Automatic Mining of Functionally Equivalent Code Fragments via Random Testing

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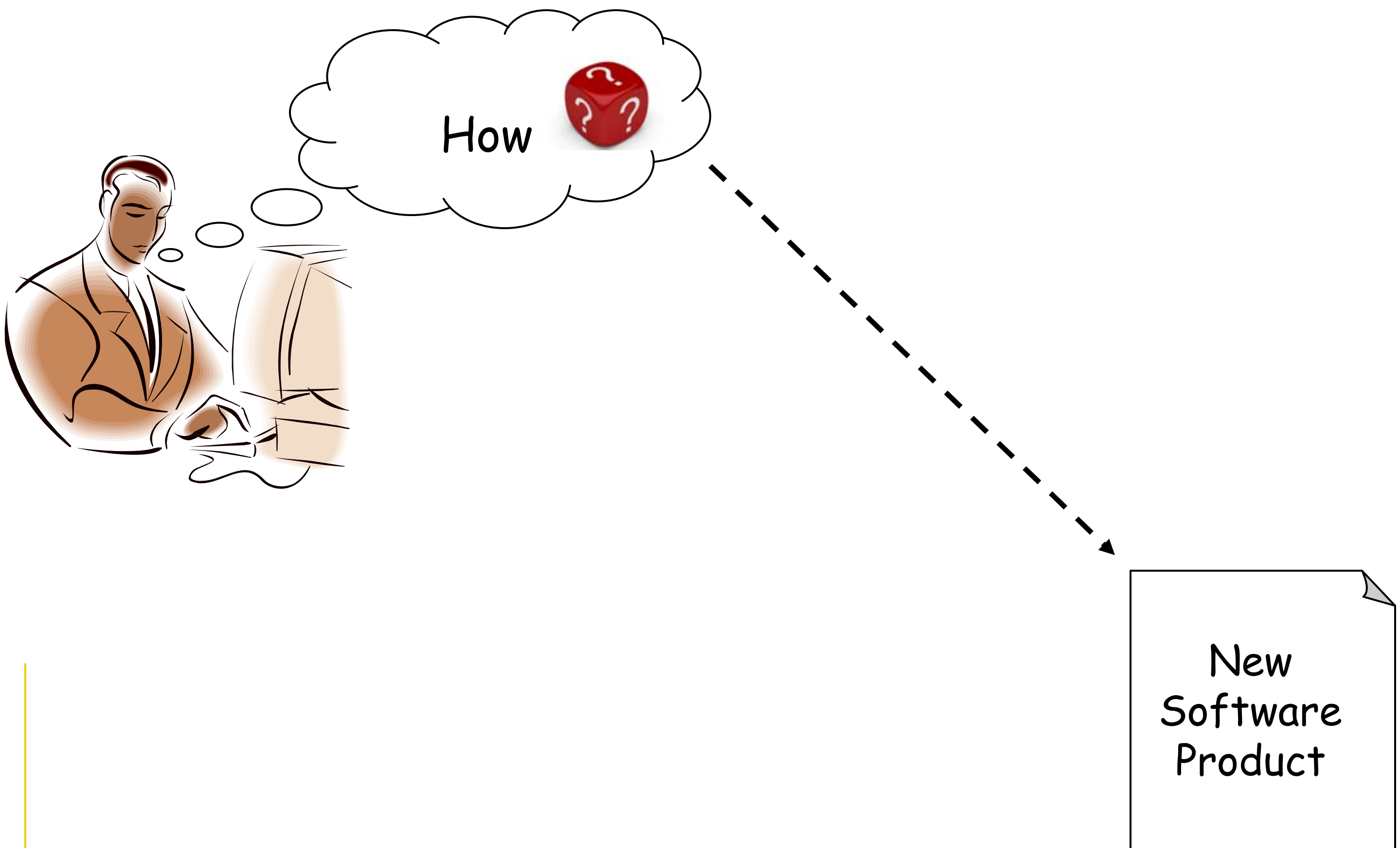
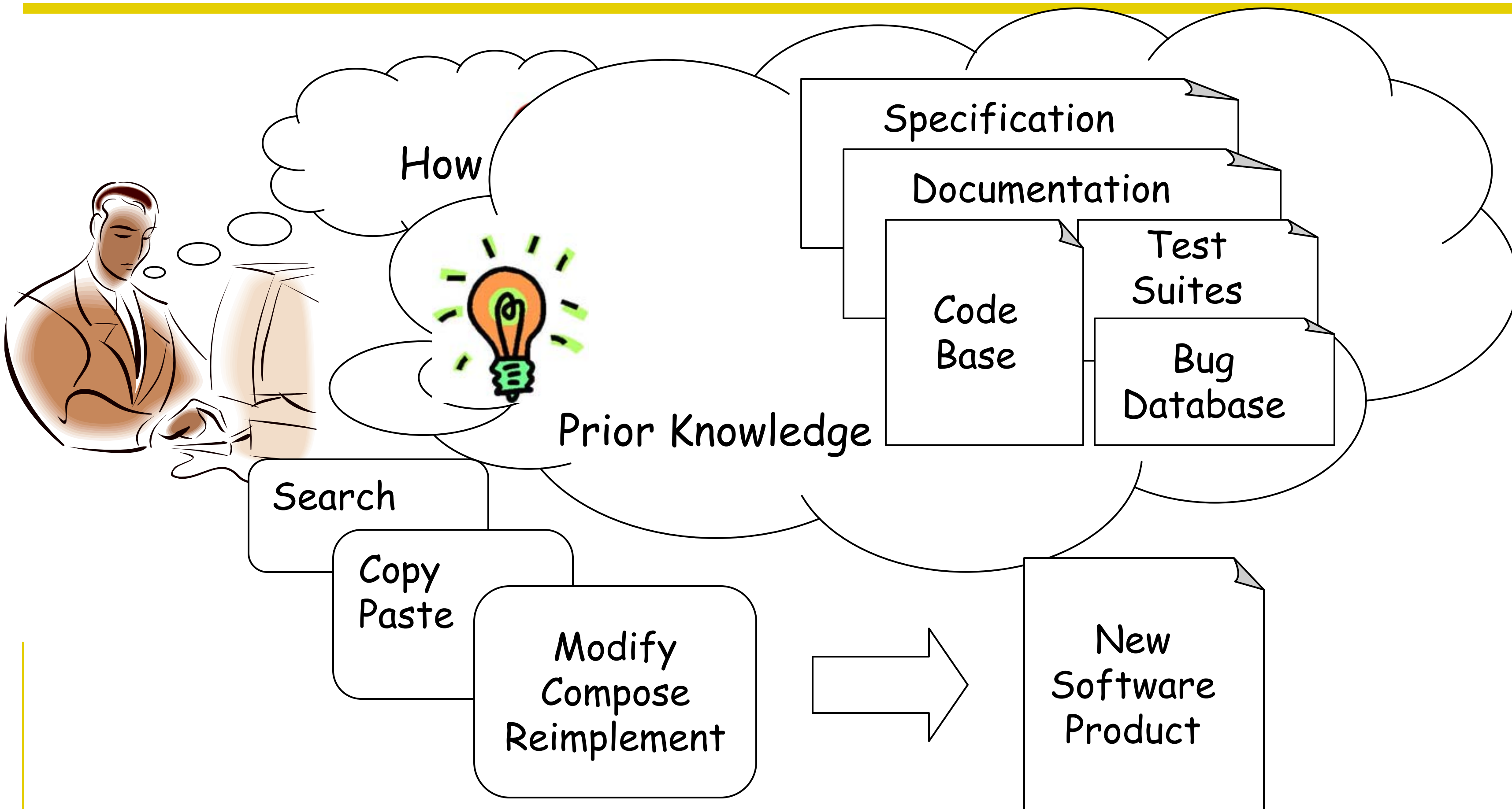
Cloning in Software Development



