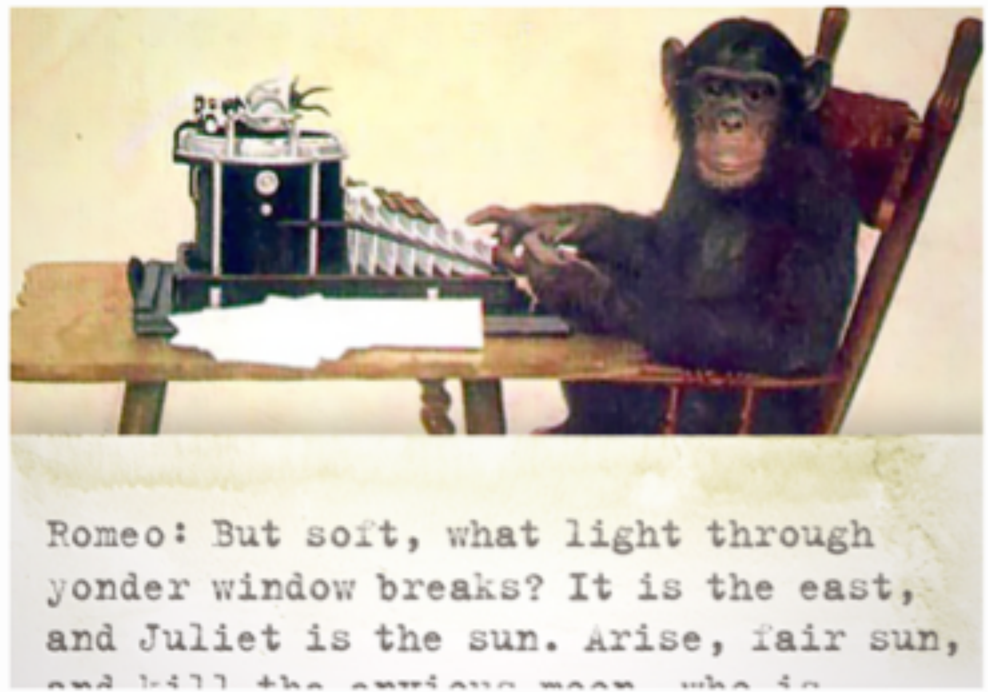
Random Testing (Fuzzing)

- Feed random inputs to a program
- Observe whether it behaves “correctly”
  - Execution satisfies given specification
  - Or just doesn’t crash
    - A simple specification
- Special case of mutation analysis

Random Testing

The Infinite Monkey Theorem

"A monkey hitting keys at random on a typewriter keyboard will produce any given text, such as the complete works of Shakespeare, with probability approaching 1 as time increases."



Random Testing: Case Studies

- UNIX utilities: Univ. of Wisconsin's Fuzz study
- Mobile apps: Google's Monkey tool for Android
- Concurrent programs: Cuzz tool from Microsoft

A Popular Fuzzing Study

- Conducted by Barton Miller @ Univ of Wisconsin
- 1990: Command-line fuzzer, testing reliability of UNIX programs
  - Bombards utilities with random data
- 1995: Expanded to GUI-based programs (X Windows), network protocols, and system library APIs
- Later: Command-line and GUI-based Windows and OS X apps

Fuzzing UNIX Utilities: Aftermath

- 1990: Caused 25-33% of UNIX utility programs to crash (dump state) or hang (loop indefinitely)

- 1995: Systems got better... but not by much!

  "Even worse is that many of the same bugs that we reported in 1990 are still present in the code releases of 1995."

A Silver Lining: Security Bugs

- gets() function in C has no parameter limiting input length

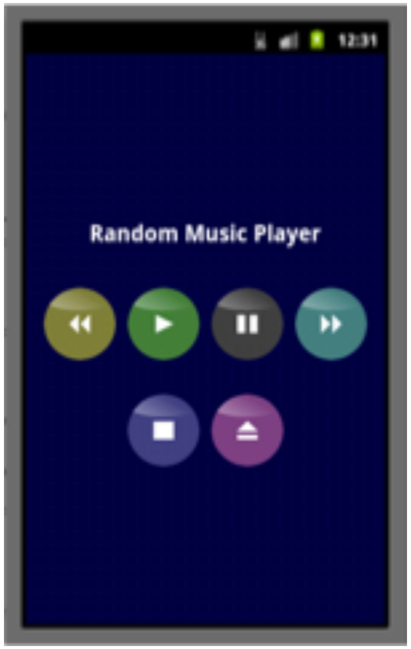
  ⇒ programmer must make assumptions about structure of input

