Spezifikation von Abdeckungskriterien mit FQL

Testen
WS 2021

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Thomas Lemberger

FQL

- Basis: Holzer, Tautschnig, Veith, Schallhart: How did You Specify Your Test Suite?
- Spezifikationssprache für Test-Abdeckungskriterien

Terminologie

- CFA $\mathcal{A} = (L, l_0, E)$
- Transitionssystem $\mathcal{T} = (S, R, s_0)$
  - Zustandsraum S von Programmzuständen
  - Transitionsrelation $R \subseteq S \times S$
  - Anfangszustand s_0
- CFA $\mathcal{A}$ impliziert ein Transitionssystem $\mathcal{T}_{\mathcal{A}}$.
- Programmpfad $\pi = \langle s_0 s_1 \dots s_n \rangle$,
  Subpfad $\pi^{i \dots j} = \langle s_i s_{i+1} \dots s_j \rangle$
- $\mathcal{L}(\mathcal{T})$ sind alle Pfade durch $\mathcal{T}$, beginnend bei s_0

Prädikate

- Zustands-Prädikat φ über S
- Pfad-Prädikat ϕ über S^*
- Pfadmengen-Prädikat Φ über 2^{S^*}

- $s \models \varphi$, $s \in S$
- $\pi \models \phi$, $\pi \in S^*$
- $\Gamma \models \Phi$, $\Gamma \subseteq S^*$

- Pfad-Prädikat-Konkatenation:
  $\pi \models \phi_1 \cdot \phi_2$ iff
  $\pi^{0\ldots n} \models \phi_1$ and $\pi^{n\ldots|\pi|-1} \models \phi_2$

Tests

- Testfall ist Programmpfad seiner Ausführung
- Test-Suite ist Menge von Programmpfaden
- Abdeckungs-Kriterium Φ ist Funktion von CFA zu Pfadmengen-Prädikat

Gegeben CFA $\mathcal{A} = (L, l_0, E)$ und Abdeckungs-Kriterium Φ:
$\Phi(\mathcal{A}) = \Phi^{\mathcal{A}}$.
Test-Suite $\Gamma \subseteq \mathcal{L}(\mathcal{T}_{\mathcal{A}})$ erfüllt Abdeckungskriterium Φ falls $\Gamma \models \Phi^{\mathcal{A}}$

- Abdeckungs-Kriterium Φ ist *einfach*, wenn:
  1. $\Phi(\mathcal{A}) = \Phi^{\mathcal{A}} = \{\phi_1, \ldots, \phi_k\}$
  2. $\Gamma \models \Phi^{\mathcal{A}}$ gdw. $\forall \phi_i \in \Phi^{\mathcal{A}}.\exists \pi \in \Gamma.\pi \models \phi_i$

Abdeckungs-Kriterien

FQL-Syntax zur Beschreibung einfacher Abdeckungs-Kriterien:

$$
\begin{aligned}
\Phi &::= && \text{in } T \text{ cover } C \text{ passing } P \\
C &::= && C + C \mid C.C \mid (C) \mid N \mid S \mid ''P'' \\
P &::= && P + P \mid P.P \mid (P) \mid N \mid S \mid P^* \\
\\
N &::= && \texttt{NODES}(T) \mid \texttt{EDGES}(T) \mid \texttt{PATHS}(T, k) \\
T &::= && F \mid \texttt{PRED}(T, \varphi) \mid \texttt{COMPOSE(T, T)} \\
&&& \mid T|T \mid T\&T \mid \texttt{SETMINUS}(T, T) \\
F &::= && \texttt{ID} \mid \texttt{@BASICBLOCKENTRY} \mid \ldots
\end{aligned}
$$

$$\texttt{NODES}(T) = \sum_{n \in nodes(T[\mathcal{A}])} n$$

$$\texttt{EDGES}(T) = \sum_{e \in edges(T[\mathcal{A}])} e$$

$$\texttt{PATHS}(T, k) = \sum_{p \in paths_k(T[\mathcal{A}])} p$$

Filter-Funktionen

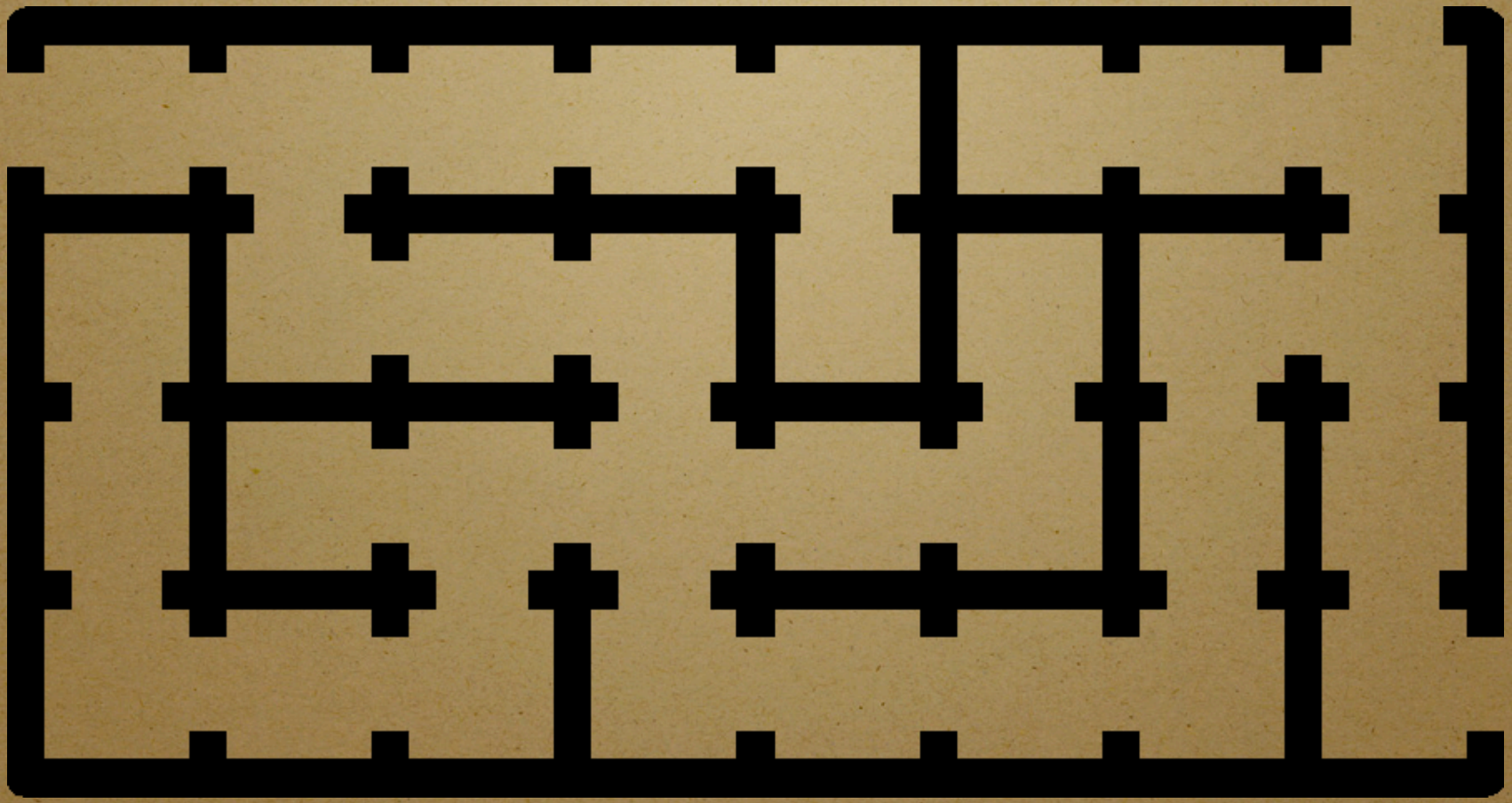
- CFA Transformer $T : \mathit{CFA} \mapsto \mathit{CFA}$.
- Ein Filter F ist ein CFA Transformer. Gegeben CFA $\mathcal{A} = (L, l_0, E)$,
  $F[\mathcal{A}] = (L', l_0', E')$ mit $L' \subseteq L$, $E' \subseteq E$, $l_0 \in L'$, und
  $E' \subseteq L' \times \mathit{Ops} \times L'$
- Beispiele: `@BASICBLOCKENTRY`, `@DECISIONEDGE`, `@FILE`

FQL zu Pfad-Prädikaten

$$\Phi = \text{in } G \text{ cover } C \text{ passing } P$$

1. $C' = C$ angewandt auf $G[\mathcal{A}]$ mit Auswertung von `NODES`, `EDGES`, `PATHs`
2. $P' = P$ mit Auswertung von `NODES`, `EDGES`, `PATHs`
3. $\Phi(\mathcal{A}) = \mathcal{L}(\text{cover } C' \text{ passing } P')$