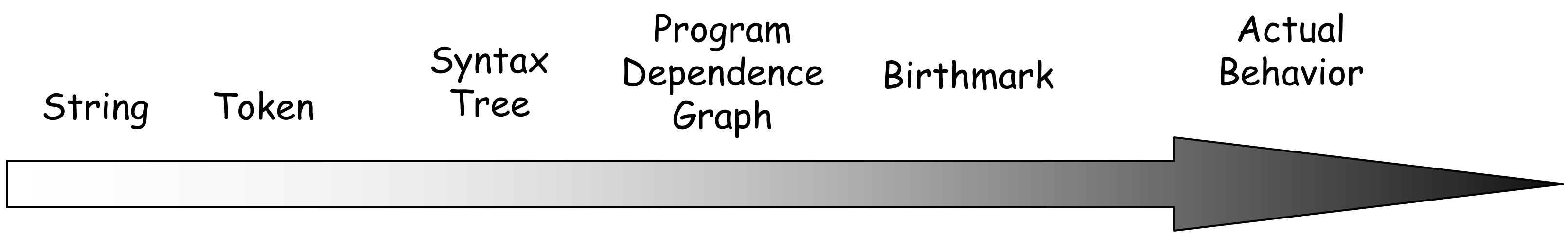
Cloning in Software Development



Applications of Clone Detection

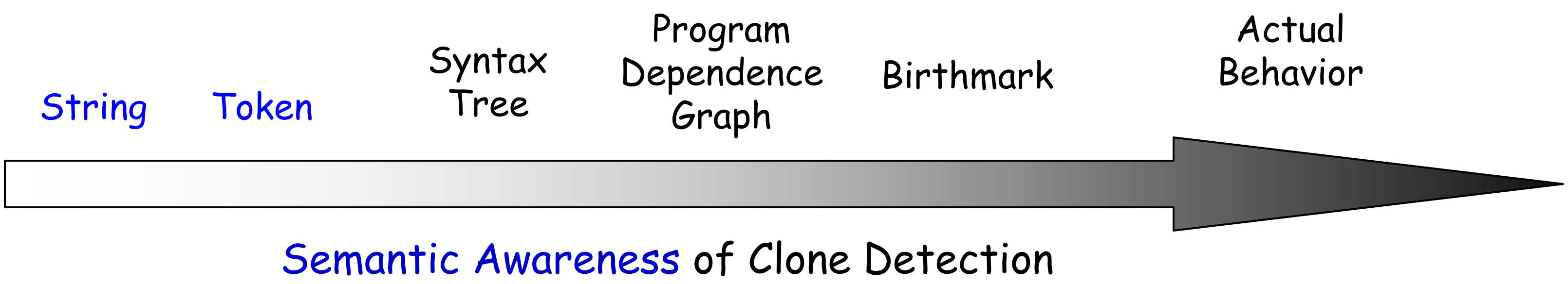
- Refactoring
- Pattern mining
- Reuse
- Debugging
- Evolution study
- Plagiarism detection

A Spectrum of Clone Detection



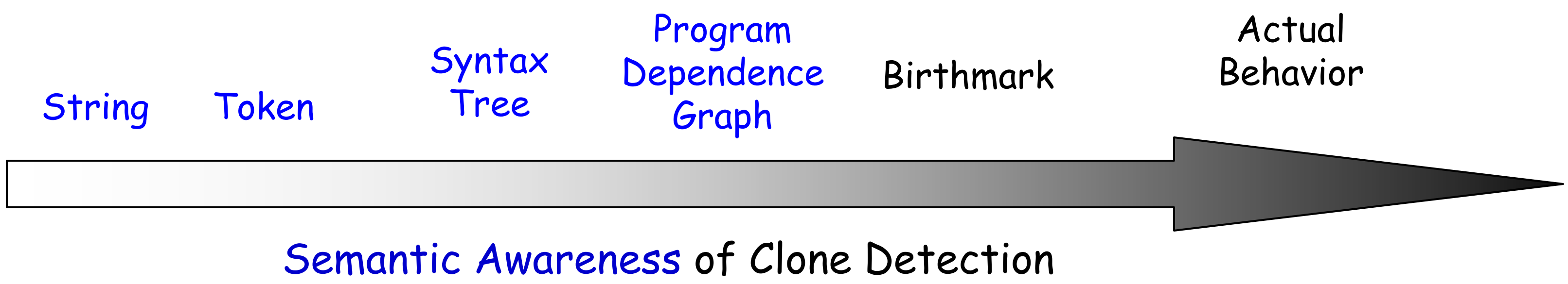
Semantic Awareness of Clone Detection

A Spectrum of Clone Detection



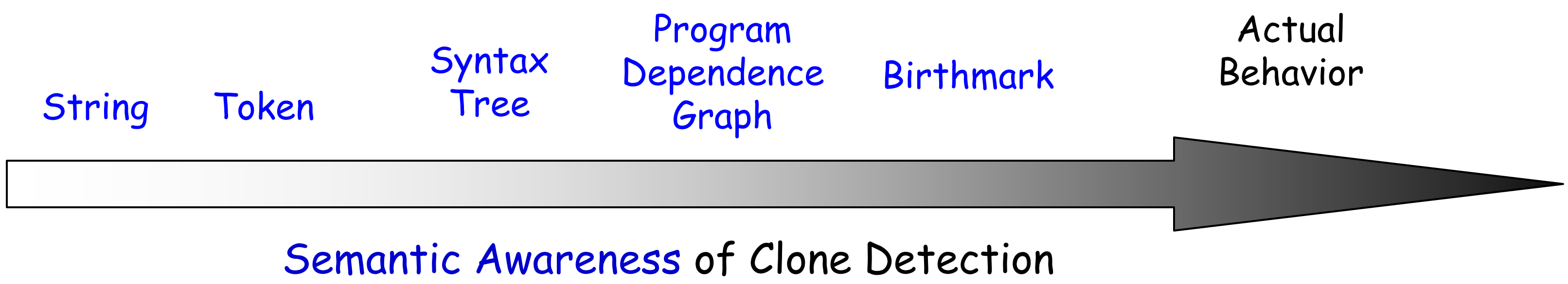
- 1992: Baker, parameterized string algorithm
- 2002: Kamiya et al., CCFinder
- 2004: Li et al., CP-Miner
- 2007: Basit et al., Repeated Tokens Finder