- Causes reliability issues and security breaches
  - Second most common cause of errors in 1995 study

- Solution: Use fgets(), which includes an argument limiting the maximum length of input data

Fuzz Testing for Mobile Apps

```
class MainActivity extends Activity implements
OnClickListener {
   void onCreate(Bundle bundle) {
      Button buttons = new Button[] { play, stop, ... };
      for (Button b : buttons) b.setOnClickListener(this);
   }
   void onClick(View target) {
      switch (target) {
      case play:
         startService(new Intent(ACTION_PLAY));
         break;
      case stop:
         startService(new Intent(ACTION_STOP));
         break;
      ...
   }
}
```

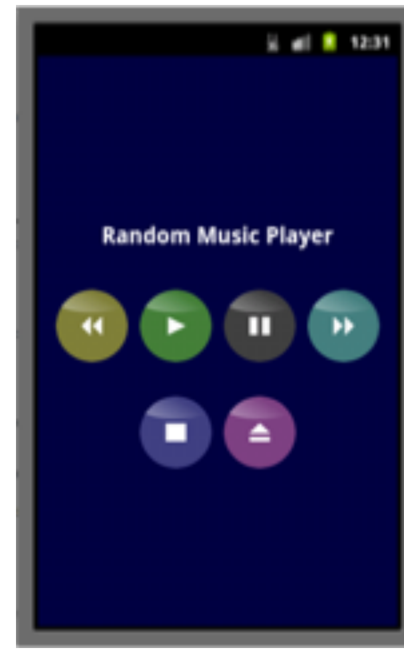


Generating Single-Input Events

```
class MainActivity extends Activity implements
OnClickListener {
   void onCreate(Bundle bundle) {
      Button buttons = new Button[] { play, stop, ... };
      for (Button b : buttons) b.setOnClickListener(this);
   }
   void onClick(View target) {
      switch (target) {
      case play:
         startService(new Intent(ACTION_PLAY));
         break;
      case stop:
         startService(new Intent(ACTION_STOP));
         break;
      ...
   }
}
```

TOUCH(136,351)

TOUCH(136,493)



TOUCH(x, y) where x, y are randomly generated:

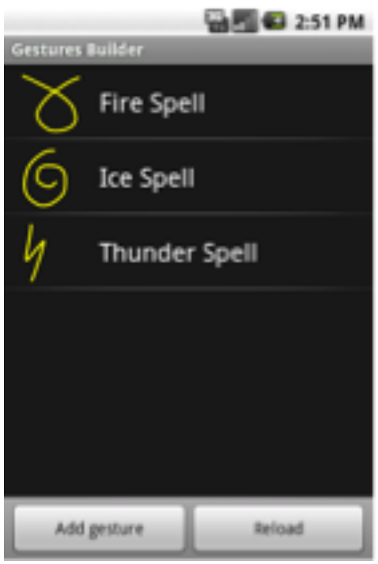
x in [0..480], y in [0..800]

Black-Box vs. White-Box Testing

TOUCH(x1, y1) TOUCH(x2, y2) TOUCH(x3, y3)

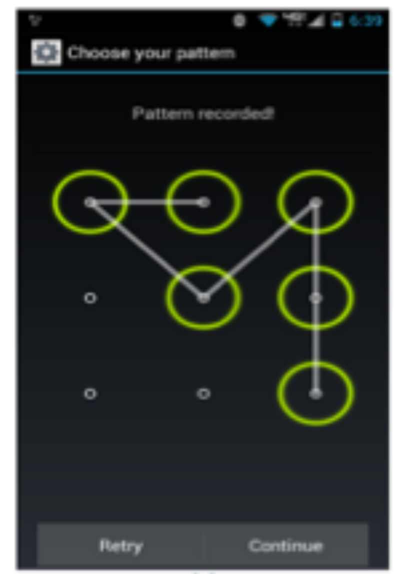
Generating Gestures

`DOWN(x1,y1) MOVE(x2,y2) UP(x2,y2)`



(x1,y1)

(x2,y2)



Grammar of Monkey Events

test_case := *event* *

event := *action* (*x* , *y*) | …

action := **DOWN** | **MOVE** | **UP**

x := **0** | **1** | … | x_limit

y := **0** | **1** | … | y_limit

QUIZ: Monkey Events

Give the correct specification of TOUCH and MOTION events in Monkey's grammar using UP, MOVE, and DOWN statements.

