Decomposition Instead of Self-Composition for Proving the Absence of Timing Channels

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Timos Antonopoulos, Yale
Paul Gazzillo, Yale
Michael Hicks, UMD
Eric Koskinen, Yale
Tachio Terauchi, JAIST
Shiyi Wei, UMD

Side-channel attacks

Applications contain secrets like passwords

Side channels can leak such secrets indirectly

Side channel of interest: running time

```
Changing password for paul.
(current) UNIX password:
Enter new UNIX password:
Retype new UNIX password:
```

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      return false;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

Number of loop iterations reveals correct character count

```
Changing password for paul.
(current) UNIX password:
Enter new UNIX password:
Retype new UNIX password:
```

Loop iterations now independent of correct characters

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confi
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      ~~return false;~~ correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

Timing Channel Freedom

$$\forall \pi_1, \pi_2.$$
$$in(\pi_1)[low] = in(\pi_2)[low]$$
$$\Rightarrow$$
$$time(\pi_1) = time(\pi_2) \pm c$$

This means low input values for each traces

- Running time does not depend on secret
- Any two traces have roughly same running time for same low input
- A 2-safety property, i.e., must relate pairs of traces to prove property

Self-Composition

```
boolean chpass(real_pwd_A, real_pwd_B, input_pwd_A, input_pwd_B, ...) {
 assume(input_pwd_A == input_pwd_B);
 assume(new_pwd_A == new_pwd_B);
 ...
 result_A =
```

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

```
 result_B =
```

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

```
  assert(equivalent(time_a, time_b))
}
```

- Describes all pairs of traces
- Analyze composite program
- Use non-relational analysis
- Discovering invariants between distinct programs can be challenging for many verifiers

Reframe Timing Channel Freedom

$$\forall \pi_1, \pi_2.$$
$$in(\pi_1)[low] = in(\pi_2)[low]$$
$$\Rightarrow$$
$$time(\pi_1) = time(\pi_2) \pm c$$

$$\exists f.\ \forall \pi.$$
$$time(\pi) = f\,(in(\pi)[low]) \pm c$$

- Function of public inputs *only*
- Non-relational: in terms of one trace
- Implies timing channel freedom, a relational property

Prove with Running Time Analysis

```
for (int i = 0; i < new_pwd.length; i++) {
  matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
}
```

Static Running Time Analysis

$$\text{time}(\pi) = f\,(\text{in}(\pi)[\text{new\_pwd}]) = \text{new\_pwd.length}$$

- Finds running time function f
- Implies timing channel freedom

Finding f Is Hard

- Programs can have nested conditionals and loops
  - Many branches on public inputs
  - At any program point
  - In loop headers
- f can be *piecewise* with complex cases

$$f = \left\{ \dots \begin{cases} \left\{ \dots \begin{cases} \left\{ \dots \right. \\ \left\{ \dots \right. \end{cases} \right. \\ \left\{ \dots \right. \end{cases} \right.$$

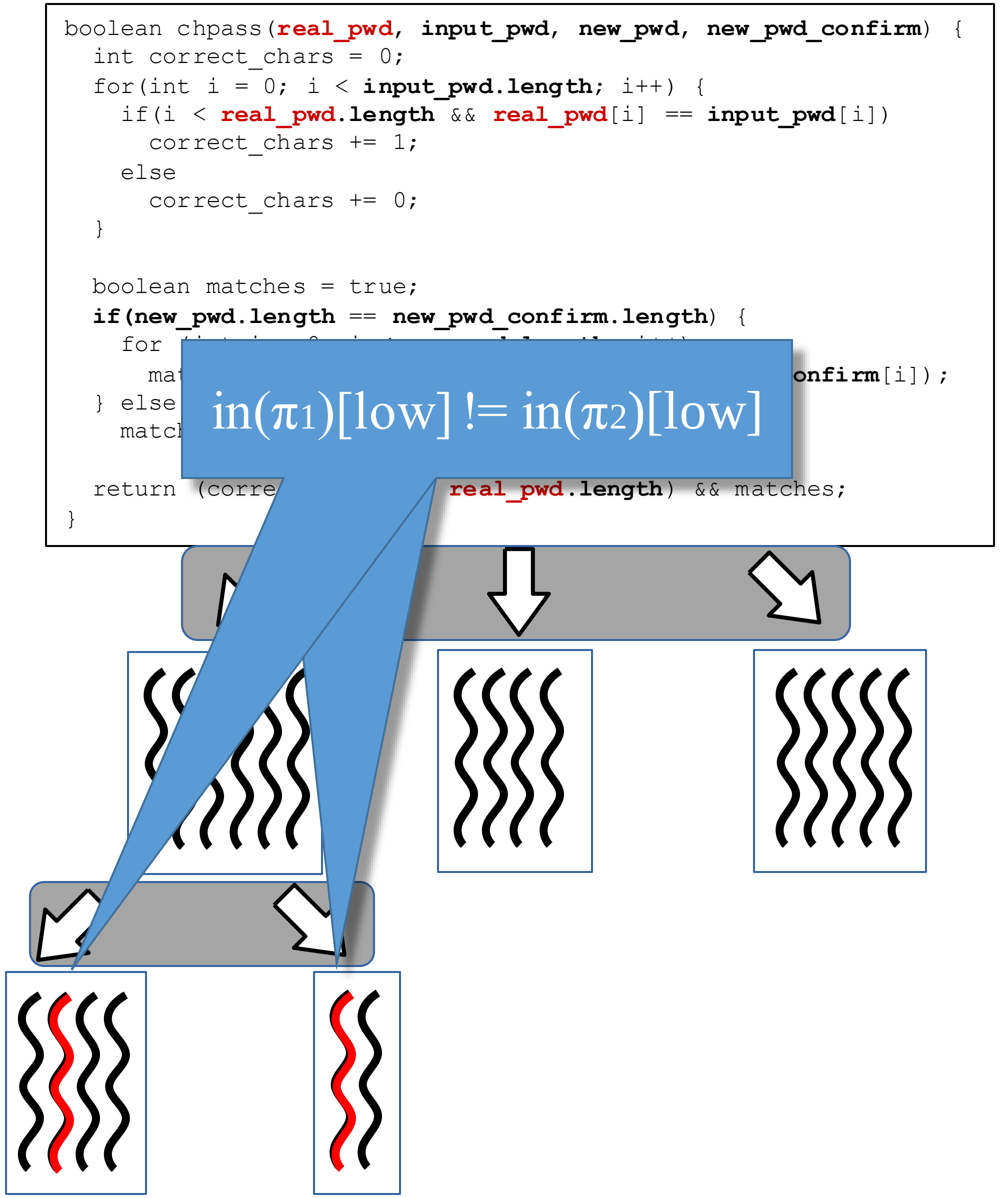
$$f = \begin{cases} \text{input\_pwd.len} * 2 + \text{new\_pwd.len} * 2 + 3 & \textbf{if } \text{new\_pwd.len == new\_pwd\_confirm.len} \\ \text{input\_pwd.len} * 2 + 4 & \textbf{if } \text{new\_pwd.len != new\_pwd\_confirm.len} \end{cases}$$