A Spectrum of Clone Detection



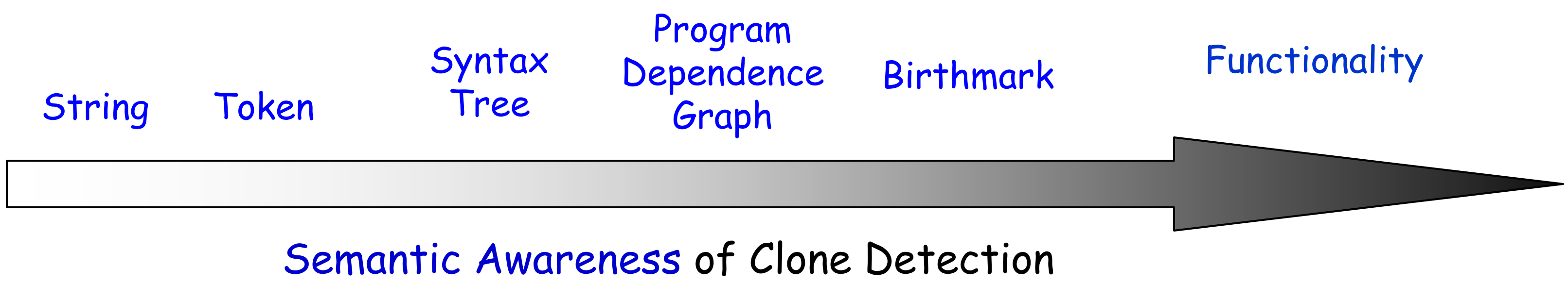
- 1998: Baxter et al., CloneDR
- 2004: Wahler et al., XML-based
- 2007: Jiang et al., Deckard
- 2000, 2001: Komondoor et al.
- 2006: Liu et al., GPLAG
- 2008: Gabel et al.

A Spectrum of Clone Detection



- 1999: Collberg et al., Software watermarking
- 2007: Schuler et al., Dynamic birthmarking
- 2008: Lim et al., Static birthmarking
- 2008: Zhou et al., Combined approach

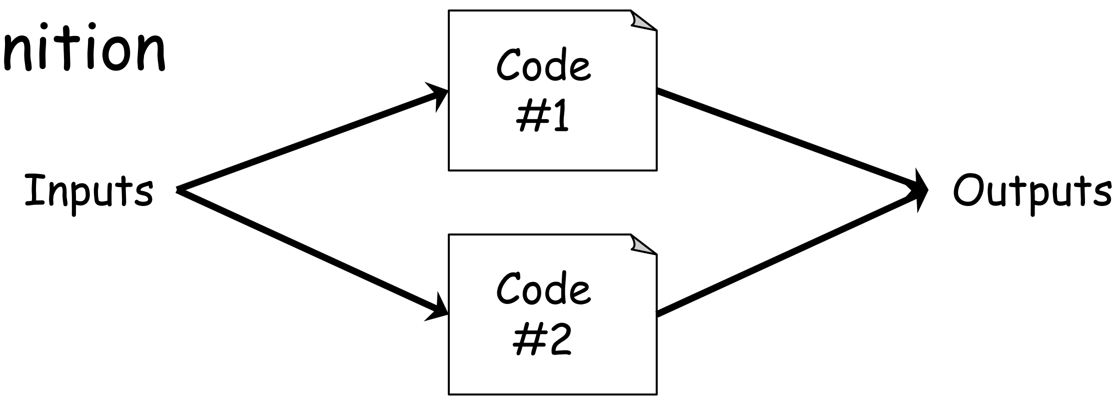
A Spectrum of Clone Detection



- Functional equivalence
  - How extensive is its existence

Functional Equivalence

- Definition



- Applicability: arbitrary piece of code
  - Source and binary
  - From whole program to whole function to code fragments
- Example: sorting algorithms
  - Bubble, selection, merge, quick, heap

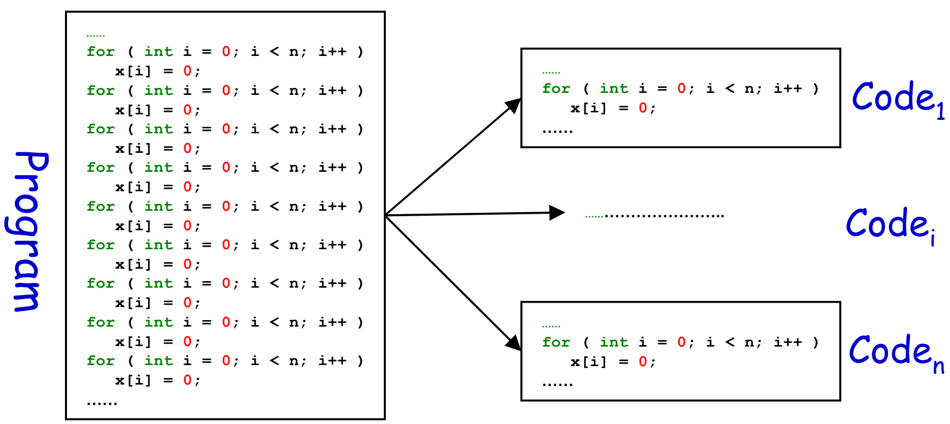
Previous Work on Program Equivalence

- [Cousineau 1979; Raoult 1980; Zakharov 1987; Crole 1995; Pitts 2002; Bertran 2005; Matsumoto 2006; Siegel 2008; …]

- Many based on formal semantics
- Consider whole programs or functions only
  - Not arbitrary code fragments
- Check equivalence among given pieces of code
  - Not scalable detection

