Dynamic Analysis

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Small change in plans

- Today: we'll talk about dynamic analysis
  - Homework 1 is posted, due March 2
- Thursday: Guest lecture
- Next Tuesday: Guest lecture
- Next Thursday:
  Finish up the overview of the class topics

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Homework 1

- Posted (already) on class website
- Due Tuesday Mar 2, 9 AM on gradescope
- On dynamic analysis (today's topic)
- Install and use an open-source tool: Daikon
- Add a very useful tool to your toolbox
- Understand how dynamic analysis works

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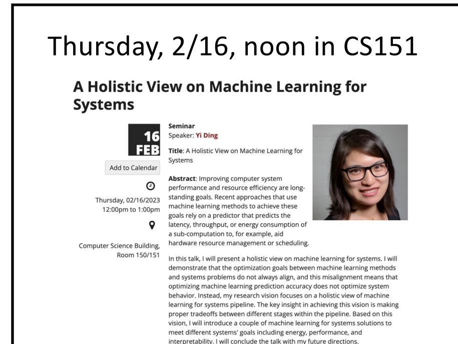

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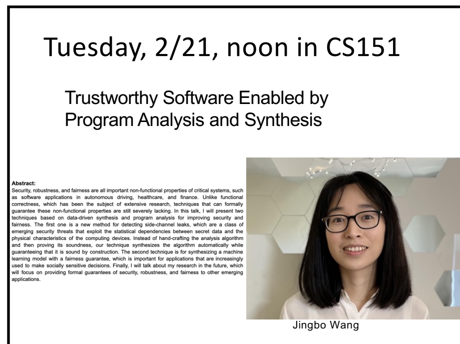

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Any questions?

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Today's plan

- Runtime monitoring
  - Rational Purify
- Dynamic invariant detection
  - Daikon

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Rational Purify

- UNICOM
  - first Rational, then bought by IBM, then sold to UNICOM
- Memory debugging
  - uninitialized memory access
  - buffer overflow
  - improper freeing of memory
- Memory leak detection
  - memory blocks that no longer have a valid pointer

https://teamblue.unicomsi.com/products/purifyplus

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The Problem (for Purify to solve)

- C/C++ are not type safe
- The compiler does not enforce type abstractions
- Does the runtime system?
  - no

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Memory

- What happens if we write here?

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The Problem (for Purify to solve)

- C/C++ are not type safe
- The compiler does not enforce type abstractions
- Does the runtime system?
  - no
- Possible to read or write outside of your intended data structure
- ... and many undesirable behaviors

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What can we do?

- Track each memory location
  One of three states:
  - Unallocated: cannot be read or written
  - Allocated but uninitialized: cannot be read
  - Allocated and initialized: can be read or written

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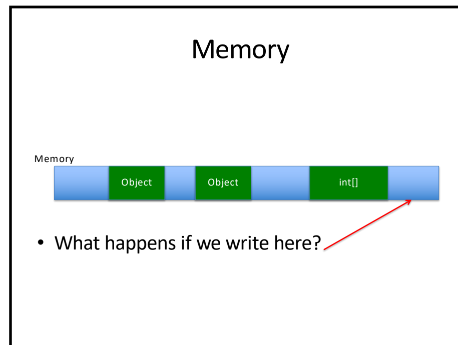

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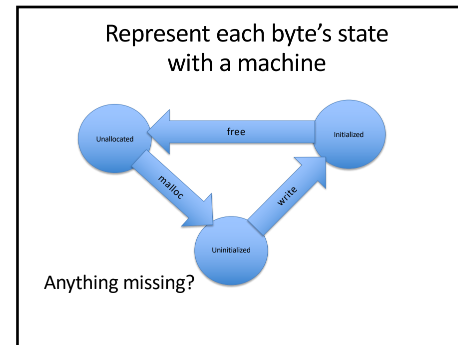

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How do we implement this?

- Keep a machine for each byte
- On each access
  - check the state of each byte
  - update the machine state
- Can instrument the binary (no need for source code)
  - Add code before each load and store
  - Represent the machines as a giant array
    - How many bits needed per byte of system memory?
- What's the overhead?
- Catches byte-level, but not bit-level errors
- Runtime CPU efficiency?
    - very slow, but worth it

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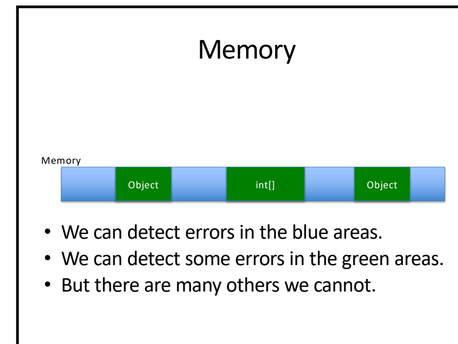

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Can we do better?

- We can detect unallocated or uninitialized accesses.

- Can we force all accesses to be that way?

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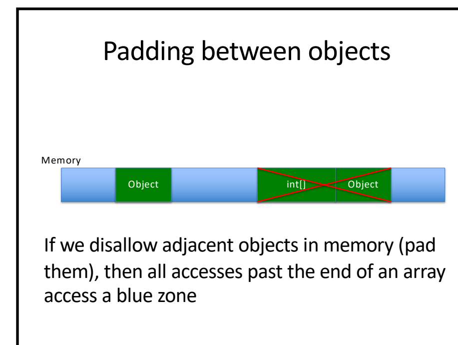

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Let memory age

- Do not allow reallocation of freed memory for some time
- Prevents errors caused by dangling pointers

- Both this and padding can be easily implemented in the malloc library

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Garbage collection

- Instead of bits, keep track of pointers to memory
- When no pointers are left, free the memory

- Where have we seen this before?