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

- Piecewise function with complex cases
- Running time analysis can't do this well

Partition the Program

- Prove freedom of partitions alone
- Must choose partitions carefully
- Prove safety of partitions *separately*
- Implies safety of complete program



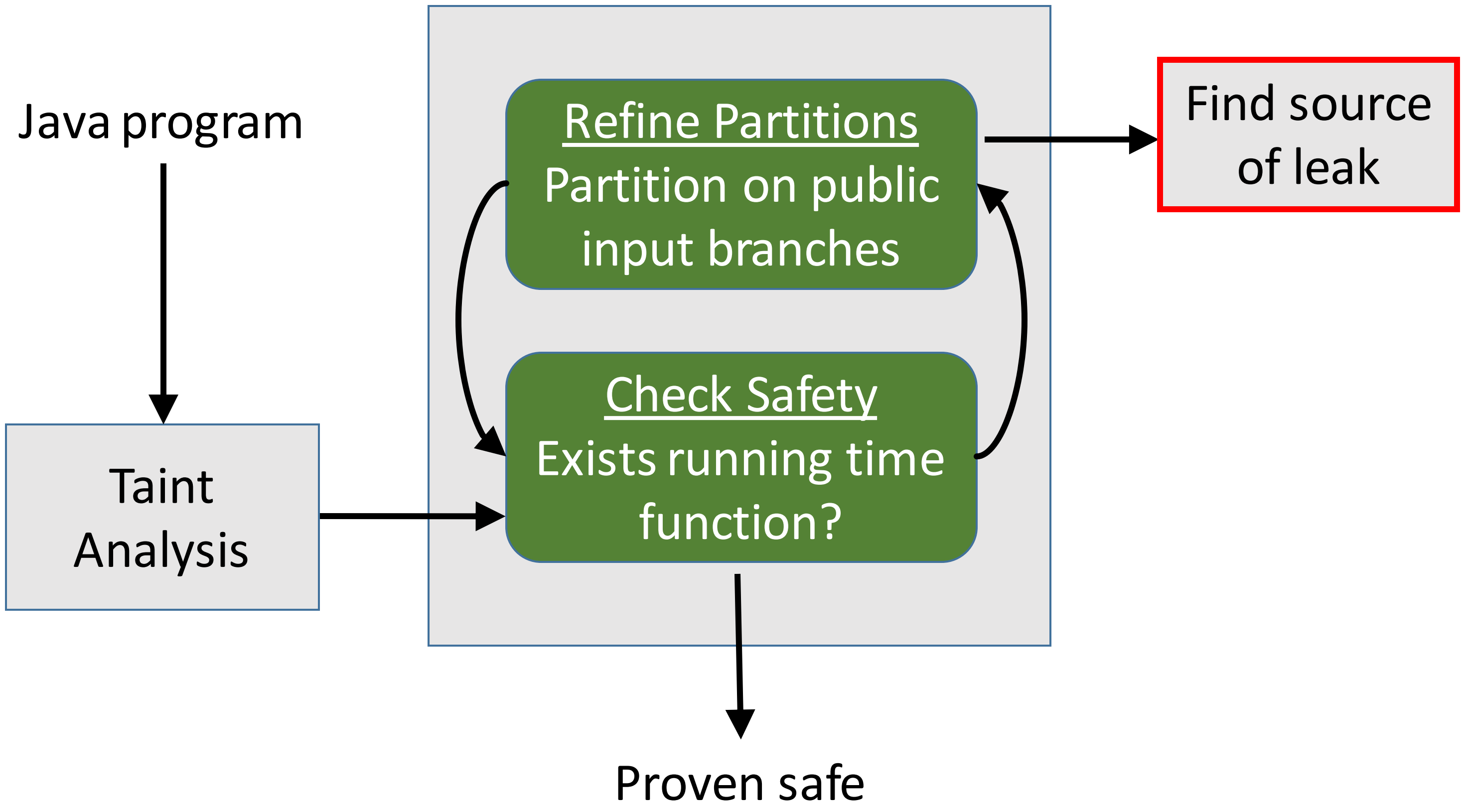
Key Idea

Solve a relational problem by proving a non-relational property about each trace in each partition, for properly chosen partitions.