Scavenger Hunt



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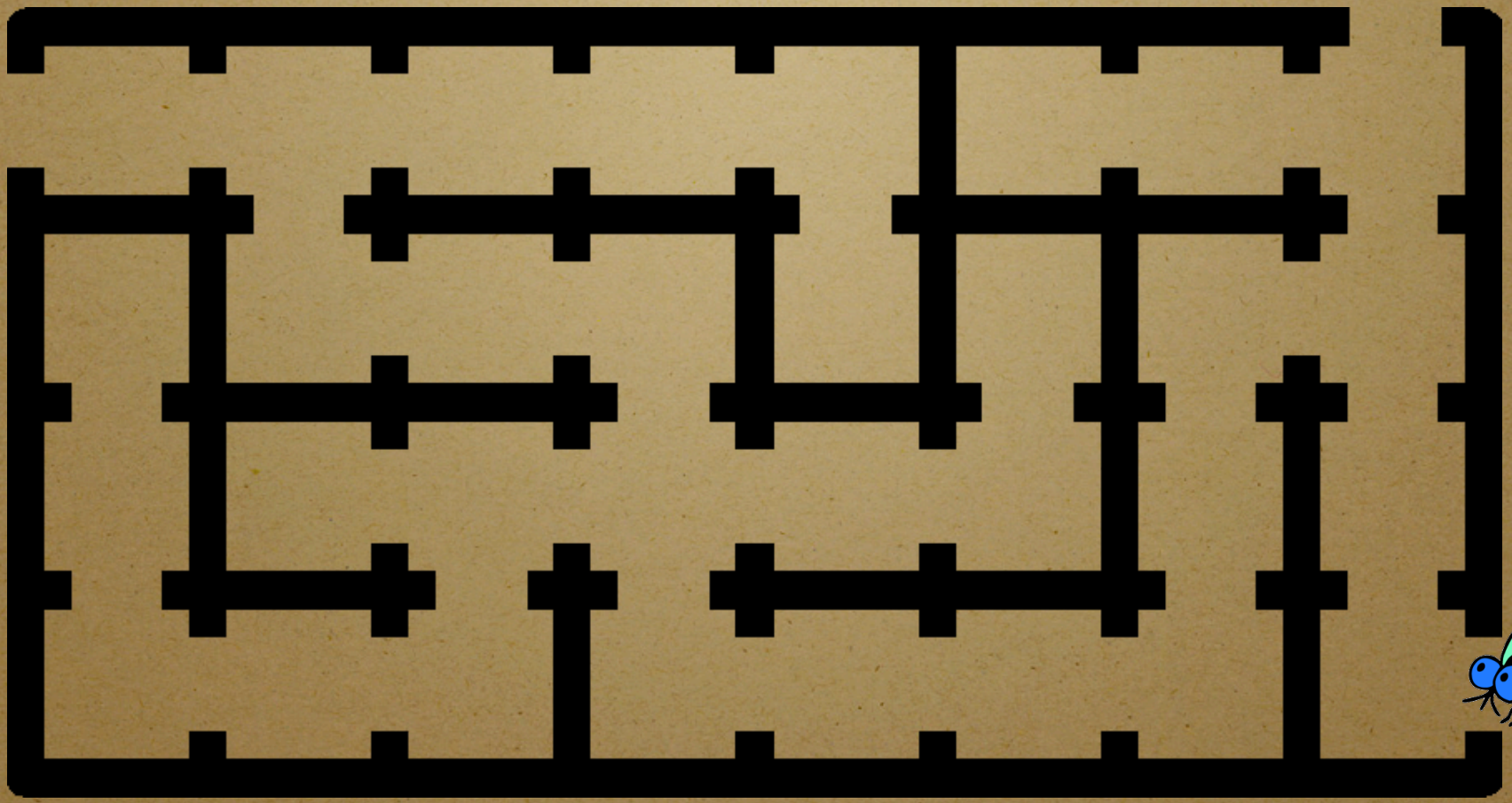

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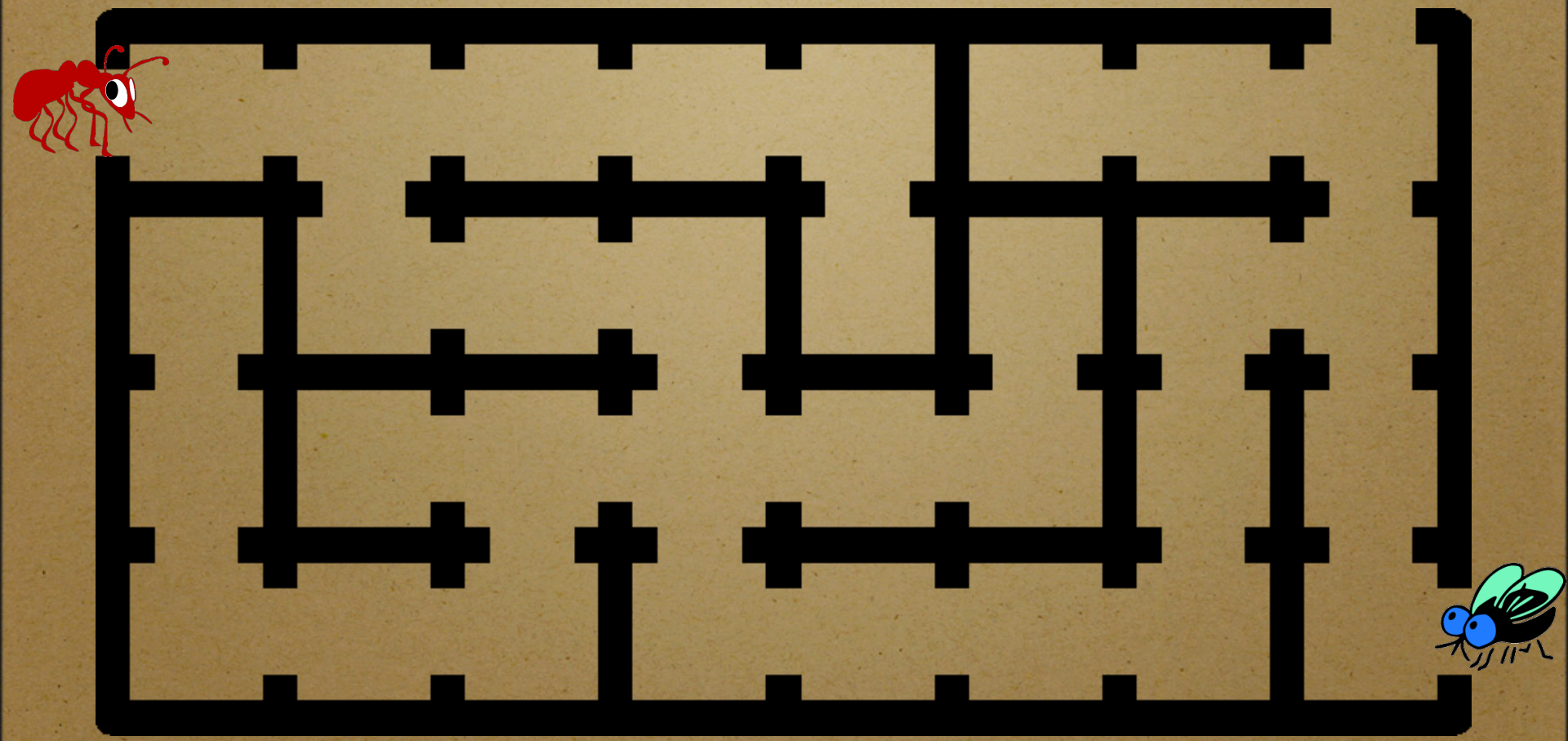

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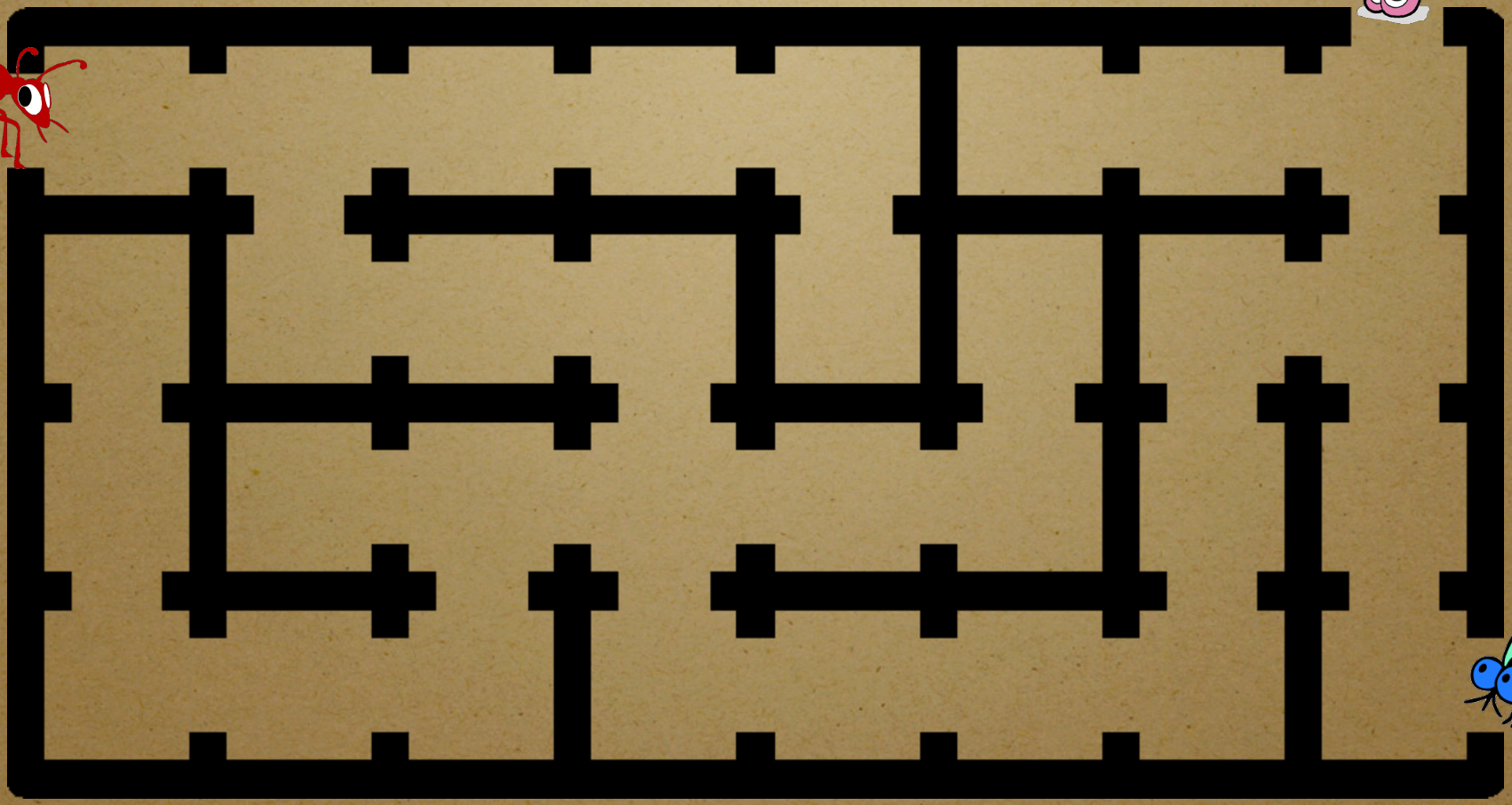

