1] or [x = 0, y = 1, z = n-1]

}
```

Next time around the loop we'll have 4 disjuncts, then 8, then 16, and so on

This won't get us anywhere useful

Widening the Abstraction

- We could try eliminate disjuncts
- Look for a conjunction that is implied by each of the disjuncts
- One such is [x+y = 1, z = n-1]
- Then we'd need to do the same thing with [x+y = 1, z = n-1] or [x = 0, y = 0, z = n]
- That gives [x + y + z = n]
- There are techniques that can do this automatically
- This is where a lot of the research action is

Tradeoffs

- We're trying to guarantee absence of errors in a certain class
- Equivalently, trying to verify properties of a certain class
- Terminology is in terms of finding errors

  TP True Positive: found a real error

  FP False Positive: false alarm

  TN True Negative: no error, no alarm—OK

  FN False Negative: missed error
- Then we have

  Sound: no false negatives

  Recall: `TP/(TP+FN)` measures how (un)sound

  `TP+FN` is number of real errors

  Complete: no false alarms

  Precision: `TP/(TP+FP)` measures how (in)complete

  `TP+FP` is number of alarms

Tradeoff Space

- Basic tradeoff is between soundness and completeness
- For assurance, we need soundness
  - When told there are no errors, there must be none

  So have to accept false alarms
- But the main market for static analysis is bug finding in general-purpose software, where they aim merely to reduce the number of bugs, not to eliminate them
- Their general customers will not tolerate many false alarms, so tool vendors give up soundness
- Will consider the implications later
- Other tradeoffs are possible
  - Give up full automation: e.g., require user annotation

Tradeoffs In Practice

Testing is complete but unsound

Spark Ada with its Examiner is sound but not fully automatic

Abstract Interpretation (e.g., PolySpace) is sound but incomplete, and may not terminate

- Astrée is pragmatically complete for its domain

Pattern matchers (e.g. Lint, Findbugs) are not based on semantics of program execution, neither sound nor complete

- But pragmatically effective for bug finding

Commercial tools (e.g., Coverity, Code Sonar, Fortify, KlocWork, LDRA) are neither sound nor complete

- Pragmatically effective
- Different tools use different methods, have different capabilities, make different tradeoffs

Properties Checked

- The properties checked are usually implicit
  - e.g., uninitialized variables, divide by zero (and other exceptions), null pointer dereference, buffer overrun
- Much of this is compensating for deficiencies of C and C++
  - Some tools support Ada, Java, not much for MBD
  - But Mathworks has Design Verifier for Simulink
- Some tools support user-specified checks, but. . .
- Some tools look at resources
  - e.g., memory leaks, locks (not freed, freed twice, use after free)
- Some (e.g., AbsInt) can do quantitative analysis
  - e.g., worst case execution time, maximum stack height

Real Software

- It's not enough to check individual programs
- Need information from calls to procedures, subroutines
  - Analyze each in isolation, then produce a procedure summary for use by others
- Need summaries for libraries, operating system calls
- Analyzer must integrate with the build process
- Must present the information in a useful and attractive way
- Much of the engineering in commercial tools goes here

So How Good Are Static Analyzers?

- Some tool licences forbid benchmarking
- Hard to get representative examples
- NIST SAMATE study compared several
  - Found all had strengths and weaknesses
  - Needed a combination to get comprehensive bug detection
- This was bug finding, not assurance
- Anecdotal evidence is they are very useful for general QA
- Need to be tuned to individual environment
- e.g., Astrée tuned to Airbus A380 SCADE-generated digital filters is sound and pragmatically complete
- There are papers by Raoul Jetley and others of FDA applying tools to medical device software

Possible Futures: Combination With Testing

- Automated test generation is getting pretty good
- Use a constraint solver to find a witness to the path predicate leading to a given state
  - e.g., counterexamples from (infinite) bounded model checking using SMT solvers
- So try to see if you can generate an explicit test case to manifest a real bug for each positive turned up by static analysis
- Throw away those you cannot manifest
- Aha! Next generation of tools do this

Possible Futures: Integration With Testing

- Knowledge that possible error is unreachable is information that helps refine the abstraction
- So iterate abstraction, analysis, test generation
- Either finds error or proves its absence
- Microsoft India projects (Synergy, Dash, Yogi) explore this area
- Counterexample Guided Abstraction Refinement (CEGAR) is similar

Use in Assurance

- If you are satisfied with bug finding for standard properties
- Then one or more commercial static analyzers could do a good job for you
- If you want your own properties, talk with the vendors
- If you want soundness
  - PolySpace might work, or Simulink Design Verifier
  - Talk with the vendors (some have a "dial")
  - Roll your own

Combined Methods

- Can think of static analysis as a search for invariants
- Other tools (e.g., model checkers) can use the invariants
- The more invariants and the stronger invariants you know, the more you can verify
- Different analyzers find different (classes of) invariants
- But the tools do not disclose the invariants they find
- Cooperation would be good: an invariant bus
- There are other ways to search for candidate invariants
  - Dynamic analysis: e.g., Daikon
- Could then use static analysis to confirm these

Rolling Your Own

- There's plenty of promising research technology around
- But engineering it into an effective toolchain is a big investment
- Because of the fundamental limitations, don't expect a single solution
  - Future tools should support plugins, toolbus integrations
- Maybe collaborate with a research group

Combined Arguments for Assurance

- Remember: static code analysis is just for code defects; says nothing about whether code meets requirements
- Standards vs. argument-based safety/assurance cases
- Multi-legged arguments
  - e.g., static analysis plus testing
  - Bayesian Belief Nets (BBNs)
- Backups and monitors
  - A formally verified backup or monitor can support a claim of possible perfection (e.g., 0.999 perfection)
  - This is conditionally independent of the reliability claim for the main system (e.g., 0.999 reliable)
  - Can multiply these together: system reliability 0.999999

The End