Contributions

- Technique to prove timing channel freedom by decomposition
- Generalization to k-safety properties
- Implementation of verificaton of timing channel freedom in the Blazer tool with an evaluation

Safety Proving Algorithm



- Use taint analysis to get non-secret branches
- Use static running time bounds analysis
- Iteratively partition and check safety
- Continue partitioning until all partitions safe
- Find source of leak

Algorithm in Action: Check Safety

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_p
    for (int i = 0; i < new_
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

Entire Program

Running time analysis

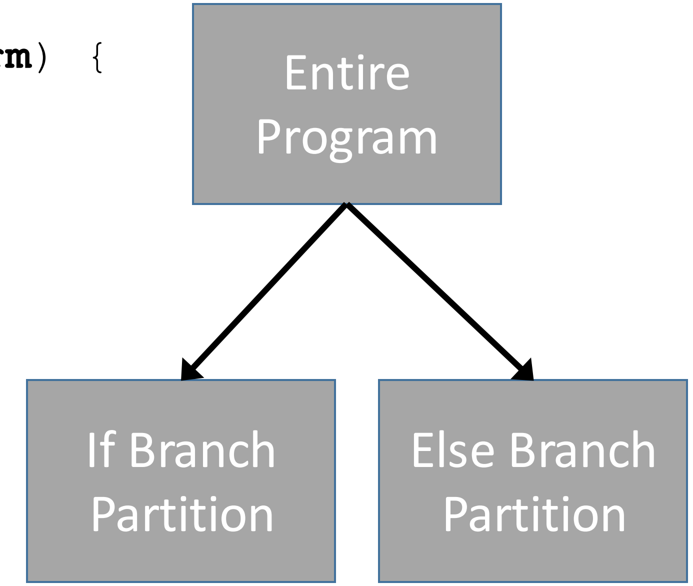
Lower: input_pwd.len * 2 + new_pwd.len * 2 + 3

Upper: input_pwd.len * 2 + 4

Secret-dependent running time could sit between upper and lower

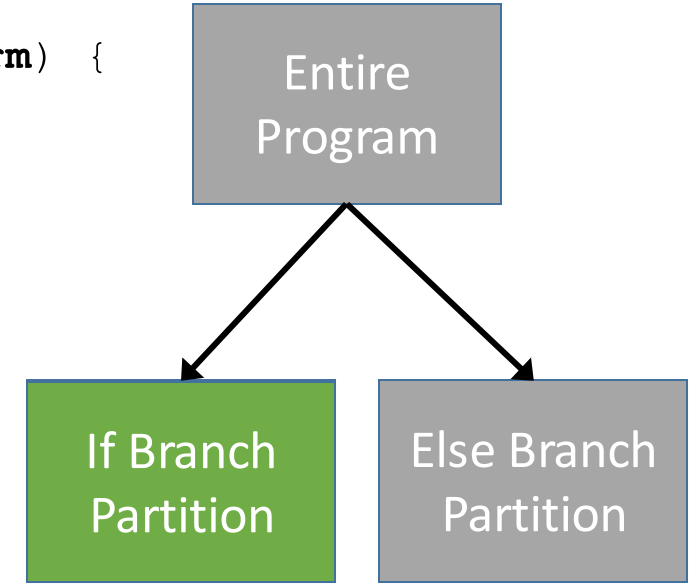
Algorithm in Action: Refine Partitions

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```



Algorithm in Action: Check New Partitions

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = match
  } else
    matches = false;

  return (correct_cha
}
```



Running time analysis

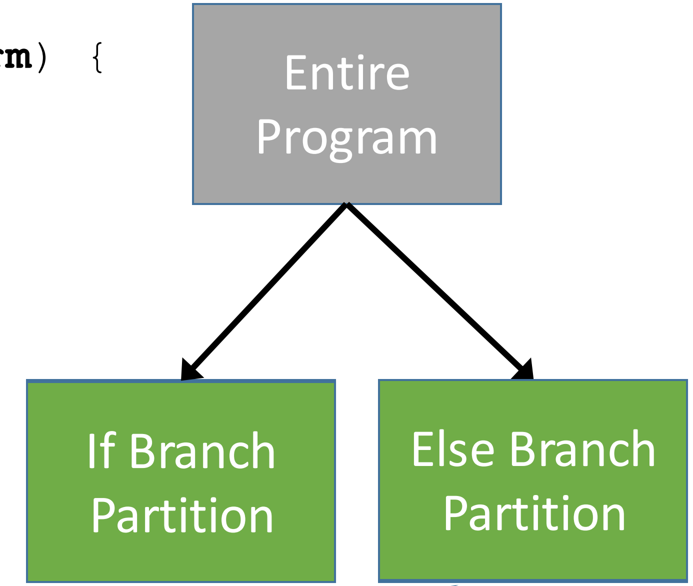
Lower: input_pwd.len * 2 + new_pwd.len * 2 + 3

Upper: input_pwd.len * 2 + new_pwd.len* 2 + 3

Tight running time bounds means safe partition

Algorithm in Action: Check New Partitions

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i
  } else
    matches = false;

  return (correct_chars == real_pwd.l
}
```