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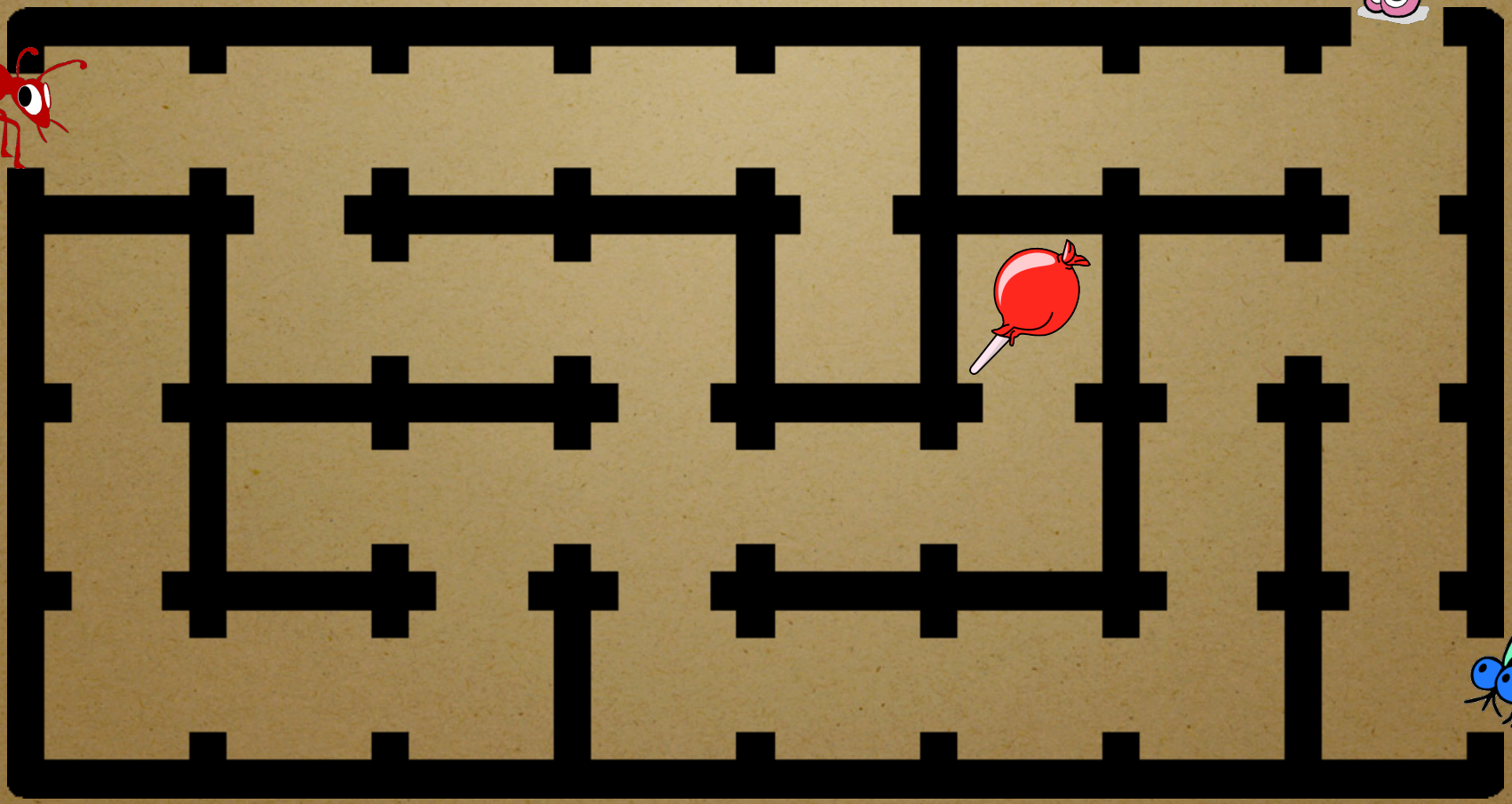

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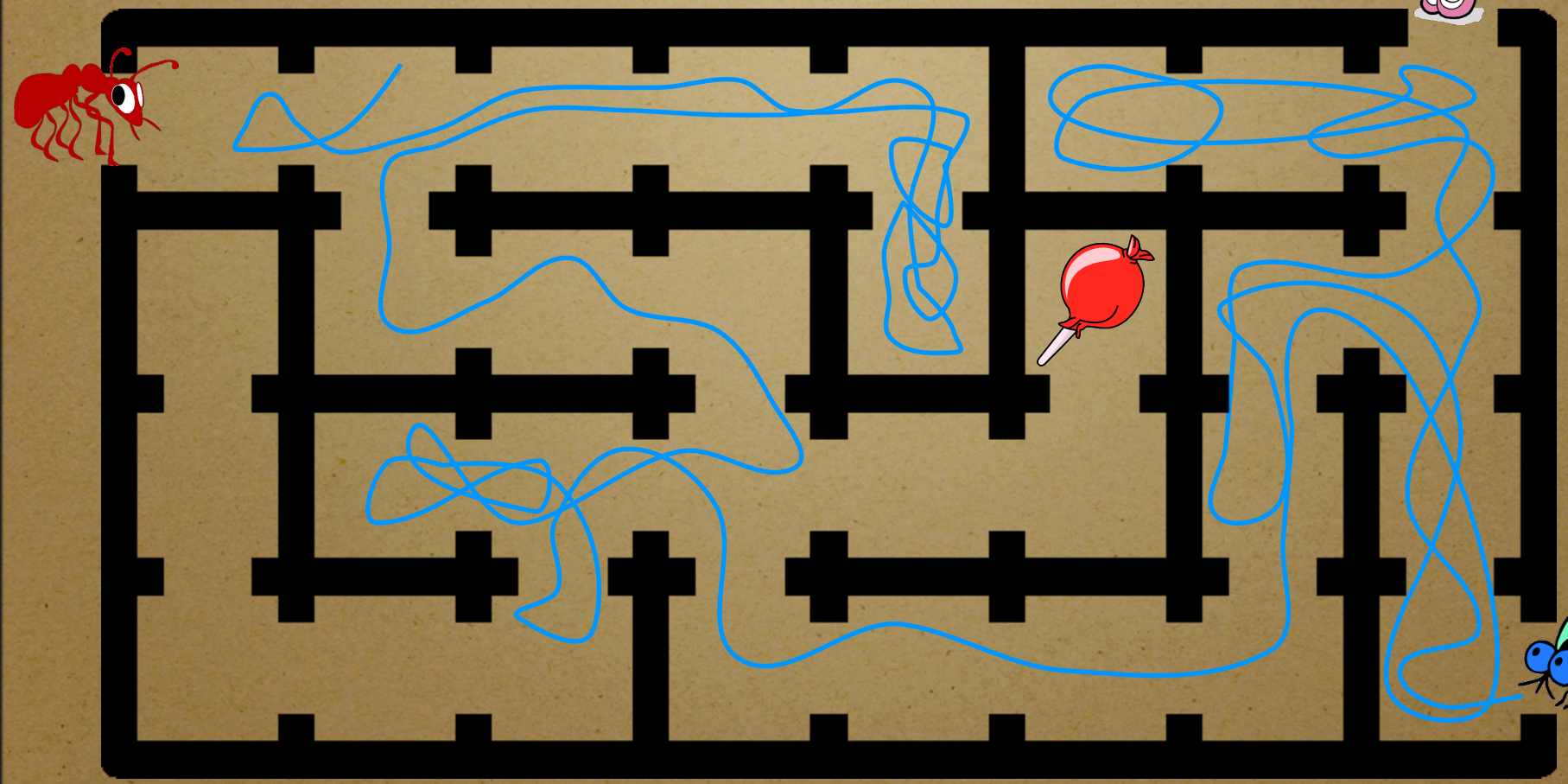