Give the specification of a TOUCH event at pixel (89,215).

Give the specification of a MOTION event from pixel (89,215) to pixel (89,103) to pixel (37,103).

QUIZ: Monkey Events

Give the correct specification of TOUCH and MOTION events in Monkey's grammar using UP, MOVE, and DOWN statements.

Give the specification of a TOUCH event at pixel (89,215).

```
DOWN(89,215) UP(89,215)
```

TOUCH events are a pair of DOWN and UP events at a single place on the screen.

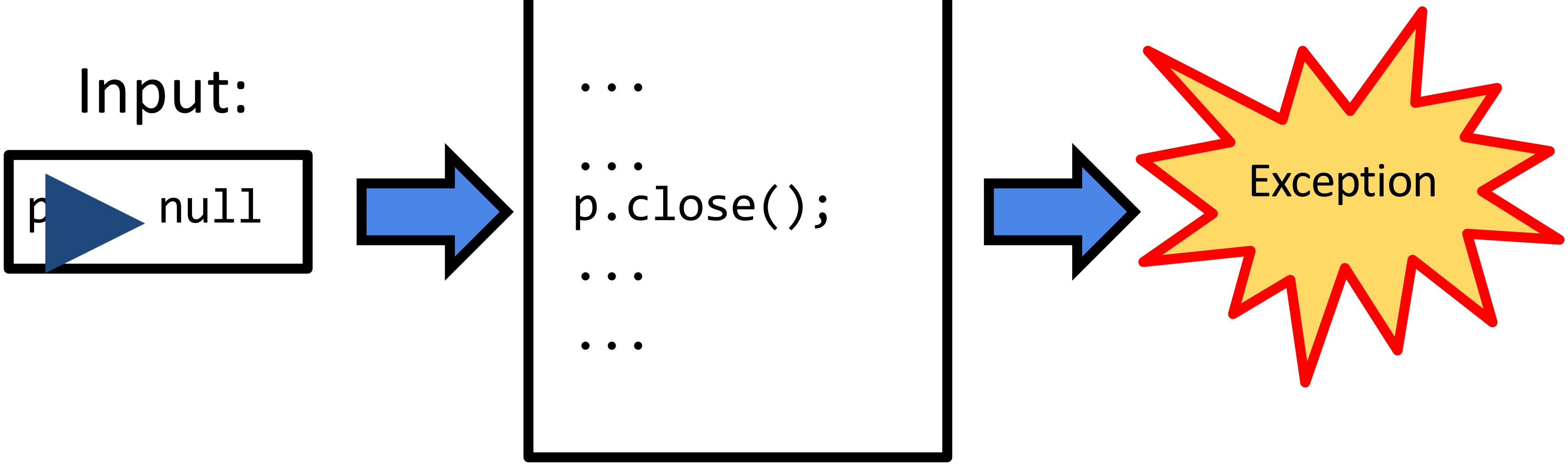
Give the specification of a MOTION event from pixel (89,215) to pixel (89,103) to pixel (37,103).

```
DOWN(89,215) MOVE(89,103)
MOVE(37,103) UP(37,103)
```