Running time analysis

Lower: input_pwd.len * 2 + 4

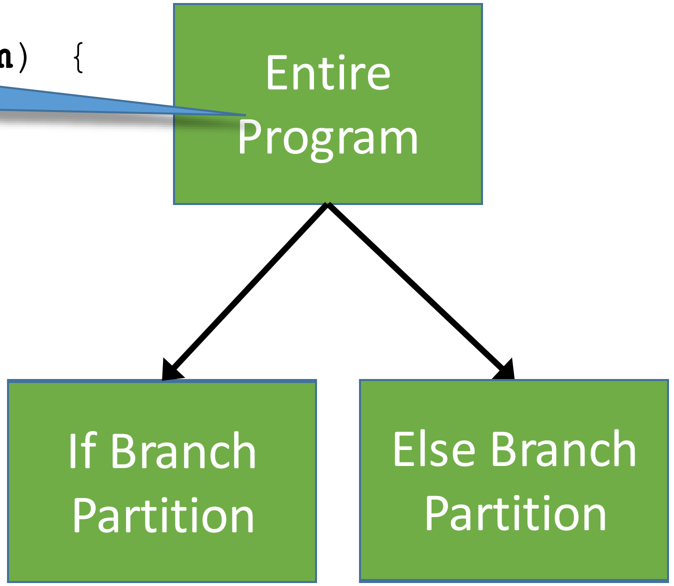
Upper: input_pwd.len * 2 + 4

Tight running time bounds means safe partition

Algorithm in Action: Whole Program Safety

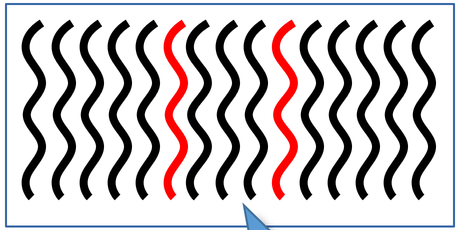
```
boolean chpass(rea ... pwd_confirm) {
  int correct_char ...
  for(int i = 0; i ...
    if(i < real_pw ... input_pwd[i])
      correct_chars += 1;
    else
      correct_chars += 0;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

Safety of all partitions means whole program is safe



General k-Safety Properties

k-Safety Properties



E.g., for 2-safety consider all pairs of traces

$$q(C) \triangleq \forall \pi_1, \ldots, \pi_k \in [\![C]\!]^k . \Phi_q(\pi_1, \ldots, \pi_k)$$

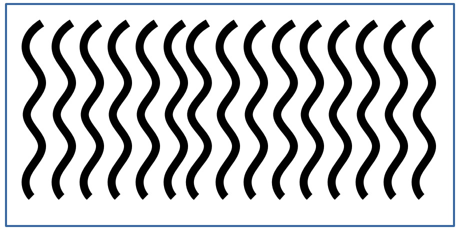
$in(\pi_1)[low] = in(\pi_2)[low]$

$\Rightarrow$

$time(\pi_1) = time(\pi_2) \pm c$

- Reason about combinations of k traces
- To disprove k-safety, you need k traces

Relational by Property Sharing



For a k-safety property q, RBPS(P,q) =

$$\forall \pi_1, \ldots, \pi_k . \bigwedge_{1 \leq i \leq k} P(\pi_i) \Rightarrow \Phi_q(\pi_1, \ldots, \pi_k)$$

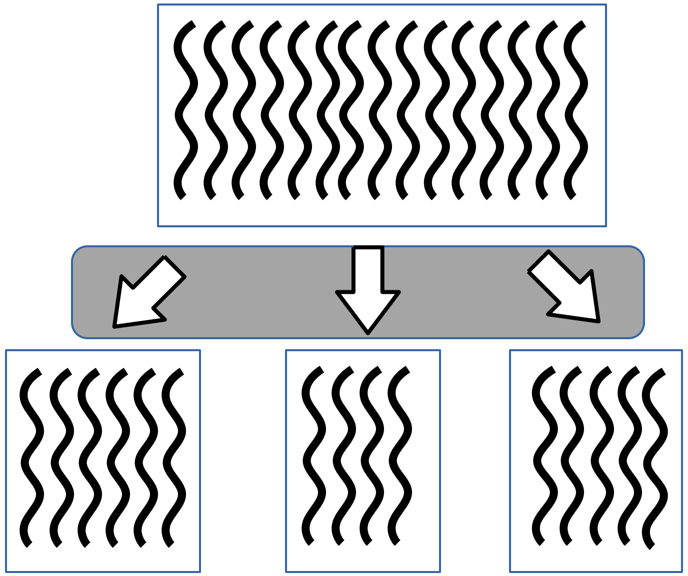
time(π) = f (in(π)[low]) ± c

in(π_1)[low] = in(π_2)[low]

$\Rightarrow$

time(π_1) = time(π_2) ± c

ψ-Quotient Partitioning



$\mathfrak{T} = \{T_1, T_2, T_3\}$

$\mathfrak{T}$ is a ψ-quotient partition provided that:

$$\forall \pi_1, \ldots, \pi_k \in [\![C]\!]^k.$$
$$\psi(\pi_1, \ldots, \pi_k) \Rightarrow \exists T \in \mathfrak{T}. \bigwedge_{1 \leq i \leq k} \pi_i \in T$$

$in(\pi_1)[low] = in(\pi_2)[low]$