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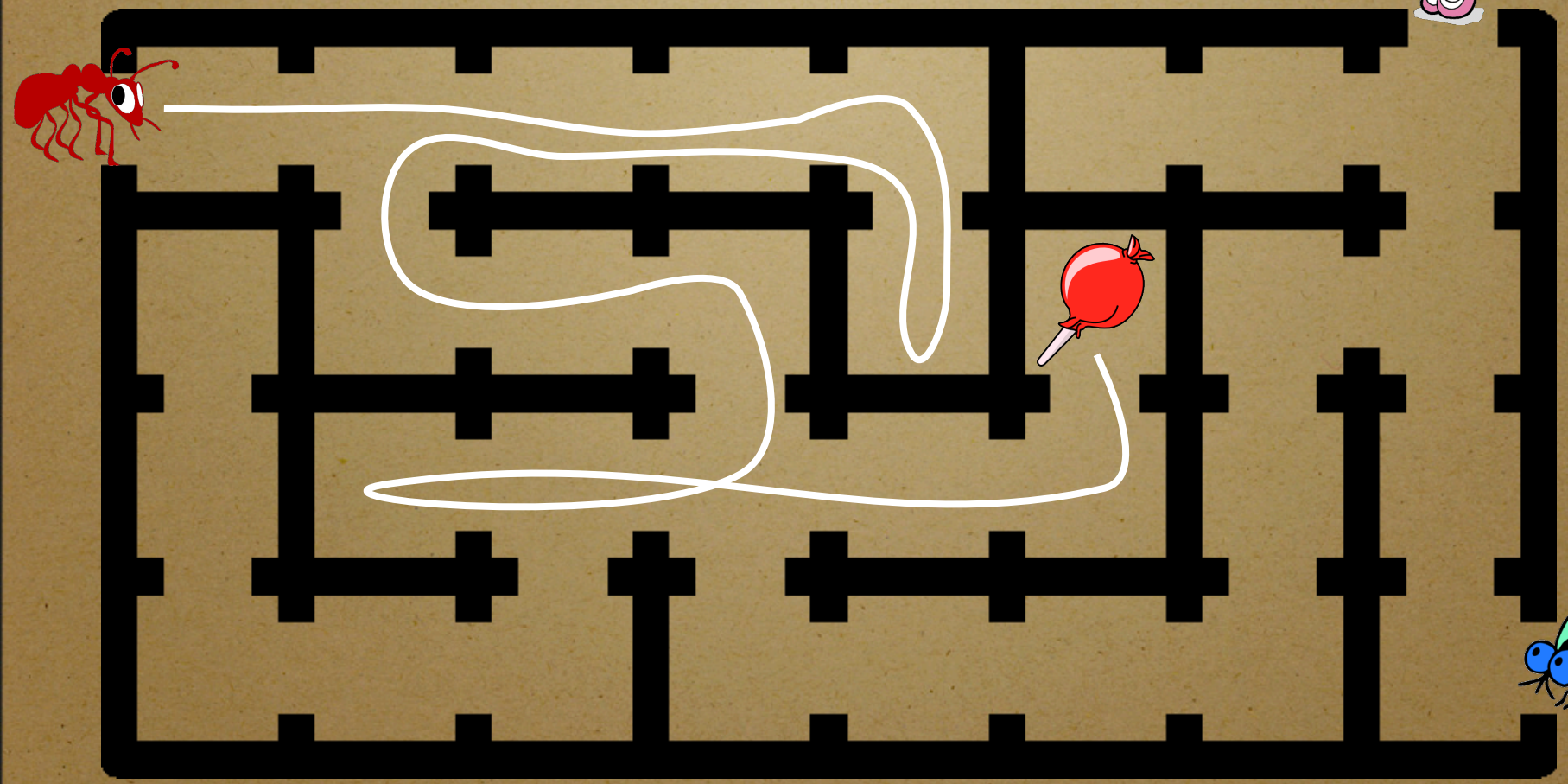

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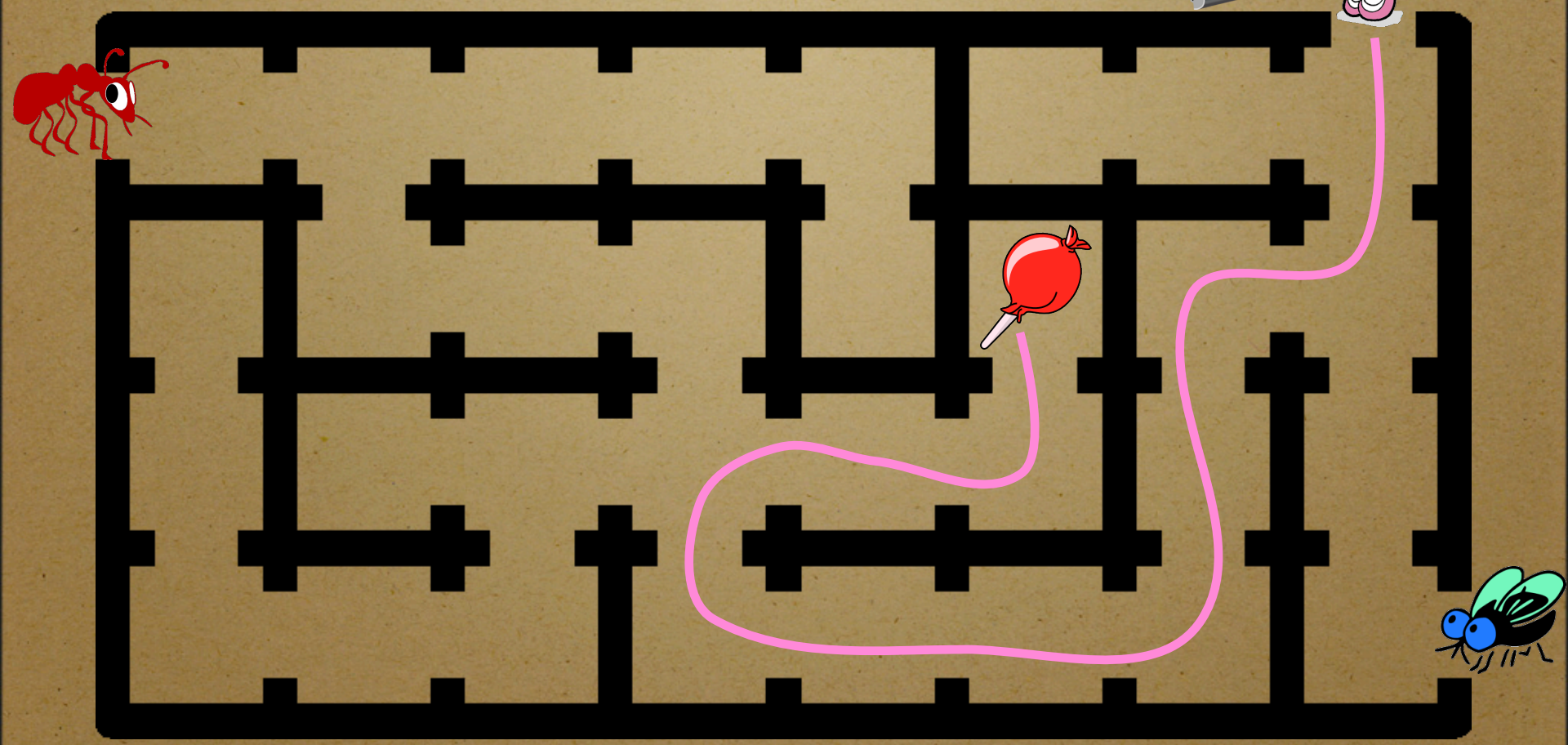
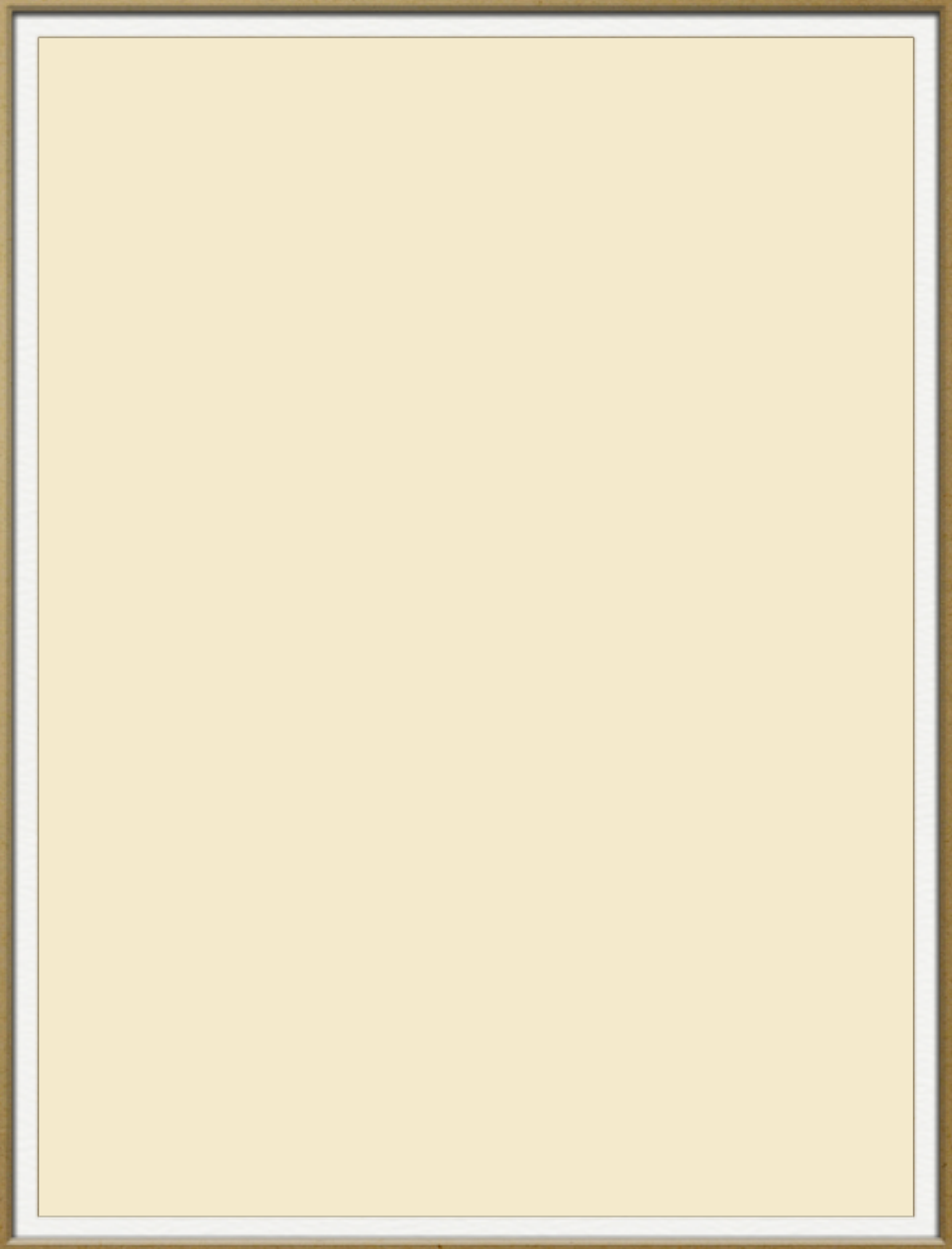