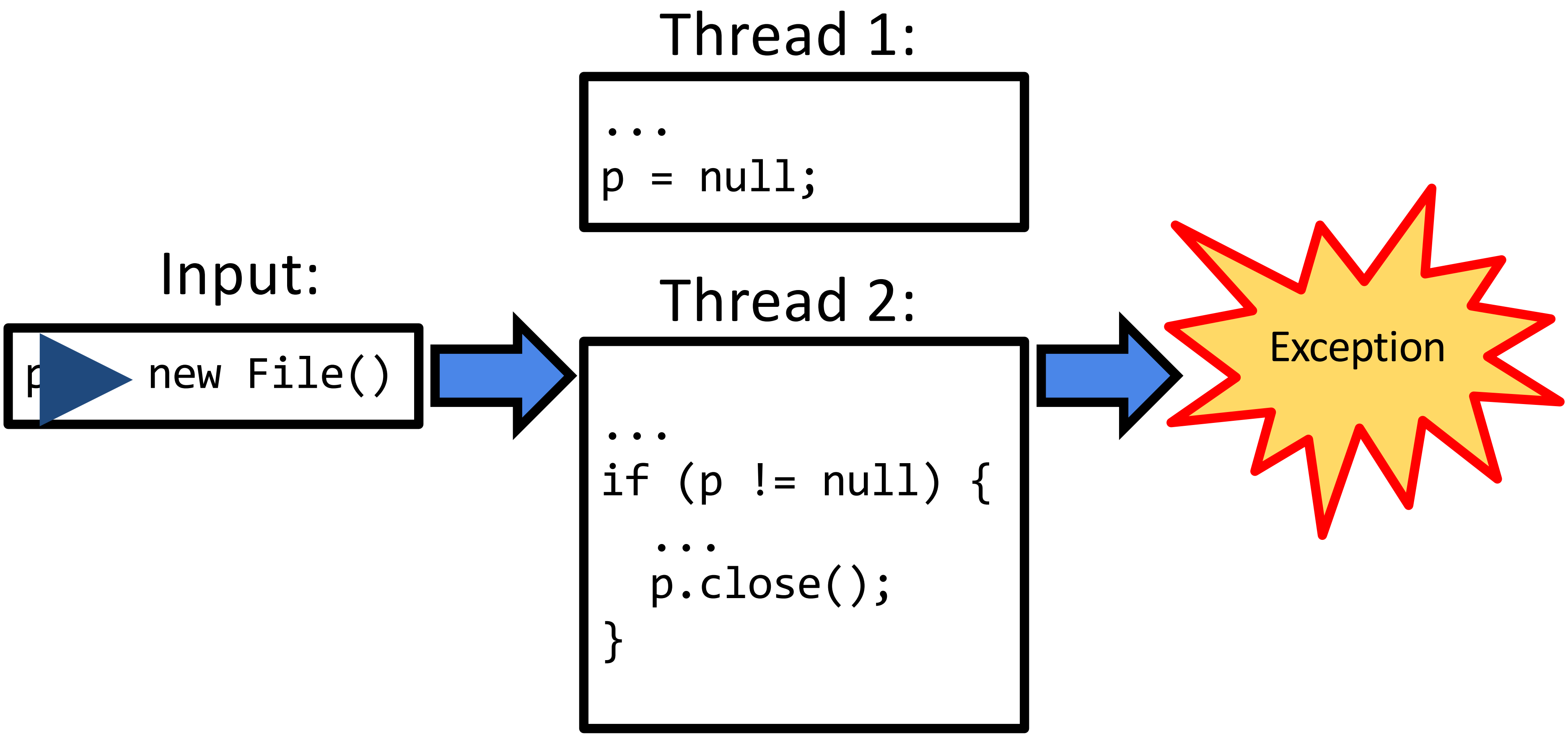
MOTION events consist of a DOWN event somewhere on the screen, a sequence of MOVE events, and an UP event.

Testing Concurrent Programs

Sequential Program:



Testing Concurrent Programs



Concurrency Testing in Practice

Thread 1:

```
Sleep();
p = null;
```

Input:

```
p new File()
```

Thread 2:

```
Sleep();
if (p != null) {
  Sleep();
  p.close();
}
```

Cuzz: Fuzzing Thread Schedules

- Introduces Sleep() calls:
  - Automatically (instead of manually)
  - Systematically before each statement (instead of those chosen by tester)

=> Less tedious, less error-prone

- Gives worst-case probabilistic guarantee on finding bugs

Depth of a Concurrency Bug

- Bug Depth = the number of ordering constraints a schedule has to satisfy to find the bug

Bug Depth: Example 1

- Bug Depth = the number of ordering constraints a schedule has to satisfy to find the bug

Thread 1:

```
...
T t = new T();
...
...
...
```

Thread 2:

```
...
...
if (t.state == 1)
    ...
...
```

Bug Depth: Example 2

- Bug Depth = the number of ordering constraints a schedule has to satisfy to find the bug

Thread 1:

```
...
p = null;
...
```

Thread 2:

```
...
if (p != null) {
   ...
   p.close();
}
```

Depth of a Concurrency Bug

- Bug Depth = the number of ordering constraints a schedule has to satisfy to find the bug

- Observation exploited by Cuzz: bugs typically have small depth

QUIZ: Concurrency Bug Depth

Specify the depth of the concurrency bug in the following example:

Then specify all ordering constraints needed to trigger the bug. Use the notation (x,y) to mean statement x comes before statement y, and separate multiple constraints by a space.