$\Rightarrow$

$time(\pi_1) = time(\pi_2) \pm c$

A k-safety property F can be partitioned in this way if

$$\forall C. \forall \pi_1, \ldots, \pi_k \in [\![C]\!]^k.$$
$$(\psi(\pi_1, \ldots, \pi_k) \Rightarrow \Phi_q(\pi_1, \ldots, \pi_k)) \Rightarrow \Phi_q(\pi_1, \ldots, \pi_k)$$

$in(\pi_1)[low] = in(\pi_2)[low]$

Soundness Theorem

Theorem 3.1 (Soundness). *Suppose that q is ψ-quotient partitionable, and $\mathfrak{T}$ is a ψ-quotient partition for a program C. Then, $q(C)$ holds if for each $T \in \mathfrak{T}$, there exists P such that (i) $\mathsf{RBPS}(P, q)$, and (ii) for each $\pi \in [\![C]\!] \cap T$, $P(\pi)$.*

(Proof in paper)

Other k-Safety Properties

- Determinism

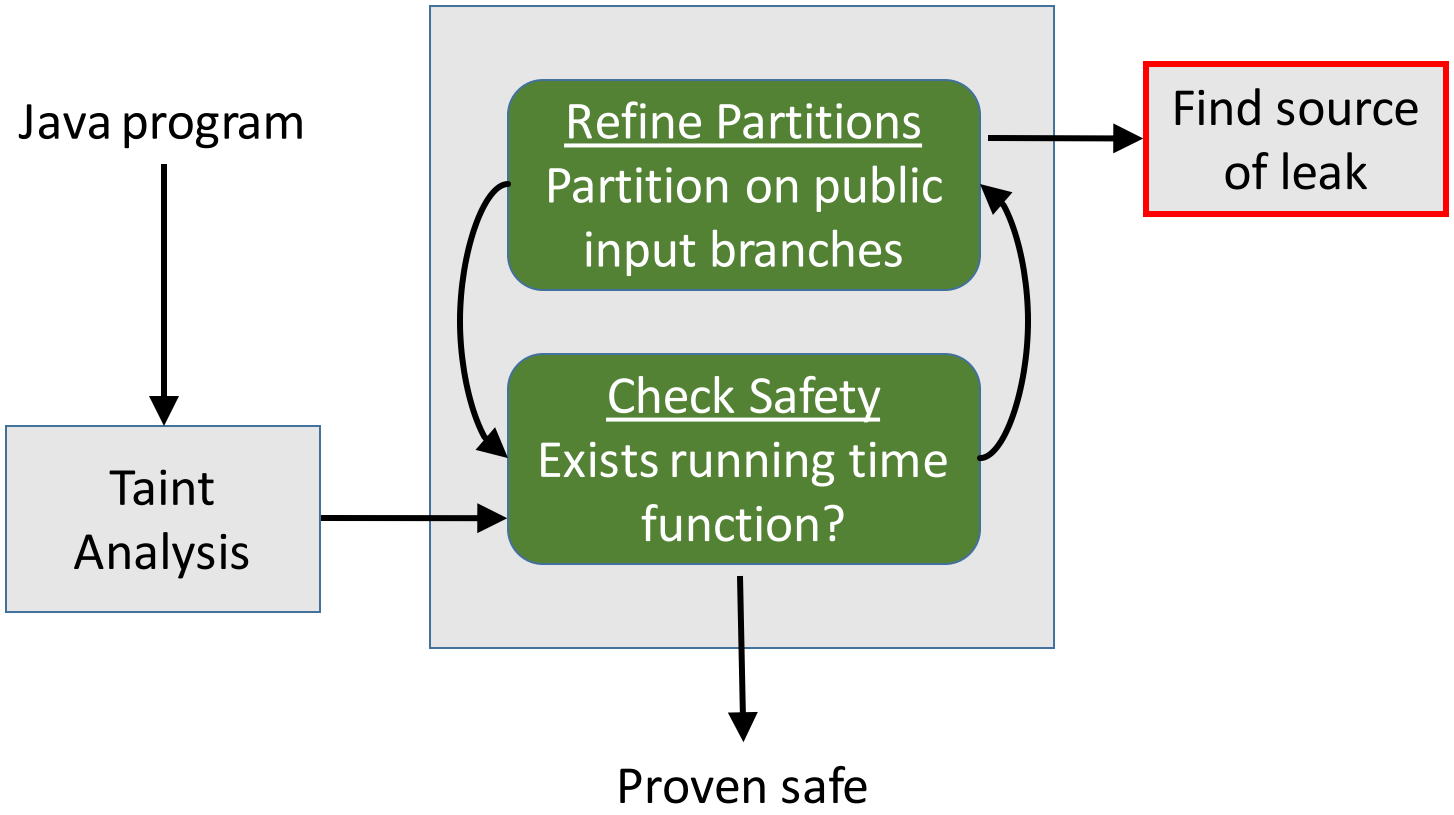
$$det(C) \triangleq \forall\, \pi_1, \pi_2.\\ in(\pi_1) = in(\pi_2) \Rightarrow out(\pi_1) = out(\pi_2).$$

- Relaxed timing channel freedom

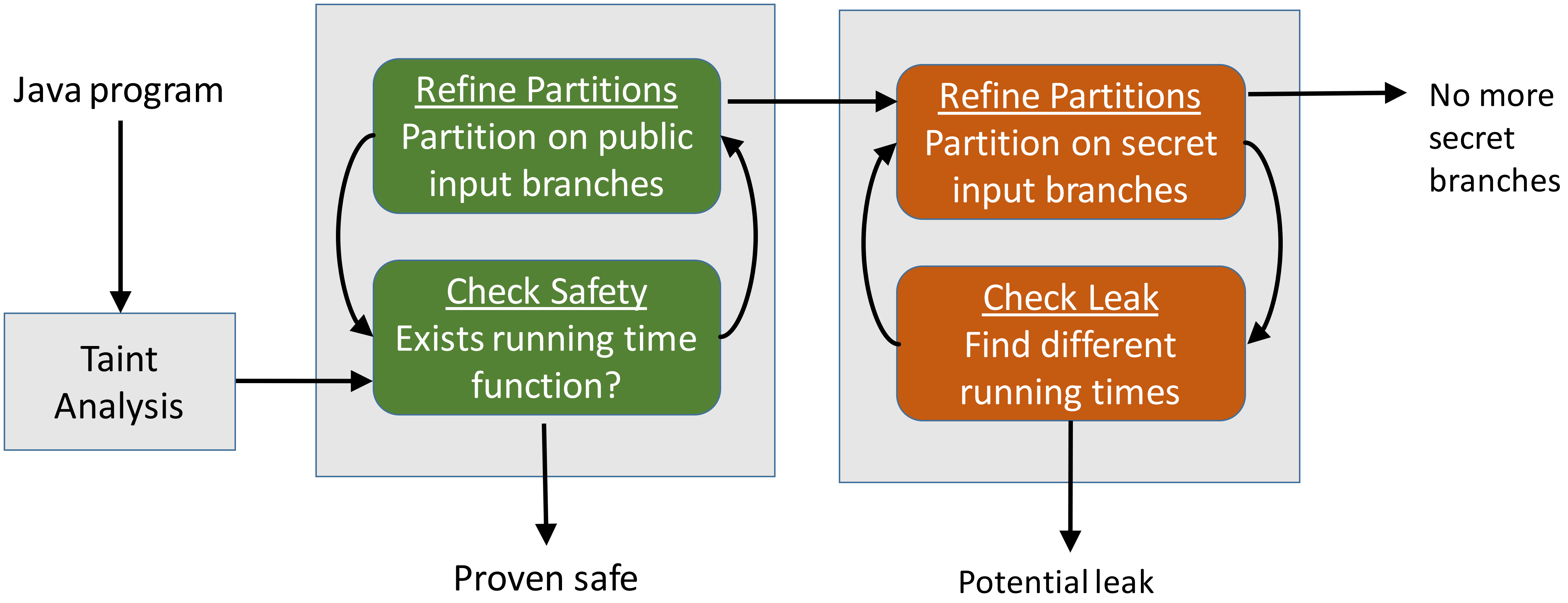
$$ktcf(C) \triangleq \forall\, \pi_1, \pi_2, \pi_3 \in [\![C]\!]^3.\\ \big(in(\pi_1)[\boldsymbol{\ell}] = in(\pi_2)[\boldsymbol{\ell}] = in(\pi_3)[\boldsymbol{\ell}]\big) \Rightarrow\\ \big(time(\pi_1) \approx time(\pi_2) \vee\\ time(\pi_1) \approx time(\pi_3) \vee\\ time(\pi_2) \approx time(\pi_3)\big).$$

Identifying Leaks

Safety Proving Algorithm



Leak Identification Algorithm



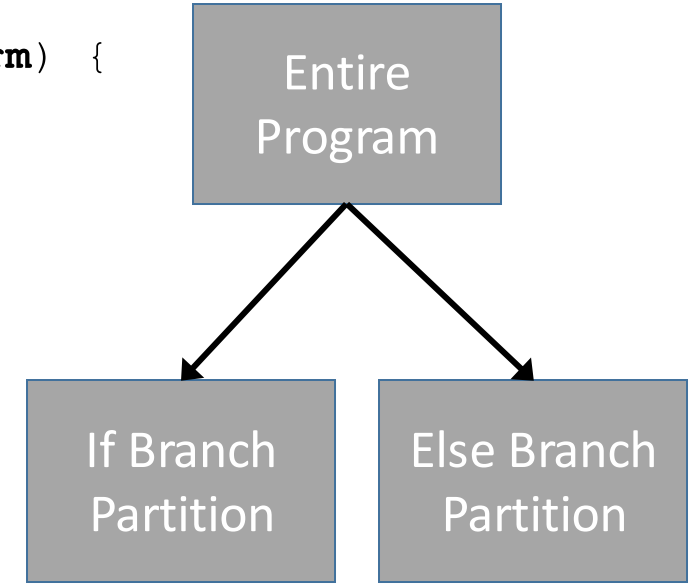
Algorithm in Action

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      return false;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```

Number of loop iterations reveals correct character count

Algorithm in Action: Attempt to Prove Safety