Software Testing



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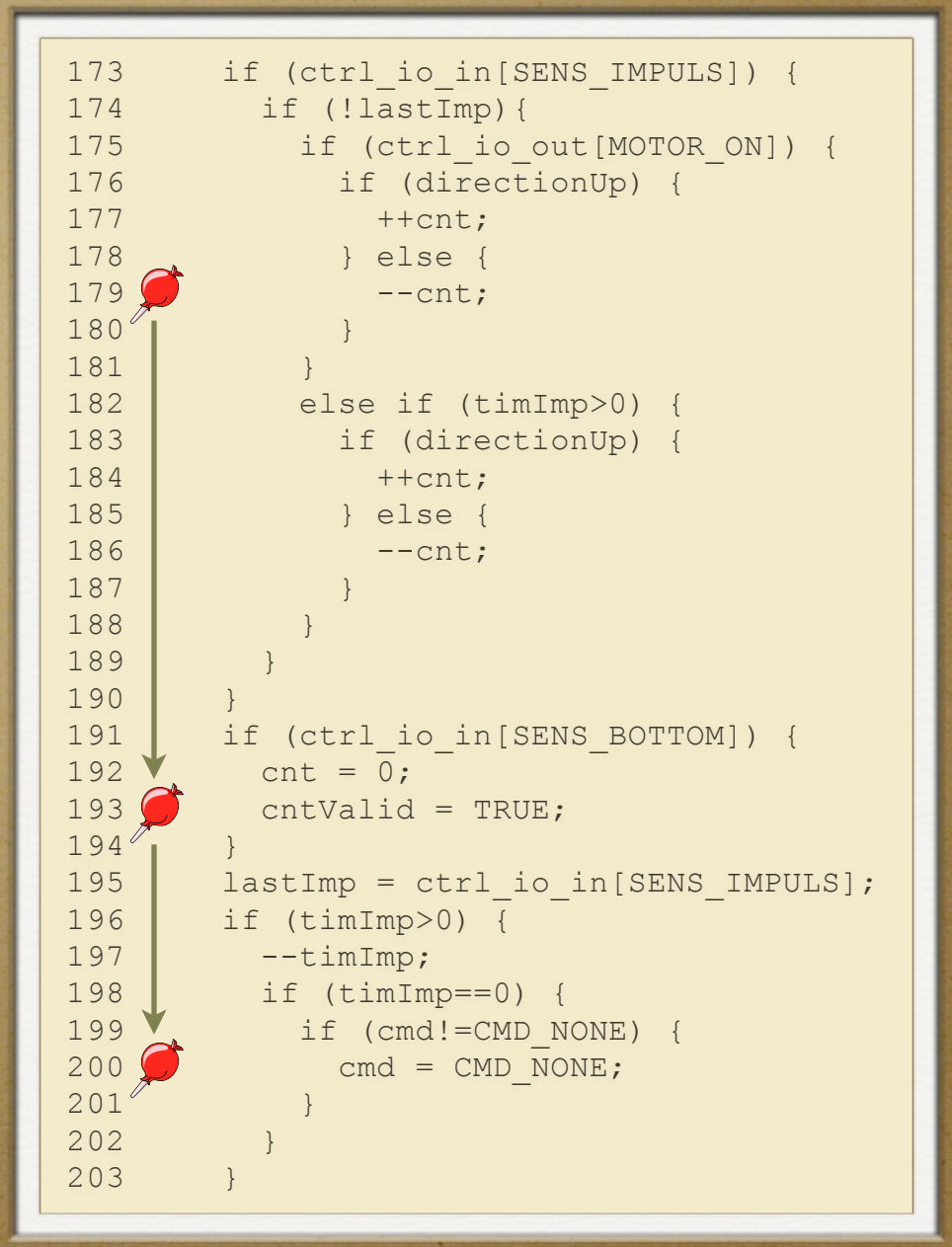

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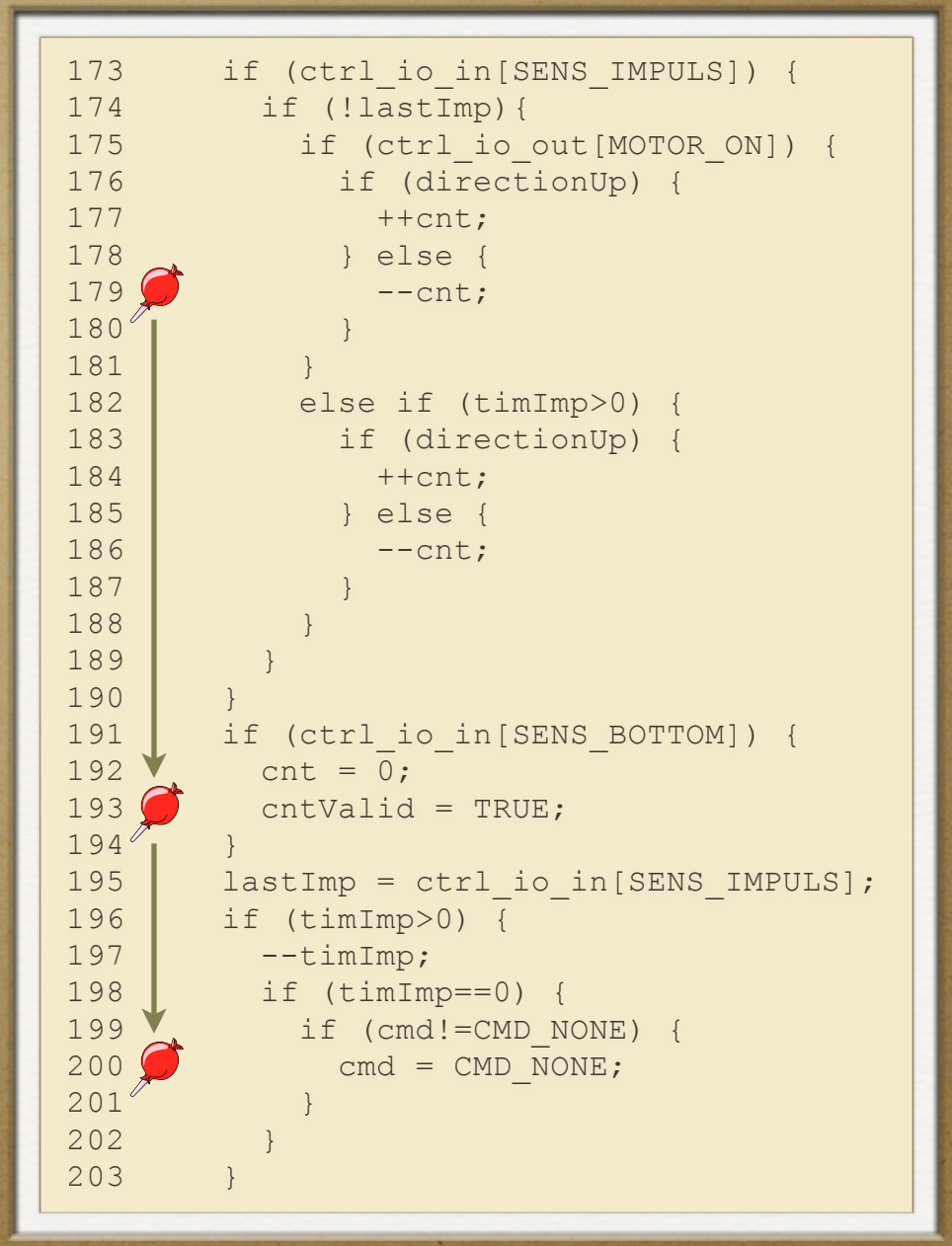

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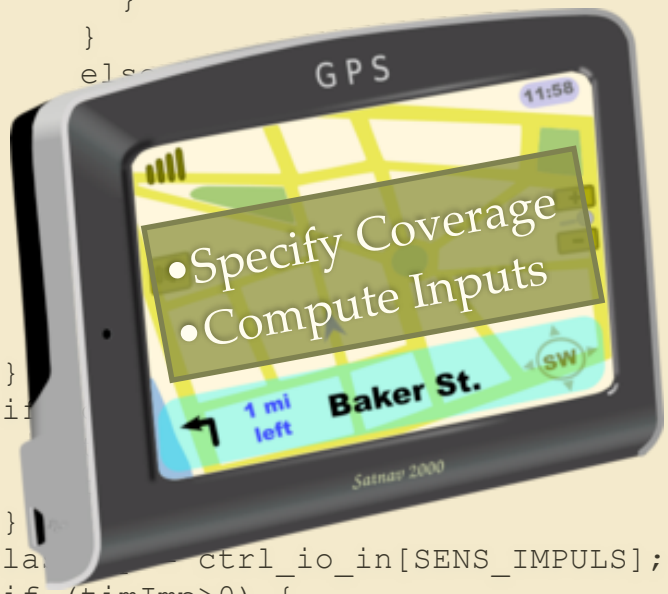

TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

How did you specify your test suite ?