Thread 1:

```
1:  lock(a);
2:  lock(b);
3:  g = g + 1;
4:  unlock(b);
5:  unlock(a);
```

Thread 2:

```
6:  lock(b);
7:  lock(a);
8:  g = 0;
9:  unlock(a);
10: unlock(b);
```

QUIZ: Concurrency Bug Depth

Specify the depth of the concurrency bug in the following example:

2

Then specify all ordering constraints needed to trigger the bug. Use the notation (x,y) to mean statement x comes before statement y, and separate multiple constraints by a space.

(1,7) (6,2)

Thread 1:

```
1:  lock(a);
2:  lock(b);
3:  g = g + 1;
4:  unlock(b);
5:  unlock(a);
```

Thread 2:

```
6:  lock(b);
7:  lock(a);
8:  g = 0;
9:  unlock(a);
10: unlock(b);
```

Cuzz Algorithm

```
Input:
  int n;                  // # of threads
  int k;             // # of steps - guessed from previous runs
  int d;             // target bug depth - randomly chosen
State:
  int pri[] = new int[n];     // thread priorities
  int change[] = new int[d-1];  // when to change priorities
  int stepCnt;                  // current step count
```

```
Initialize() {
  stepCnt = 0;
  a = random_permutation(1,n);
  for (int tid = 0; tid < n; tid++)
    pri[tid] = a[tid] + d;
  for (int i = 0; i < d-1; i++)
    change[i] = rand(1,k);
}
```

```
Sleep(tid) {
  stepCnt++;
  if (stepCnt == change[i] for some i)
    pri[tid] = i;
  while (tid is not highest priority
         enabled thread)
    ;
}
```

Probabilistic Guarantee

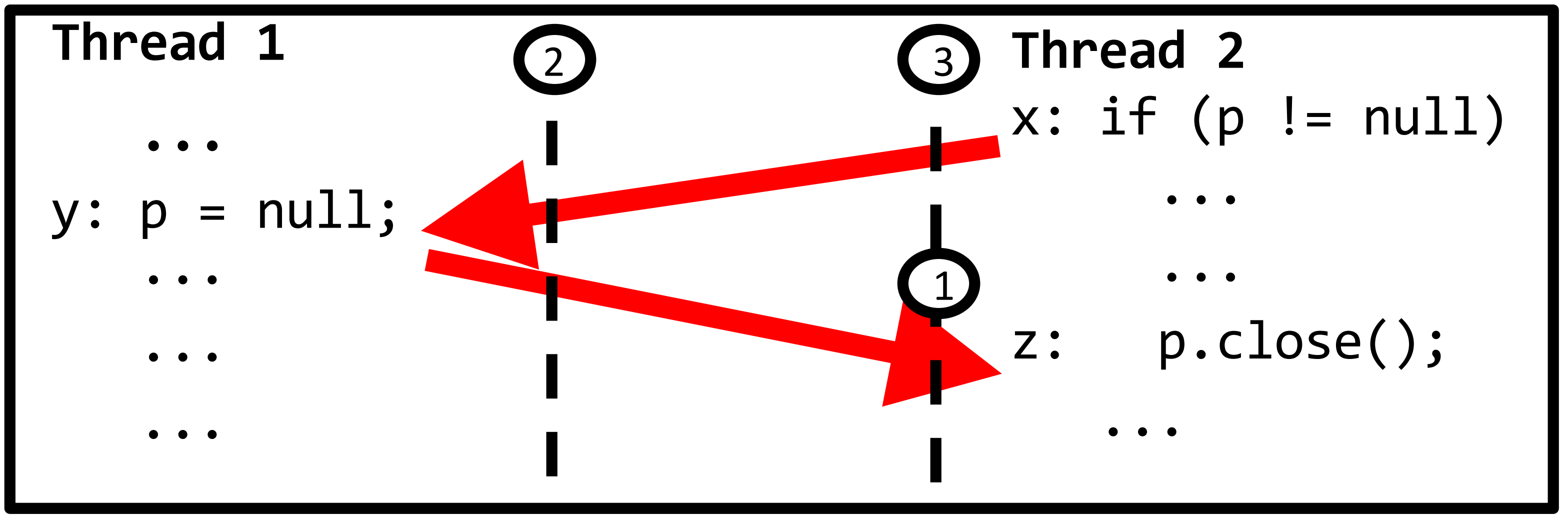
Given a program with:

- n threads (~tens)
- k steps (~millions)
- bug of depth d (1 or 2)

Cuzz will find the bug with a probability of at least

$$\frac{1}{n\,k^{d-1}}$$ in each run

Proof of Guarantee (Sketch)

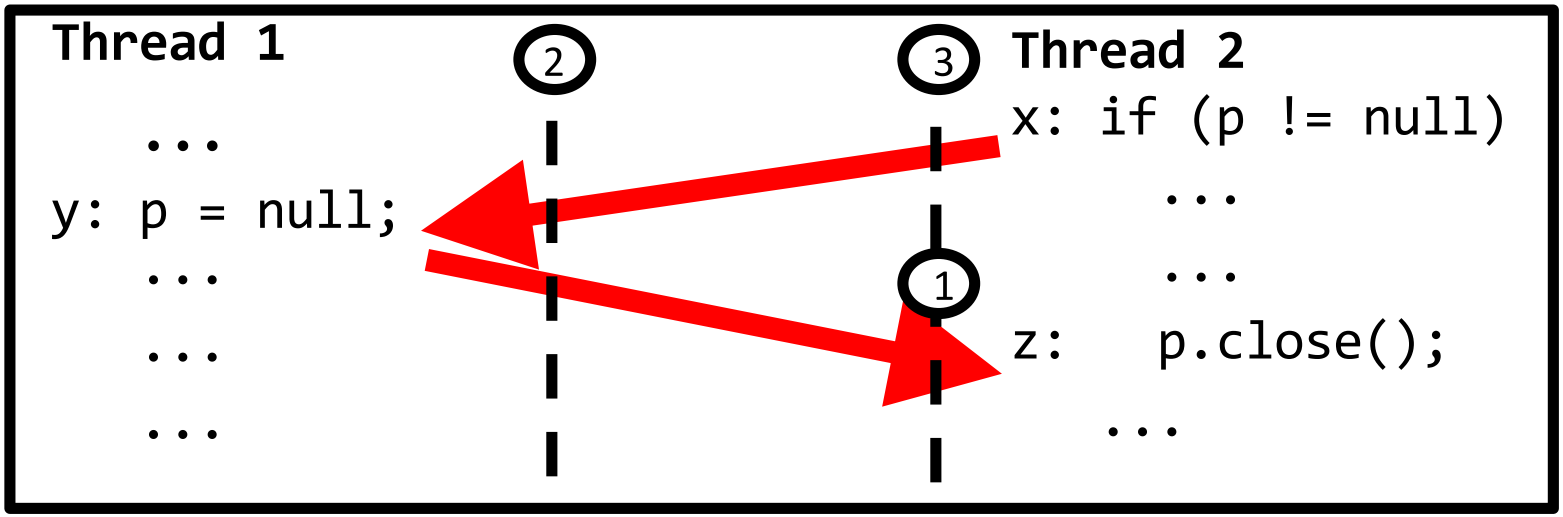


Probability(choose correct initial thread priorities) >= 1 / n

Probability(choose correct step to switch thread priorities) >= 1 / k

Probability(triggering bug) >= 1 / (nk)

Proof of Guarantee (Sketch)