```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      return false;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confi
  } else
    matches = false;

  return (correct_chars
}
```



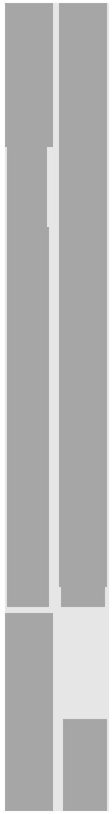
Running time analysis

Lower: 2 + new_pwd.len * 2 + 3

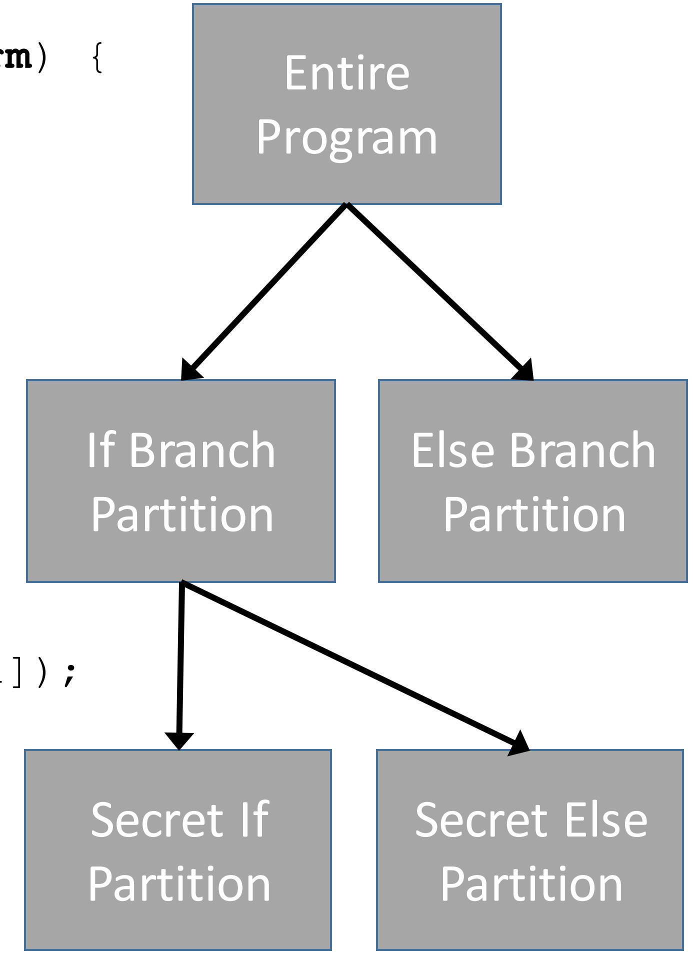
Upper: input_pwd.len * 2 + new_pwd.len * 2 + 3

Could be a secret-dependent difference in running time

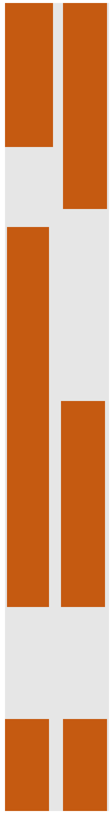
Algorithm in Action: Refine Secret Partitions