Michael Tautschnig
Formal Methods in Systems Engineering
Vienna University of Technology

Joint work with
Andreas Holzer, Christian Schallhart, and Helmut Veith

Standard Coverage Criteria

```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
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Basic Block Coverage

Requires a test suite such that each basic block is executed at least once

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1  int example(int a, int b, int c, int d)
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3    if ((a || b) && c)
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Decision Coverage

Conditional statements evaluate to true/false

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Atomic conditions evaluate to true/false

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Condition/Decision Coverage

Union of condition and decision coverage

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All Boolean combinations of atomic conditions in complex conditions

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```

a	b	c
F	F	F
F	F	T
F	T	F
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Def-Use Coverage

Cover all definition/use pairs of a variable *d*

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Def-Use Coverage

Cover all definition/use pairs of a variable *d*

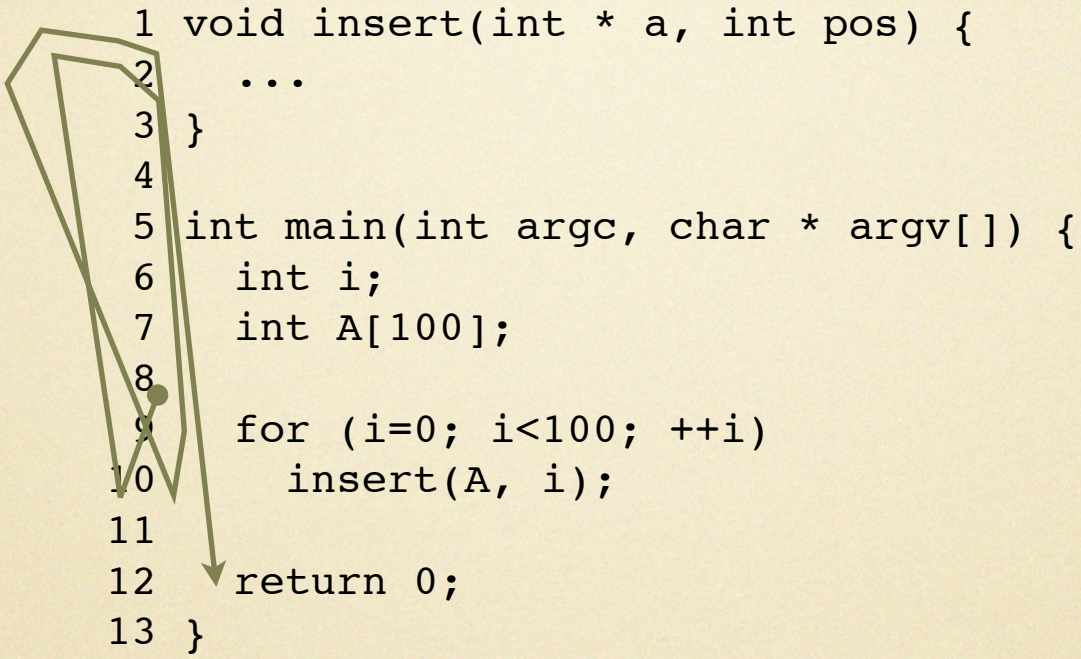
Beyond Standard Criteria

```
 1 void insert(int * a, int pos) {
 2   ...
 3 }
 4
 5 int main(int argc, char * argv[]) {
 6   int i;
 7   int A[100];
 8
 9   for (i=0; i<100; ++i)
10     insert(A, i);
11
12   return 0;
13 }
```

Loop-Bounded Path Coverage

- All paths through *main* and *insert*
- Pass each statement two times

Beyond Standard Criteria



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3  }
4
5  int main(int argc, char * argv[]) {
6    int i;
7    int A[100];
8
9    for (i=0; i<100; ++i)
10     insert(A, i);
11
12   return 0;
13 }
```

Loop-Bounded Path Coverage

- All paths through *main* and *insert*
- Pass each statement two times

Beyond Standard Criteria

```
 1 int partition(int a[], int left, int right) {
 2   int v = a[right], i = left - 1, j = right, t;
 3   for (;;) {
 4     while (a[++i] < v) ;
 5     while (j > left && a[--j] > v) ;
 6     if (i >= j) break;
 7     t = a[i]; a[i] = a[j]; a[j] = t;
 8   }
 9   t = a[i]; a[i] = a[right]; a[right] = t;
10   return i;
11 }
```

Cartesian Block Coverage

All pairs and triples of basic blocks in function *partition*

Beyond Standard Criteria

```
 1 int partition(int a[], int left, int right) {
 2   int v = a[right], i = left - 1, j = right, t;
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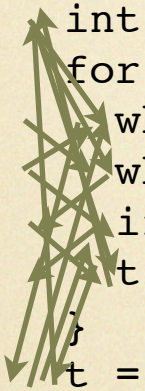
 6     if (i >= j) break;
 7     t = a[i]; a[i] = a[j]; a[j] = t;
 8   }
 9   t = a[i]; a[i] = a[right]; a[right] = t;
10   return i;
11 }
```



Cartesian Block Coverage

All pairs and triples of basic blocks in function *partition*

Specs for Working Programmers

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

Cover Specific Lines of Code

Lines 4 and 6

Specs for Working Programmers

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

Cover Specific Lines of Code

Lines 4 and 6

Specs for Working Programmers

```
 1 void eval(int * a, int first, int last) {
 2   if (first > last) return;
 3   printf("a[%d]=%d\n", first, a[first]);
 4   eval(a+1, first+1, last);
 5   return;
 6 }
 7
 8 int main(int argc, char * argv[]) {
 9   int i;
10   int A[100];
11
12   for (i=0; i<100; ++i)
13     insert(A, i);
14
15   eval(A, 0, 100);
16   return 0;
17 }
```

Restricted Scope of Analysis

Basic block coverage in function *eval* only

Specs for Working Programmers

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 1 void eval(int * a, int first, int last) {
 2   if (first > last) return;
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 4   eval(a+1, first+1, last);
 5   return;
 6 }
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 9   int i;
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11
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13     insert(A, i);
14
15   eval(A, 0, 100);
16   return 0;
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```

Restricted Scope of Analysis

Basic block coverage in function *eval* only

Specs for Working Programmers

```
 1 void sort(int * a, int len) {
 2   int i, t;
 3   for (i=1; i<len; ++i) {
 4     if (compare(a[i-1], a[i])) continue;
 5     t=a[i]; a[i]=a[i-1]; a[i-1]=t;
 6   }
 7 }
 8
 9 void eval(int * a, int len) {
10   int i;
11   for (i=0; i < 3; ++i)
12     printf("a[%d]=%d\n", i, a[i]);
13 }
14
15 int main(int argc, char * argv[]) {
16   int i; int A[100];
17   for (i=0; i < 100; ++i) sort(A, 100);
18   eval(A, 100);
19   return 0;
20 }
```