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In Practice

- These ideas work pretty well and are widely used.
- Often, it is OK to pay very high performance price to get system correctness.

- Dynamic analysis instruments the program, can maintain properties at runtime.

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Today's plan

- Runtime monitoring
  - Rational Purify

→ Dynamic invariant detection
  - Daikon

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What is a program supposed to do?

- How do we know the program's specification?
- Maybe the developers wrote it down.
  - but often, that has errors

- Without a specification or some way to tell if behavior is correct, we cannot test!

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What is a specification?

- The documentation can be the specification
  - Informal
  - May contain mistakes
  - Can be hard to parse
- The program itself is a specification
  - Testing becomes a tautology
  - But is there some kind of testing this can facilitate?
    - Regression testing
  - Also great for program understanding, reasoning, etc.

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Use the program to find likely invariants

- Hypothesize an invariant
  - for example, `square(x) > 0`
- Run the program on many test inputs
  (without needing to know the outputs)
- If `square(x) > 0` in all the executions, it's a likely invariant.

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Example:

```
funny_sqrt(int x)
  bool positive = (x>0);
  if (positive)
    j = sqrt(x);
  else
    j = sqrt(-x);
  return j;
```

Test for -100 < x < 100

j ≥ 0

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What is an invariant? (j ≥ 0 is)

- Invariants hold at a program point
  - before a statement executes
  - after a statement executes
  - or maybe at all program points
- Invariants cannot reference variables out of scope
  - Is `j < abs(y)`?

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Can executions ever prove a property?

- Can show that a property holds in many executions.
- But can this method show that a property always holds?
- What can executions prove?
  - They can disprove invariants by finding an execution in which an invariant fails.

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Example: Is j always 0?

```
funny_sqrt(int x)
  bool positive = (x>0);
  if (positive)
    j = sqrt(x);
  else
    j = sqrt(-x);
  return j;
```

Test for -100 < x < 100

No, when x is -100, j is 10.

j can be between 0 and 10

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How do we know if an invariant is likely?

Thesis:

Hypothesize i is an invariant at a program point. If many test cases do not disprove the hypothesis, conclude that i likely is an invariant.

This doesn't quite work…

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Example:

```
funny_sqrt(int x)
  bool positive = (x>0);
  if (positive)
    j = sqrt(x);
  else
    j = sqrt(-x);
  return j;
```

Test for 0 < x < 100

x ≥ j
positive = true

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What went wrong?

- We had many test cases
  none disproved the invariant
- But the hypothesis is not disproved because we didn't even execute the relevant line of code.

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Example:

```
funny_sqrt(int x)
  bool positive = (x>0);
  if (positive)
    j = sqrt(x);
  else
    j = sqrt(-x);
  return j;
```

Test for 0 < x < 100

x ≥ j
positive = true

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Solution: Use statistics!

- An invariant is only likely if
  - the observations do not disprove it

  AND
  - the relevant observations are statistically significant

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How to compute statistical significance?

- For a hypothesized invariant P(x,y)
  What are the chances P(x,y) is satisfied under a random choice of x and y?
- Assume 0 ≤ x, y < 1000

P(x == y) ≈ .001
P(x < y) ≈ .5
P(x != y) ≈ .999

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What to compute

- We want a high confidence that invariants are not observed by chance
- The number of samples we need varies with the invariant
  - predicates have widely varying chances of being accidentally satisfied

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What can we do with unlikely invariants?

- If it is likely that a [non]invariant is an accident, don't report it.
- Give the user control of the confidence threshold.

An invariant may be true, but not be statistically significant when examined under some (all?) test suites.

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Which invariants do we check?

- Given a possible invariant, we can check if it is likely.
- But which possible invariants do we check? How many are there?

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How many are there?

- Ordering relationships over two variables:

$x < y$, $x == y$, $x > y$, $x \leq y$, $x \geq y$, $x \neq y$

- No problem. Just a finite number
  - If a program has n variables, how many possible such relationships are there?

$\Theta(n^2)$

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What about other types?

- $x = c$, for some constant c

many: 2^{64} for ints on a 64-bit machine = 18,446,744,073,709,551,616

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Use the computer for what it's good at

- Guess a HUGE number of possible invariants
- Check them all
- Only those that are likely true will survive
- Computers are great at this!

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So what do we do about the 18,446,744,073,709,551,616 ints?

Possible invariant: $x=c$

- Don't store any at first.
- First time you see x assigned to some c, remember that c.
- Then check if $x=c$ in all later executions.

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For others too

- Same idea for more-complex invariant types:
- For example:

  ax + b = y

- Two observations of (x,y) is sufficient to solve for the only possible (a,b).

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And others still

- We can do:

  min(array)

  max(array)

  sum(array)

  etc.

- These expressions can be like variables:

  x = min(array z)

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Review

- Guess lots of invariants
- Check which ones hold
- Keep statistics to check for statistical significance

Those guesses that survived all the executions and are statistically significant are likely true.

Does not need expected execution outputs

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In practice

- This works!
- Finds interesting invariants for complex programs.
- Gives concise specifications
- Needs fewer executions than you'd think.

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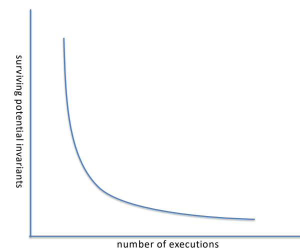
False invariants die quickly



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Daikon

- Implements dynamic invariant detection
- Open source, free to use,
- Highly robust and customizable
- Takes some time to master but very powerful
- You'll see it on homework 1

https://plse.cs.washington.edu/daikon/

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