Our Objectives

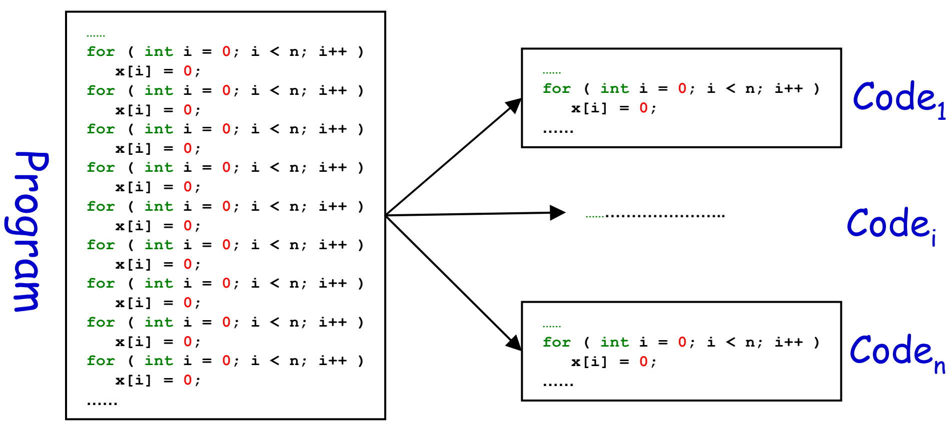
- Detect functionally equivalent code fragments



- Compare I/O behaviors directly
  - Run each piece of code with random inputs

Our Objectives — Challenges

- Detect functionally equivalent code fragments



- Large number of code fragments
- Unclear I/O interfaces

- Compare I/O behaviors directly
  - Run each piece of code with random inputs

- Huge number of code executions

Key 1: Semantic-Aware I/O Identification

- Identify input and output variables based on data flows in the code:
  - Variables used before defined are inputs
  - Variables defined but may not used are outputs

```
min = i;
j = i+1;
while (1) {
if(j >= LENGTH)
break;
if(data[j] < data[min])
min = j;
j++; }
if(min > i) {
tmp = data[min];
data[min] = data[i];
data[i] = tmp; }
```

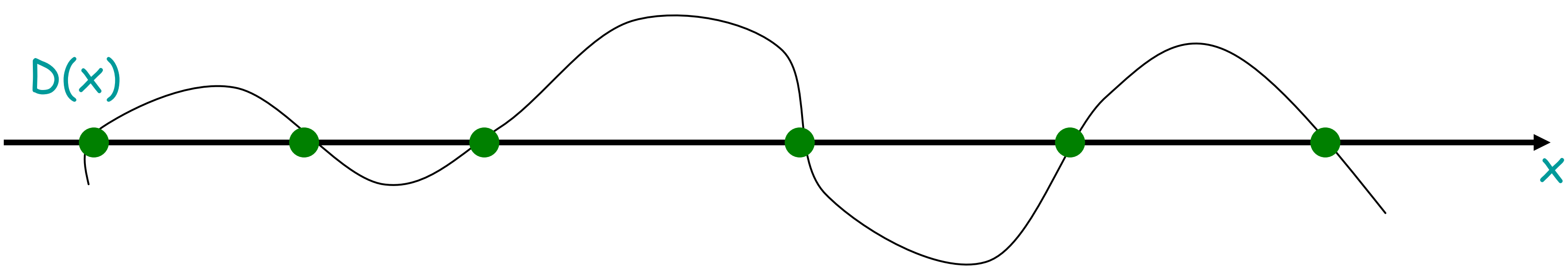
Input variables: `i` and `data`

Output variables: `data`

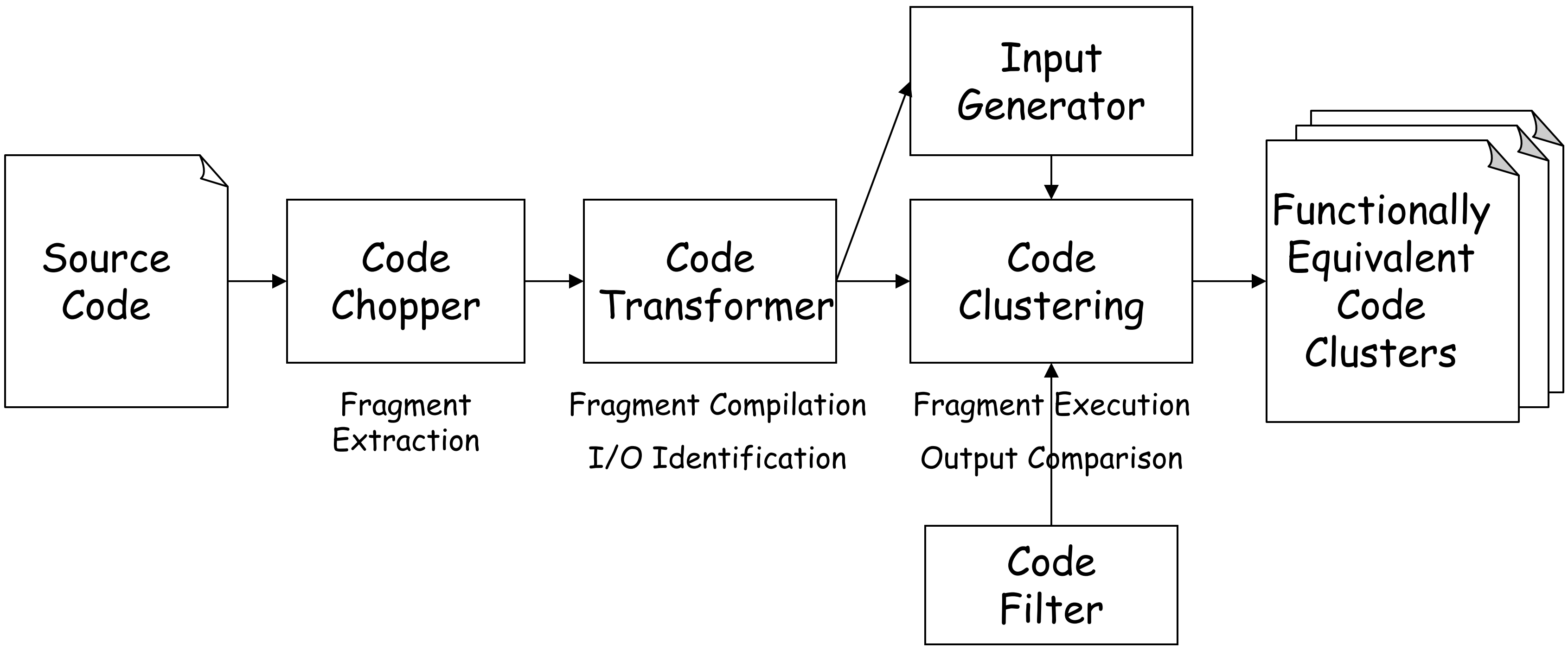
Key 2: Limit Number of Inputs

- Schwartz-Zippel lemma: polynomial identities can be tested with few random values
  - Let $D(x)$ be $p_1(x) - p_2(x)$
  - If $p_1(x) = p_2(x)$,

  - If $p_1(x) \neq p_2(x)$,
    - $D(x) = 0$ has at most finite number d of roots
    - Prob ($D(v) = 0$) is bounded by d, for any random value v from the domain of x.