Interaction Coverage

Cover all pairs of conditions in *sort* and basic blocks in *eval*

Specs for Working Programmers

```
 1 void sort(int * a, int len) {
 2   int i, t;
 3   for (i=1; i<len; ++i) {
 4     if (compare(a[i-1], a[i])) continue;
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 6   }
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 8
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13 }
14
15 int main(int argc, char * argv[]) {
16   int i; int A[100];
17   for (i=0; i < 100; ++i) sort(A, 100);
18   eval(A, 100);
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```

Interaction Coverage

Cover all pairs of conditions in *sort* and basic blocks in *eval*

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```

Constrained Inputs

- Basic block coverage in *sort*
- Each test case shall use list of 2 to 15 elements

Specs for Working Programmers

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Specs for Working Programmers

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Avoid Unfinished Code

- Basic block coverage in *example*
- Never call *unimplemented*

Specs for Working Programmers

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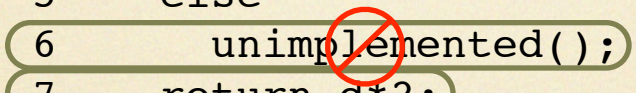
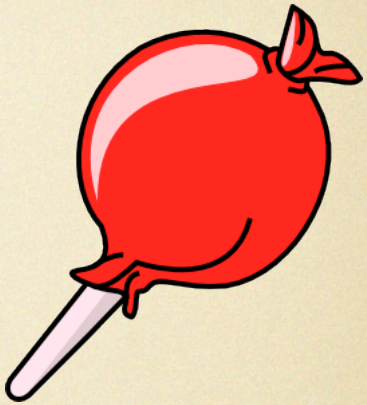


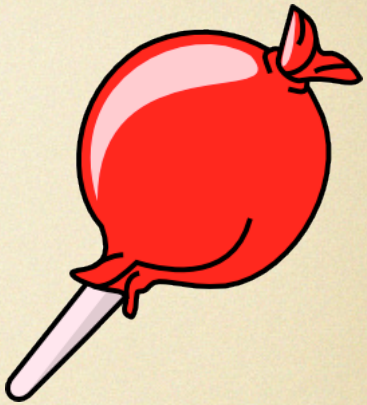
Avoid Unfinished Code

- Basic block coverage in *example*
- Never call *unimplemented*

Test Specification Language



Test Specification Language



Precise and simple formalism to describe test suites

Precise semantics

High expressive power

Simple specifications easily expressible

Suitable for working programmer

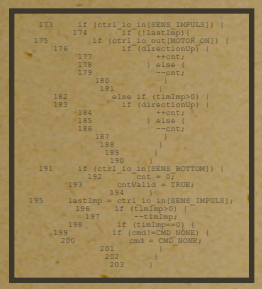
Algorithmic Solution

Algorithmic Solution

Tool for the working programmer

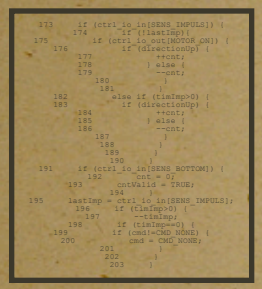
Applicability to real world C code (embedded systems)

Efficient test input generation engines