```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      return false;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
      matches = matches && (new_pwd[i] == new_pwd_confirm[i]);
  } else
    matches = false;

  return (correct_chars == real_pwd.length) && matches;
}
```



Algorithm in Action: Identify Leak



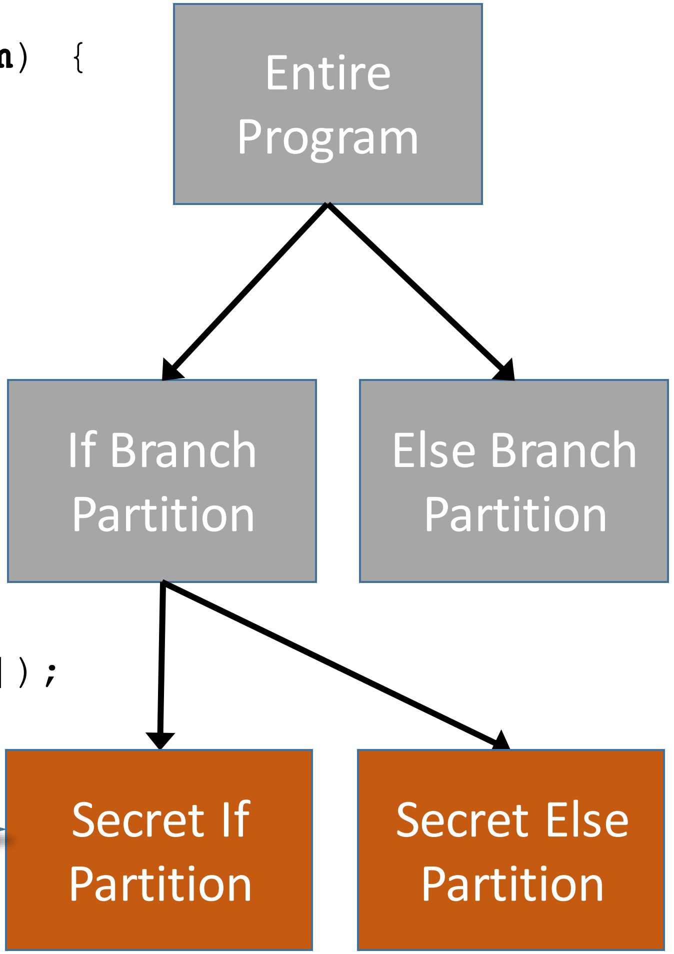
```
boolean chpass(real_pwd, input_pwd, new_pwd, new_pwd_confirm) {
  int correct_chars = 0;
  for(int i = 0; i < input_pwd.length; i++) {
    if(i < real_pwd.length && real_pwd[i] == input_pwd[i])
      correct_chars += 1;
    else
      return false;
  }

  boolean matches = true;
  if(new_pwd.length == new_pwd_confirm.length) {
    for (int i = 0; i < new_pwd.length; i++)
                                       irm[i]);
  }