EqMiner


Source Code
Code Chopper
Fragment Extraction
Code Transformer
Fragment Compilation
I/O Identification
Input Generator
Code Clustering
Fragment Execution
Output Comparison
Code Filter
Functionally Equivalent Code Clusters

Code Chopper

- Sliding windows of various sizes on serialized statements

```
min = i;

for(j=i+1; j<LENGTH; j++)
{

    if(data[j] < data[min])
        min = j;
}
if (min > i) {
    int tmp = data[min];
    data[min] = data[i];
    data[i] = tmp; }
```

```
min = i;
j = i+1;
while (1) {
if(j >= LENGTH)
break;
if(data[j] < data[min])
min = j;
j++; }
if(min > i) {
tmp = data[min];
data[min] = data[i];
data[i] = tmp; }
```

Code Transformer

- Declare undeclared variables, labels
- Define all used types
- Remove assembly code
- Replace goto, return statements
- Replace function calls
  - Replace each call with a random input variable
  - Ignore side effects, only consider return values
- Read inputs
- Dump outputs

Input Generation

- In order to share concrete input values among input variables for different code fragments, separate the generation into two phases:
  1. Construct bounded memory pools filled with random primary values and pointers. E.g.,

Primary value pool (bytes):	100	-78	......
Pointer value pool (0/1):	1	0	......

  2. Initialize each variable with values from the pools. E.g.,

```
struct { int x, y; } X;
```

Input variables: `X* x; int* y;`

```
x = malloc(sizeof(X));
x.x = 100; x.y = -78;
y = 0;
```

Code Clustering

- Eager partitioning of code fragments for a set of random inputs

f1, f2, f3, f4, f5, f6, f7, f8, f9, …, fi, …, fn

I_1 :

Code Clustering

- Eager partitioning of code fragments for a set of random inputs

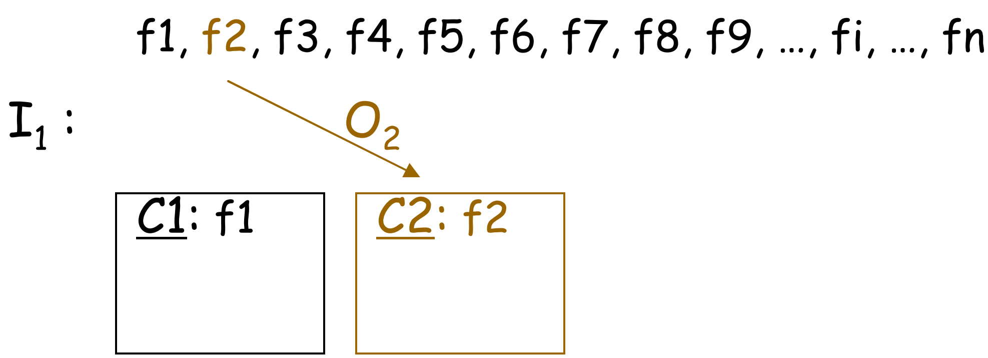
f1, f2, f3, f4, f5, f6, f7, f8, f9, …, fi, …, fn

I_1 : ↓ O_1

C1: f1

Code Clustering

- Eager partitioning of code fragments for a set of random inputs



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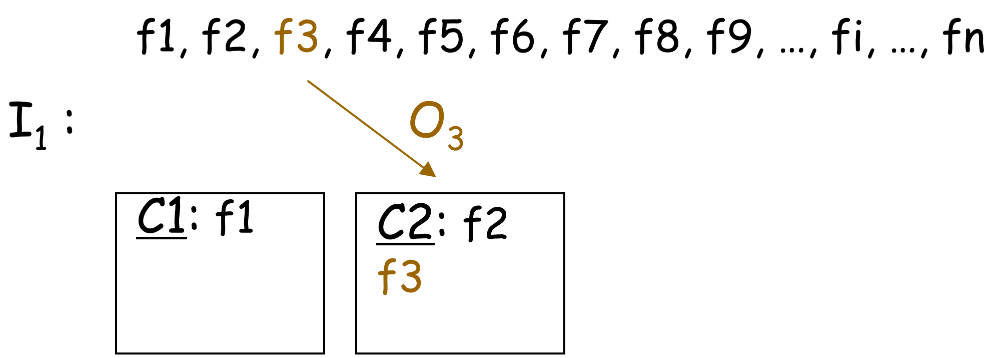

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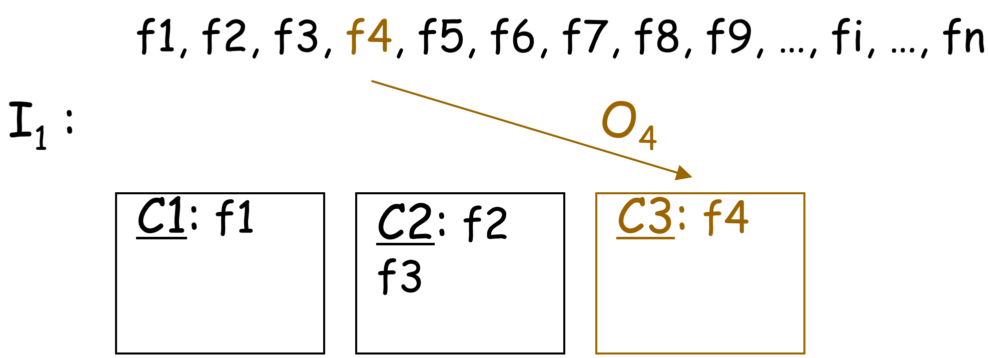
- Eager partitioning of code fragments for a set of random inputs



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I_1 :

C1: f1 f5	C2: f2 f3, f6	C3: f4	C4: f7	……	Ck: fi …, fn

Code Clustering

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f1, f2, f3, f4, f5, f6, f7, f8, f9, …, fi, …, fn