Probability(choose correct initial thread priorities) >= 1 / n

Probability(choose correct step to switch thread priorities) >= 1 / k

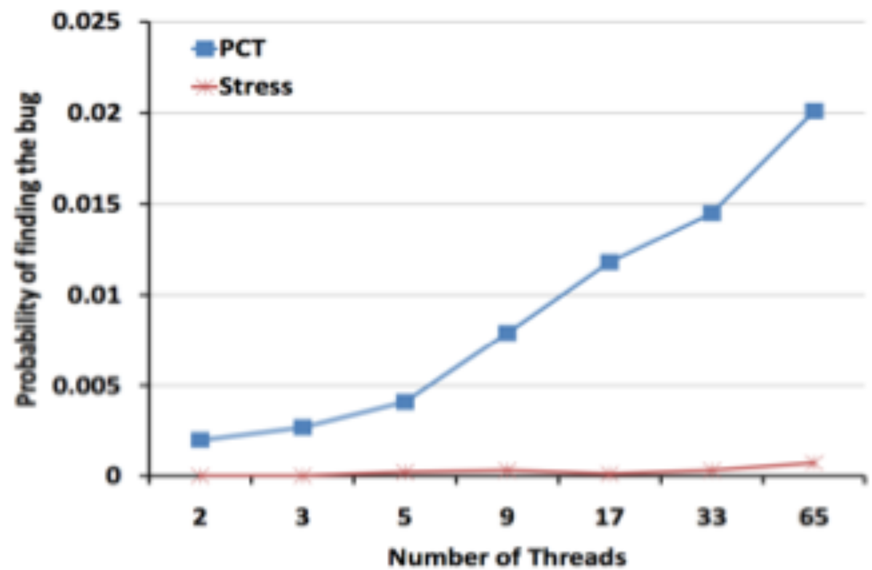
Probability(triggering bug) >= 1 / (nk)

Measured vs. Worst-Case Probability

- Worst-case guarantee is for hardest-to-find bug of given depth

- If bugs can be found in multiple ways, probabilities add up!

- Increasing number of threads helps
  - Leads to more ways of triggering a bug



Cuzz Case Study

Measure bug-finding probability of stress testing vs. Cuzz

- Without Cuzz: 1 Fail in 238,820 runs
  - ratio = 0.000004187
- With Cuzz: 12 Fails in 320 runs
  - ratio = 0.0375

1 day of stress testing = 11 seconds of Cuzz testing!

Cuzz: Key Takeaways

- Bug depth: useful metric for concurrency testing efforts

- Systematic randomization improves concurrency testing

- Whatever stress testing can do, Cuzz can do better
  - Effective in flushing out bugs with existing tests
  - Scales to large number of threads, long-running tests
  - Low adoption barrier

Random Testing: Pros and Cons

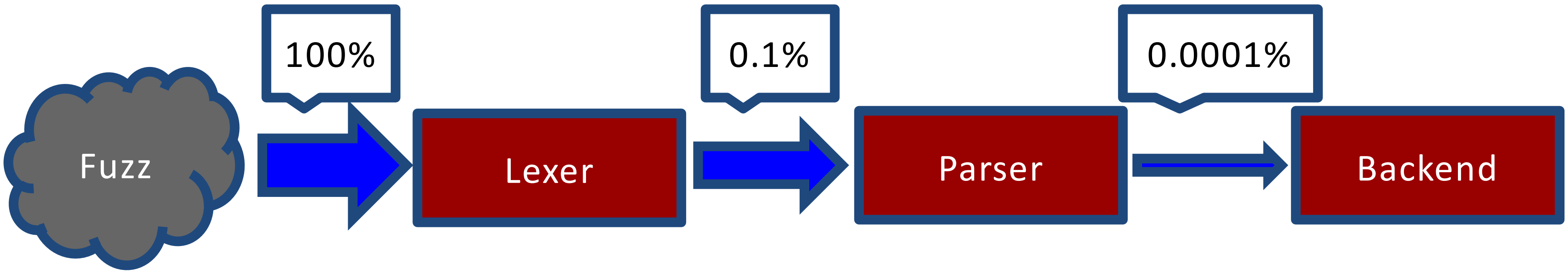
Pros:

- Easy to implement
- Provably good coverage given enough tests
- Can work with programs in any format
- Appealing for finding security vulnerabilities

Cons:

- Inefficient test suite
- Might find bugs that are unimportant
- Poor coverage

Coverage of Random Testing



- The lexer is very heavily tested by random inputs
- But testing of later stages is much less efficient

What Have We Learned?

Random testing:

- Is effective for testing security, mobile apps, and concurrency
- Should complement not replace systematic, formal testing
- Must generate test inputs from a reasonable distribution to be effective
- May be less effective for systems with multiple layers (e.g. compilers)