  r                                             ;
}
```

Running time analysis

Lower: 2 + new_pwd.len * 2 + 3

Upper: input_pwd.len * 2 + new_pwd.len * 2 + 3

Could be a secret-dependent difference in running time



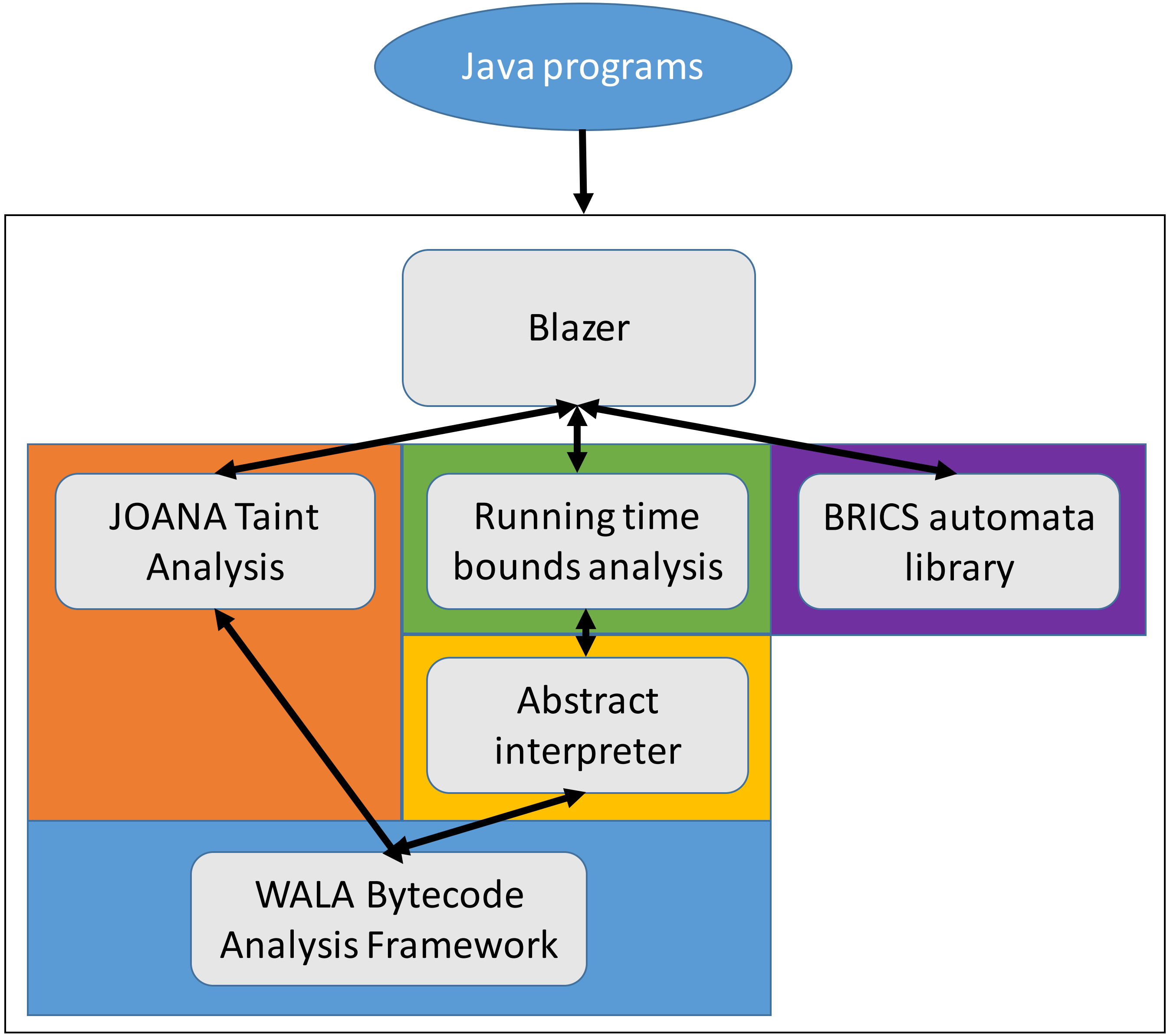
Blazer

An Implementation for Timing Channel Freedom

Architecture

- Taint analysis for public/secret branches
- BRICS library for partitioning
- Running time analysis based on abstract interpreter invariants

Component (Scala)	SLoC
Blazer	4,302
Running time analysis	1,517
Abstract interpreter	4,416



Benchmarks

- Three types of Java benchmarks
  - MicroBench – 12 small, simple examples
  - STAC - 6 from DARPA challenge programs
  - Literature – 6 adapted from literature
- DARPA/STAC benchmarks extracted from large, real-world program
  - Use other techniques to find potentially vulnerable hot methods
- The benchmarks are a few lines to a few dozen
  - One safe version
  - One unsafe version

Benchmark	Size	Safety Time (s)	w/Attack Time (s)
MicroBench			
array_safe	16	1.60	–
array_unsafe	14	0.16	0.70
loopBranch_safe	15	0.23	–
loopBranch_unsafe	15	0.65	1.54
nosecret_safe	7	0.35	–
notaint_unsafe	9	0.28	1.77
sanity_safe	10	0.63	–
sanity_unsafe	9	0.30	0.58
straightline_safe	7	0.21	–
straightline_unsafe	7	22.20	28.49
unixlogin_safe	16	0.86	–
unixlogin_unsafe	11	0.77	1.27
STAC			
modPow1_safe	18	1.47	–
modPow1_unsafe	58	218.54	464.52
modPow2_safe	20	1.62	–
modPow2_unsafe	106	7813.68	31758.92
pwdEqual_safe	16	2.70	–
pwdEqual_unsafe	15	1.30	2.90
Literature			
gpt14_safe	15	1.43	–
gpt14_unsafe	26	219.30	1554.64
k96_safe	17	0.70	–
k96_unsafe	15	1.29	3.14
login_safe	18	6.54	–
login_unsafe	17	4.40	9.10

- Size in basic blocks
- Time to prove safety
  - Average of 5 runs
- If not safe, time to prove attack
  - Average of 5 runs
- A few seconds or less for most benchmarks
  - 22.20s at most for safety proving

Proved safety or leak for all.

Benchmark	Size	Safety Time (s)	w/Attack Time (s)
MicroBench			
array_safe	16	1.60	–
array_unsafe	14	0.16	0.70
loopBranch_safe	15	0.23	–
loopBranch_unsafe	15	0.65	1.54
nosecret_safe	7	0.35	–
notaint_unsafe	9	0.28	1.77
sanity_safe	10	0.63	–
sanity_unsafe	9	0.30	0.58
straightline_safe	7	0.21	–
straightline_unsafe	7	22.20	28.49
unixlogin_safe	16	0.86	–
unixlogin_unsafe	11	0.77	1.27
STAC			
modPow1_safe	18	1.47	–
modPow1_unsafe	58	218.54	464.52
modPow2_safe	20	1.62	–
modPow2_unsafe	106	7813.68	31758.92
pwdEqual_safe	16	2.70	–
pwdEqual_unsafe	15	1.30	2.90
Literature			
gpt14_safe	15	1.43	–
gpt14_unsafe	26	219.30	1554.64
k96_safe	17	0.70	–
k96_unsafe	15	1.29	3.14
login_safe	18	6.54	–
login_unsafe	17	4.40	9.10

Scalability of Leak Identification

- Notable outliers
- Minutes or hours
- Related to block size
- Likely due to many partitions

Future Directions

- More fine-grained partitioning strategies for timing channel freedom
- Scaling Blazer to larger programs
- Using other running time analyses
  - E.g., dynamic running time analysis
- Application to other k-safety properties
  - New non-relational properties
  - New partitioning properties

Conclusion

- Technique to prove timing channel freedom by decomposition
- Generalization to k-safety properties
- Implementation of verification of timing channel freedom in the Blazer tool with an evaluation