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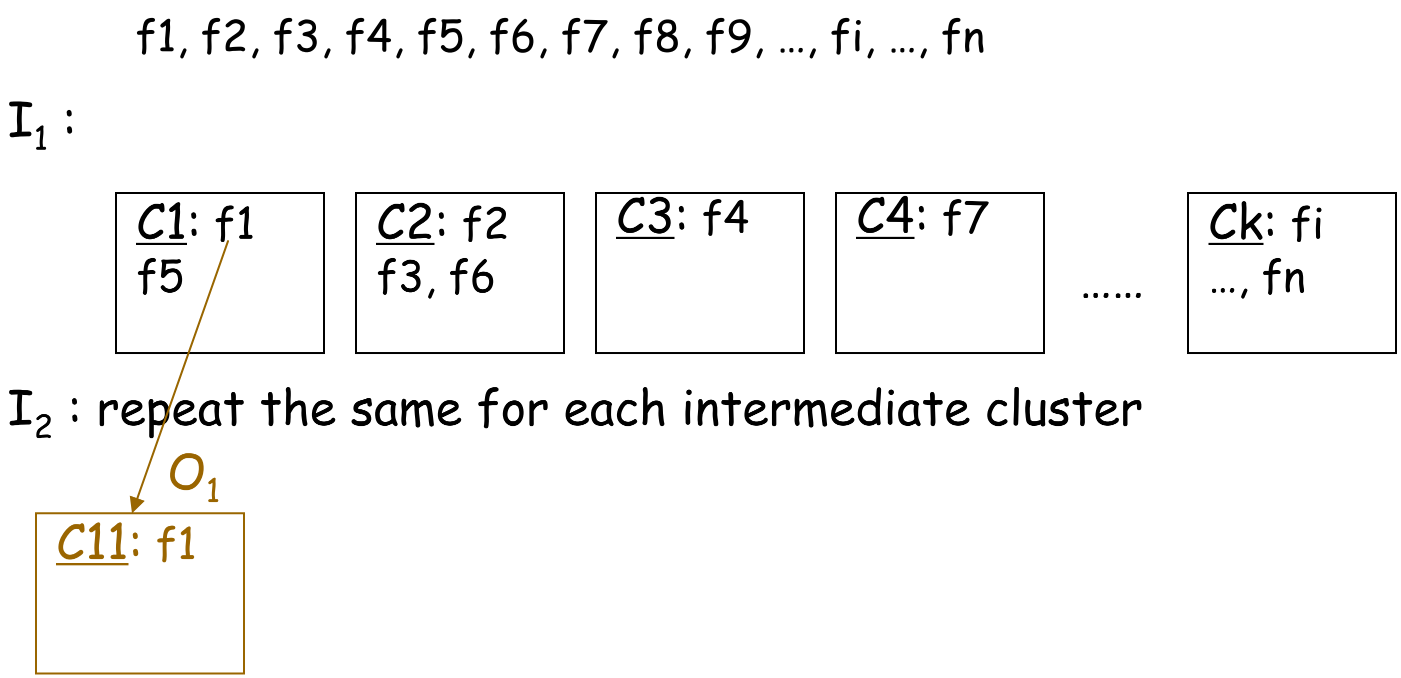
C1: f1 f5	C2: f2 f3, f6	C3: f4	C4: f7	……	Ck: fi …, fn

I_2 : repeat the same for each intermediate cluster

Code Clustering

- Eager partitioning of code fragments for a set of random inputs



Code Clustering

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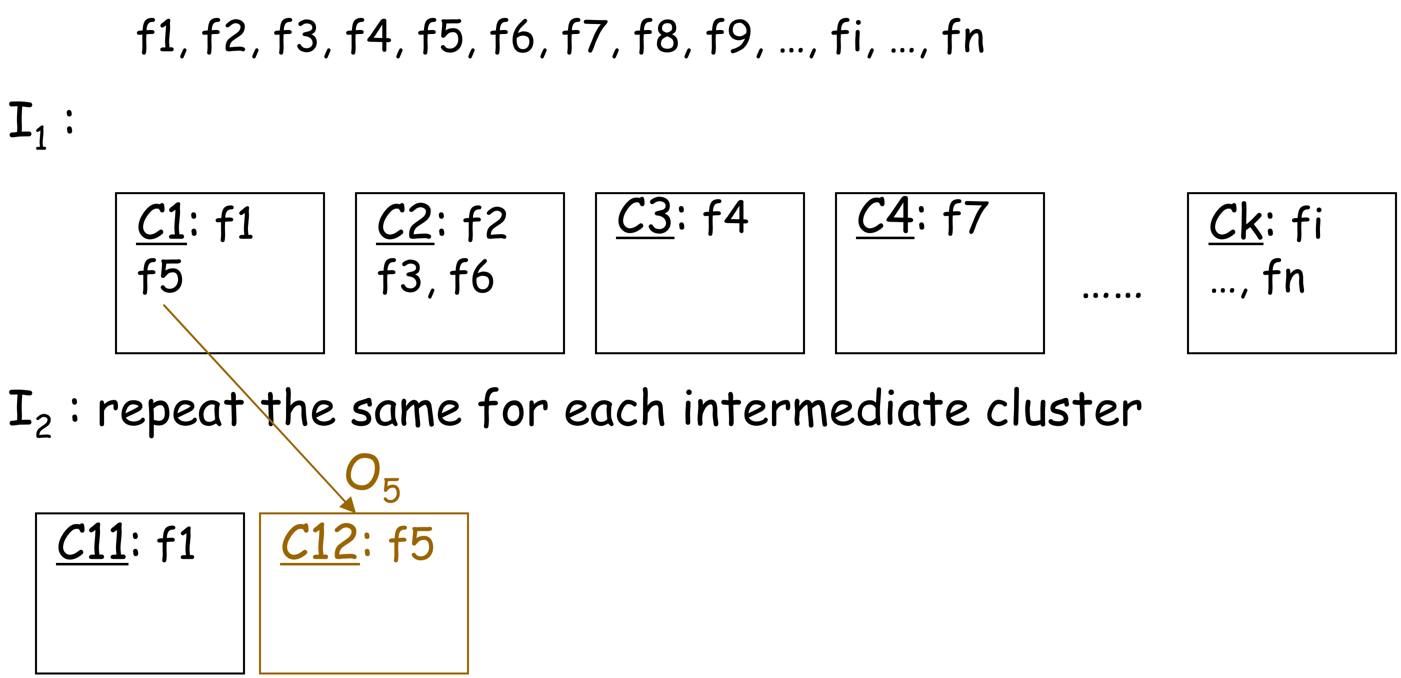


Code Clustering

- Eager partitioning of code fragments for a set of random inputs

f1, f2, f3, f4, f5, f6, f7, f8, f9, …, fi, …, fn

I_1 :

C1: f1 f5	C2: f2 f3, f6	C3: f4	C4: f7	……	Ck: fi …, fn

I_2 : repeat the same for each intermediate cluster

C11: f1	C12: f5	……	Ck1: fi fj	Ck2: fl …, fp	Ckx: fq …, fn

Code Clustering

- Eager partitioning of code fragments for a set of random inputs

f1, f2, f3, f4, f5, f6, f7, f8, f9, …, fi, …, fn

I_1 :

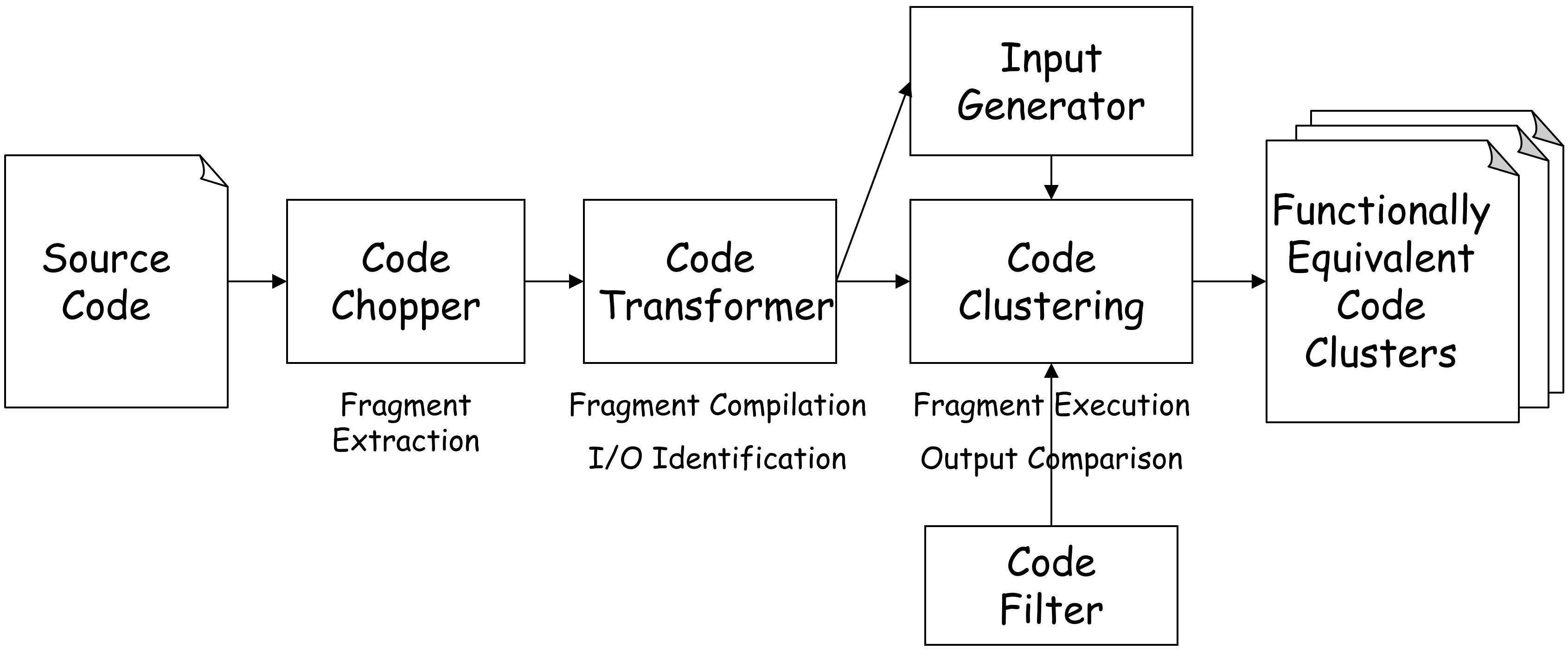
C1: f1 f5 | C2: f2 f3, f6 | C3: f4 | C4: f7 | …… | Ck: fi …, fn

I_2 : repeat the same for each intermediate cluster

C11: f1 | C12: f5 | …… | Ck1: fi fj | Ck2: fl …, fp | Ckx: fq …, fn

I_s : until only one code fragment is left for each cluster, or until a reasonable number s of inputs are used

EqMiner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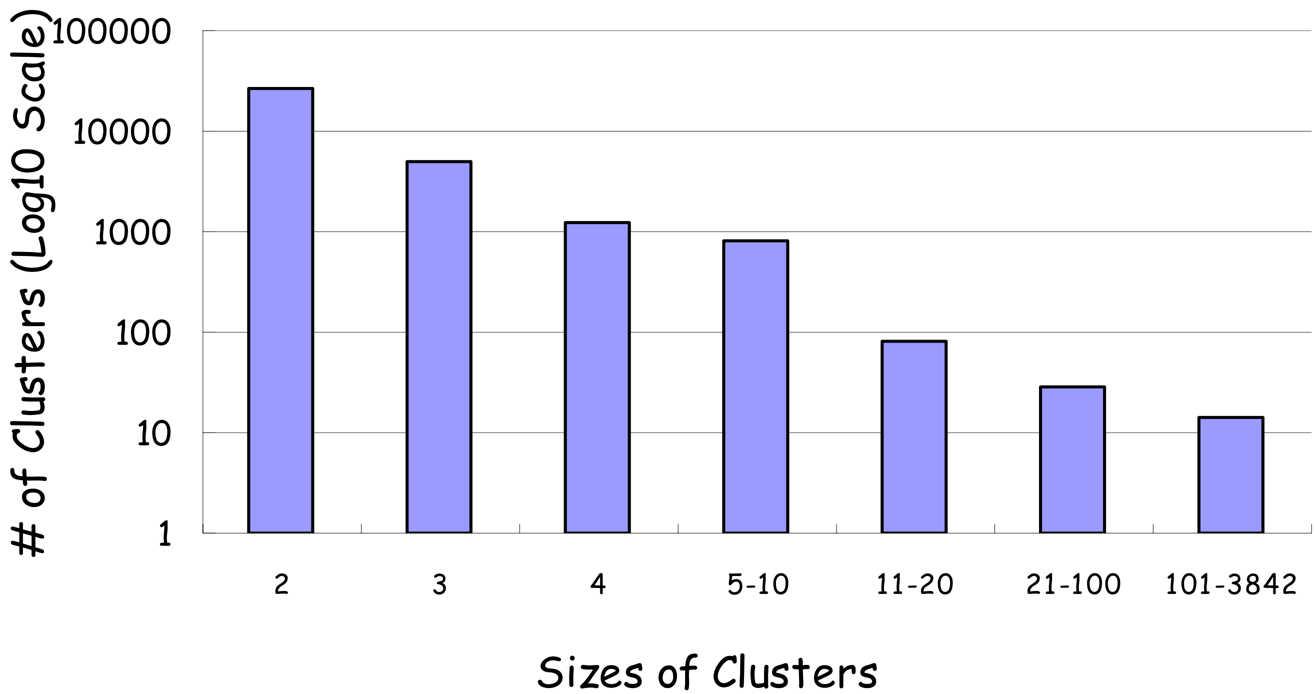
Results on Sorting Algorithms

- 5 sorting algorithms with both recursive and non-recursive versions
  - ~350 LoC
  - ~200 code fragments
- s = 10
  - 69 clone clusters reported
    - Most are portions of the algorithms
    - 4 non-recursive versions are in a same cluster

Results on the Linux Kernel

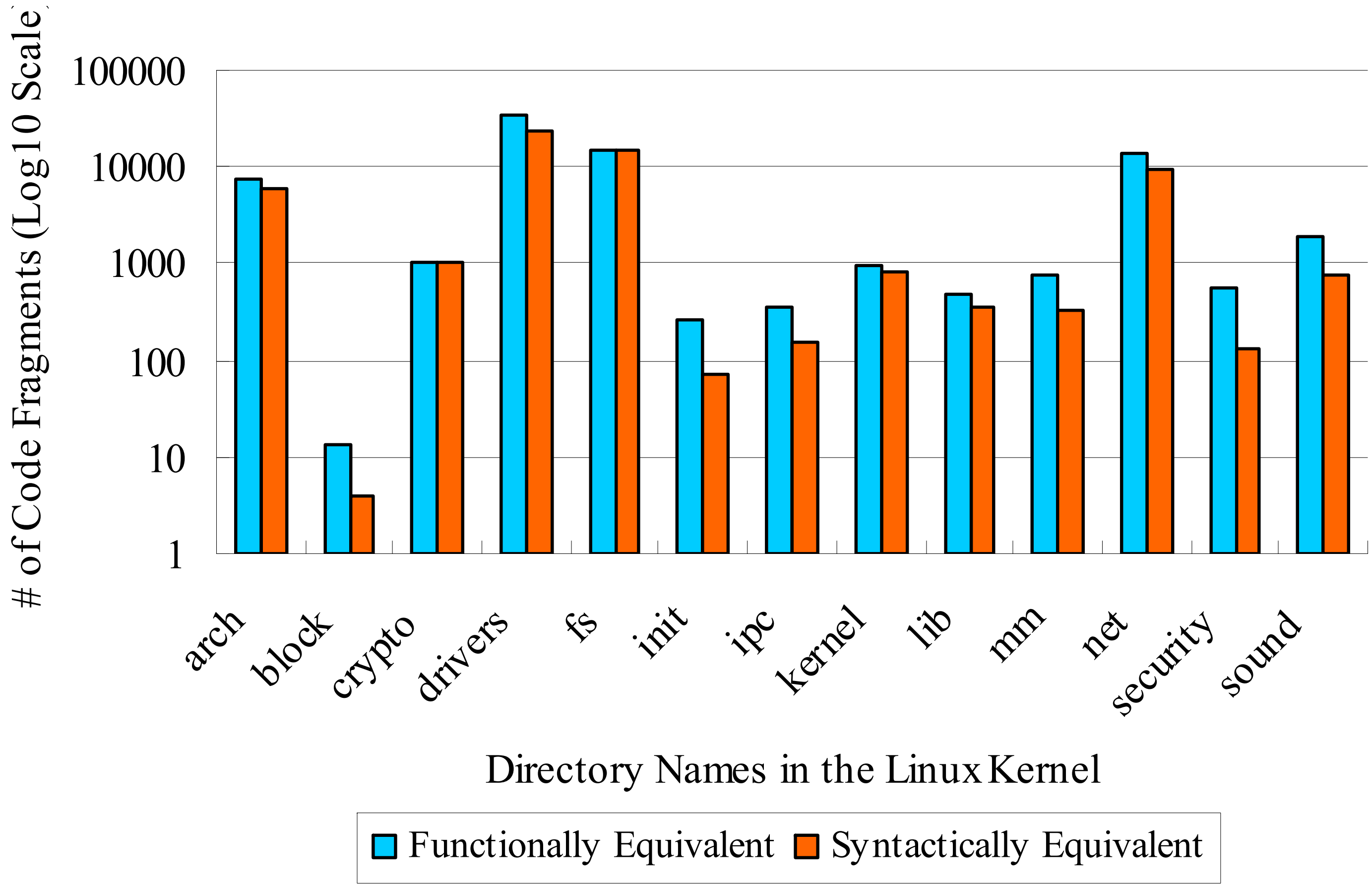
- s = 10
  - >800K code fragments were separated into 32K non-trivial clusters

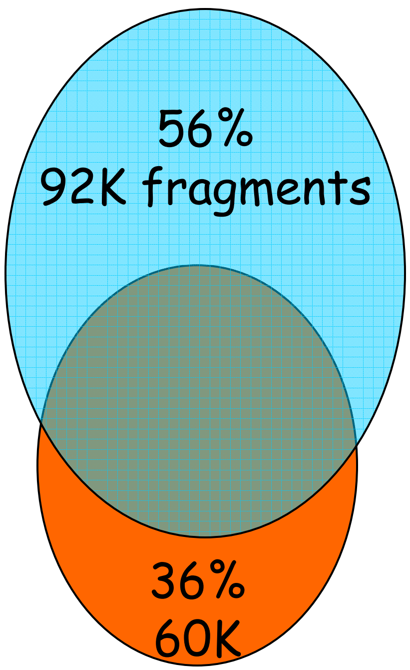


Results on the Linux Kernel

- s = 10
  - >800K code fragments were separated into 32K non-trivial clusters
- Additional 100 for 128 semi-randomly selected clusters
  - 3% of all of the code fragments became singletons
- 100 more tests
  - 0.5% additional

Differences from Syntactic Clones





Differences from Syntactic Clones

- False positives
  - Function calls
- Macro related + few outputs

```
if ( ALWAYS_FALSE ) {
   ......
} else
    output = input;
```

```
output = input;
```

- Lexical differences

```
output = input + 10;
```

```
output = input + 100;
```

```
output = 0;
if ( output < input ) {
   ...
   output = input + 1;
}
```

```
output = 0;
if ( output < input ) {
   ...
   output = output + 1;
}
```

Conclusion & Future Work

- First scalable detection of functionally equivalent code based on random testing
- Confirm the existence of many functional clones which complement syntactic clones
  - Enable further studies on functional clone patterns
  - Explore utilities of functional equivalent code

Thank you!

Questions?

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