```
173     if (ctrl_io_in[SENS_IMPULS]) {
174         if (!lastImp) {
175             if (ctrl_io_out[MOTOR_ON]) {
176                 if (directionUp) {
177                     ++cnt;
178                 } else {
179                     --cnt;
180                 }
181             }
182         } else if (timImp>0) {
183             if (directionUp) {
184                 ++cnt;
185             } else {
186                 --cnt;
187             }
188         }
189         lastImp = 0;
190     }
191     if (ctrl_io_in[SENS_BOTTOM]) {
192         cnt = 0;
193         cntValid = TRUE;
194     }
195     lastImp = ctrl_io_in[SENS_IMPULS];
196     if (timImp>0) {
197         --timImp;
198         if (timImp==0) {
199             if (cmd!=CMD_NONE) {
200                 cmd = CMD_NONE;
201             }
202         }
203     }
```

Lines 179, 193, 200



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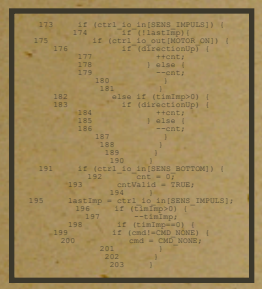
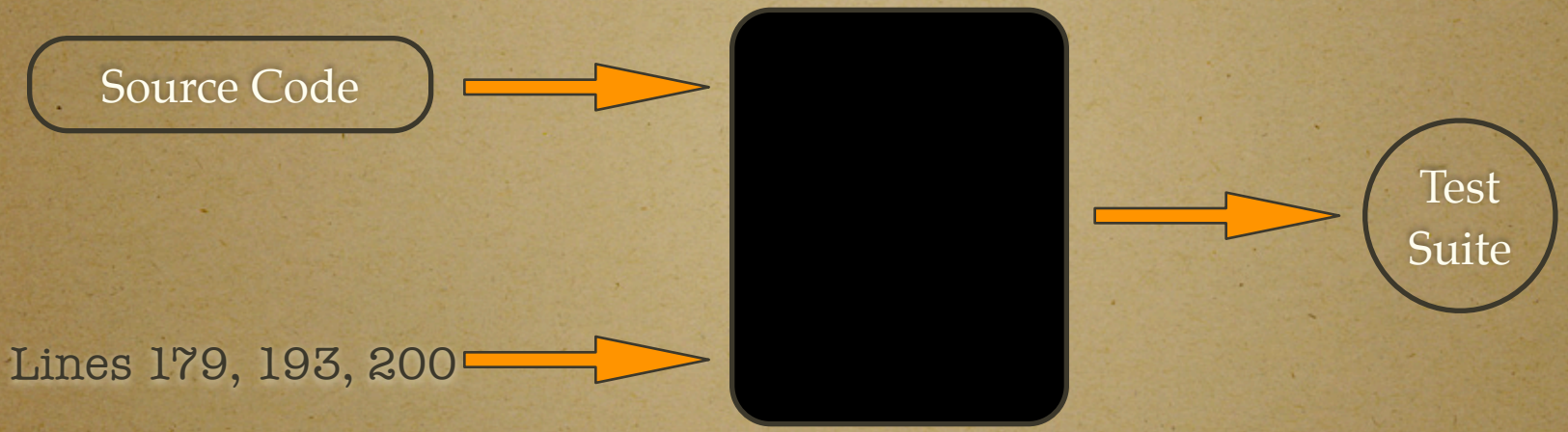
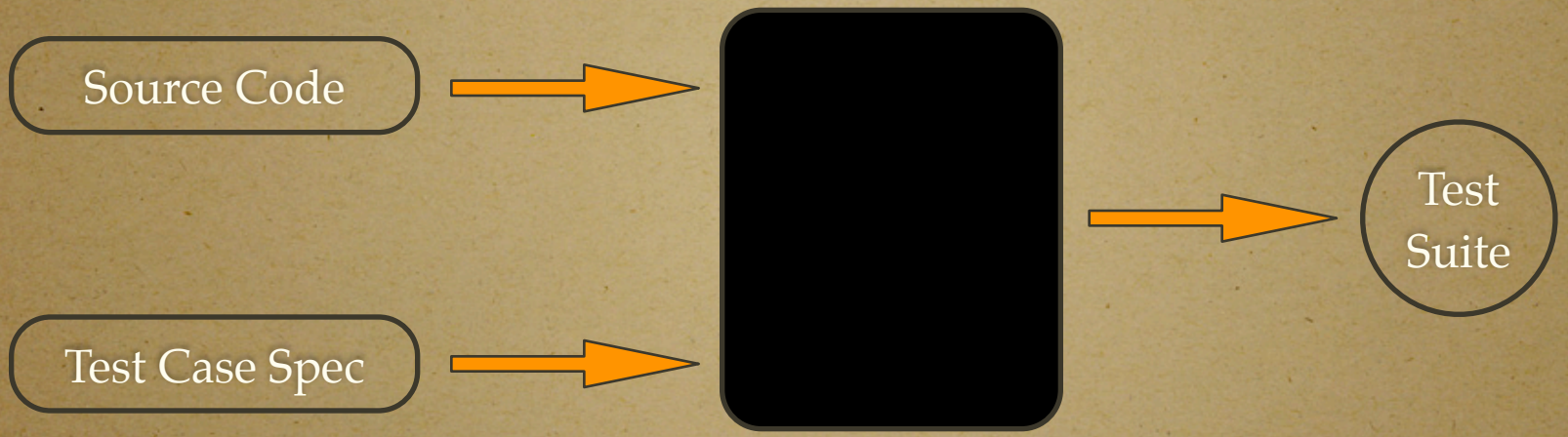
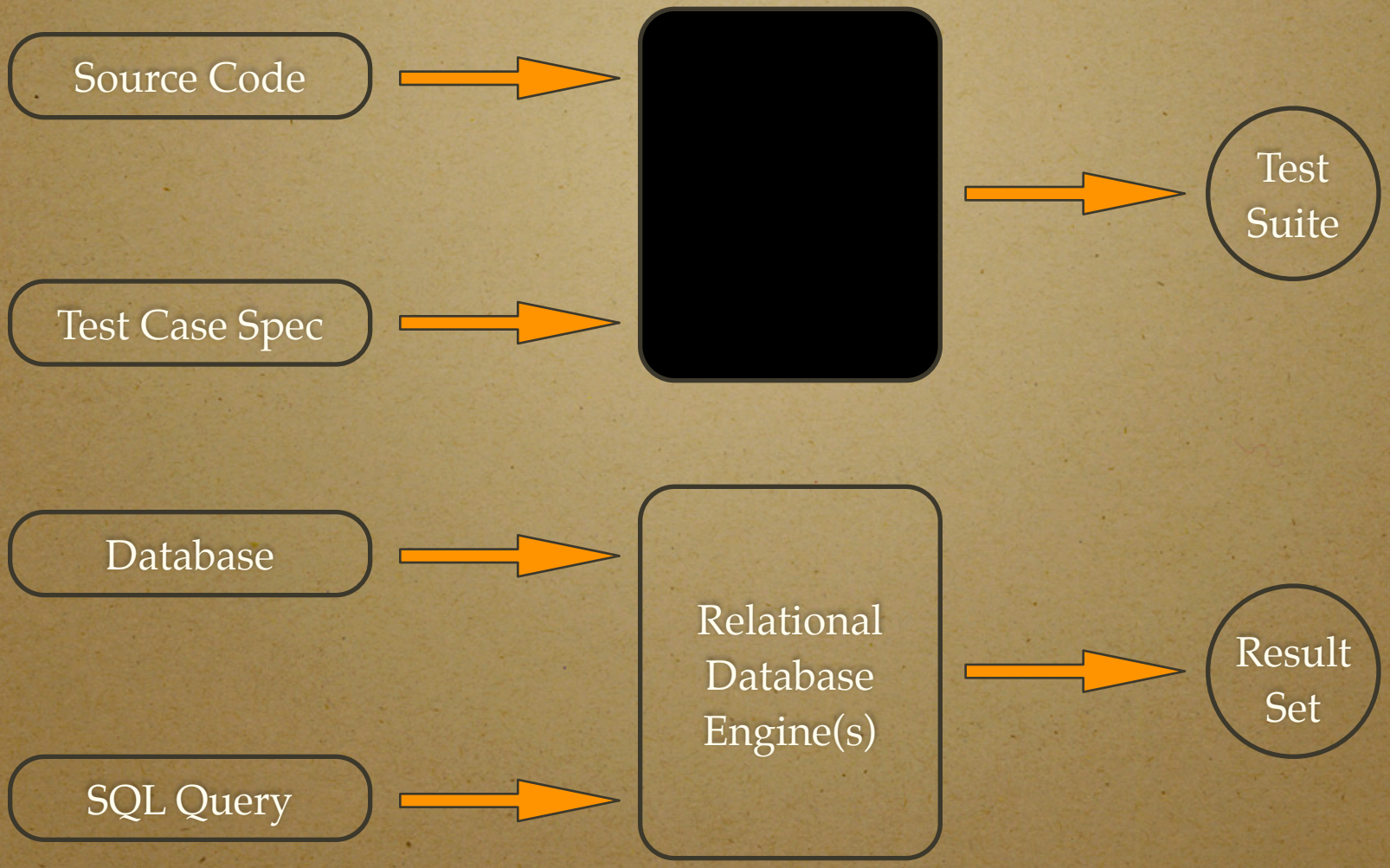


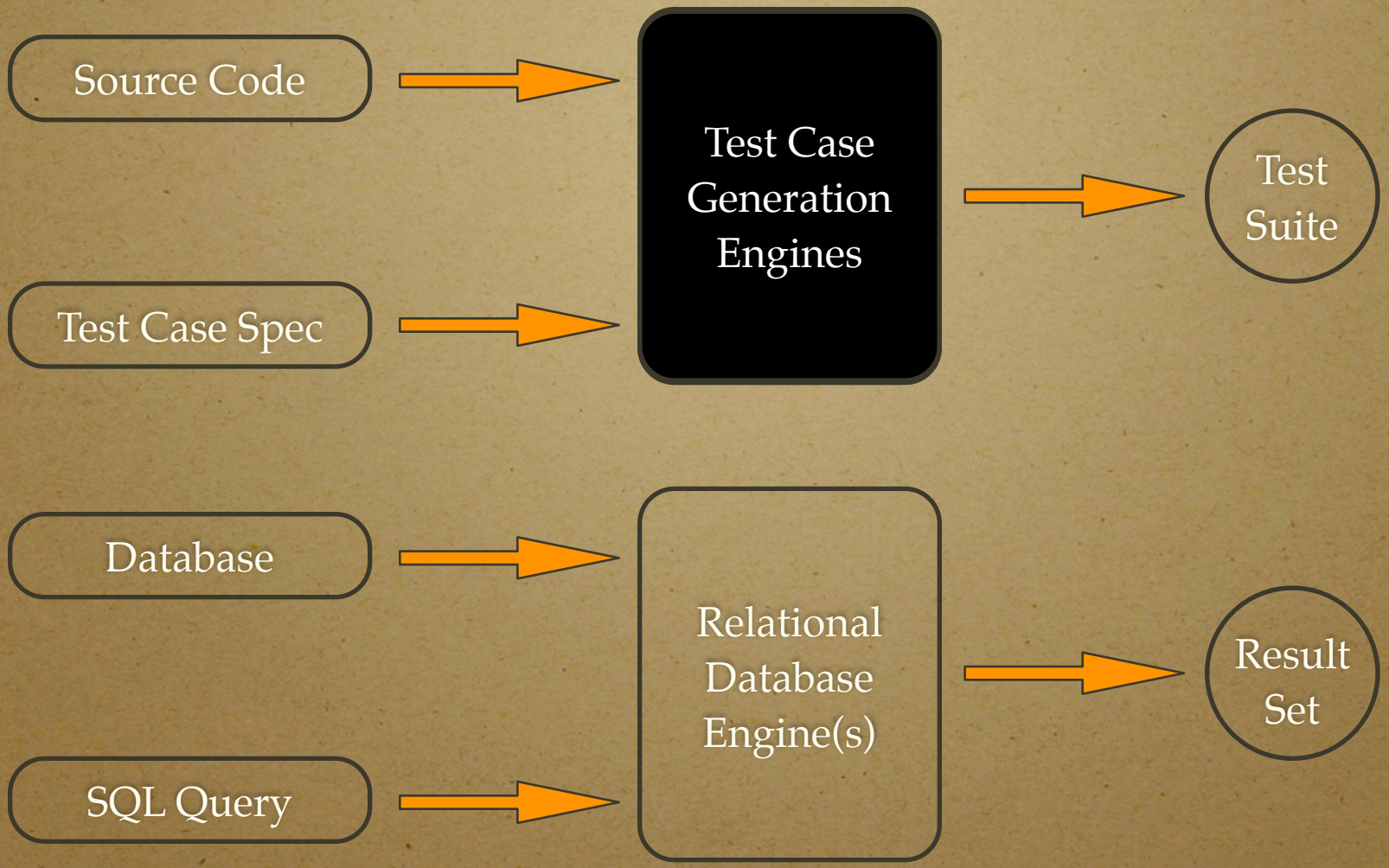
Lines 179, 193, 200

Test Suite


Source Code
Lines 179, 193, 200
Test
Suite


Source Code
Test Case Spec
Test
Suite


Source Code
Test Case Spec
Database
SQL Query
Relational Database Engine(s)
Test Suite
Result Set


Source Code
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Test Case Generation Engines
Test Suite
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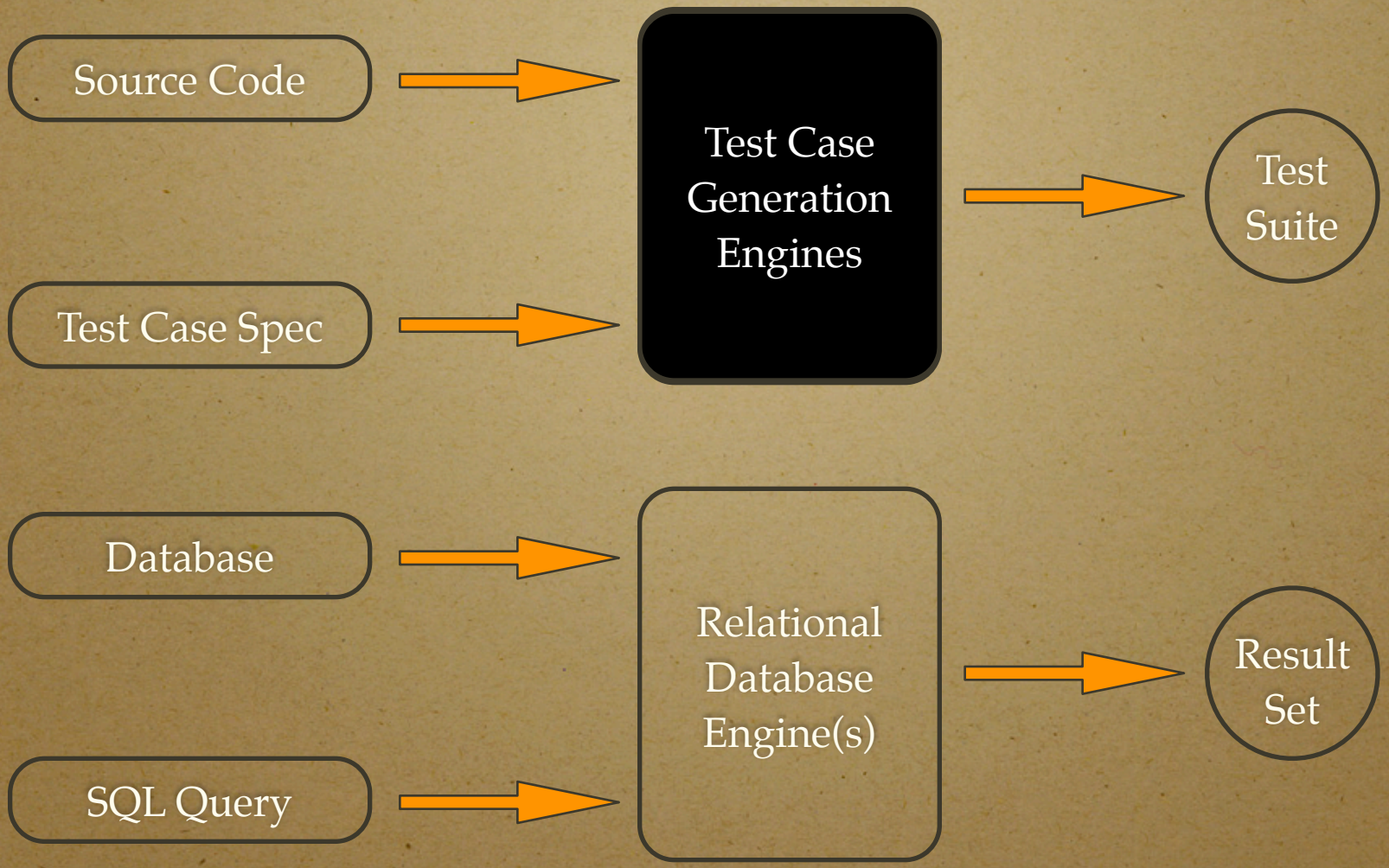
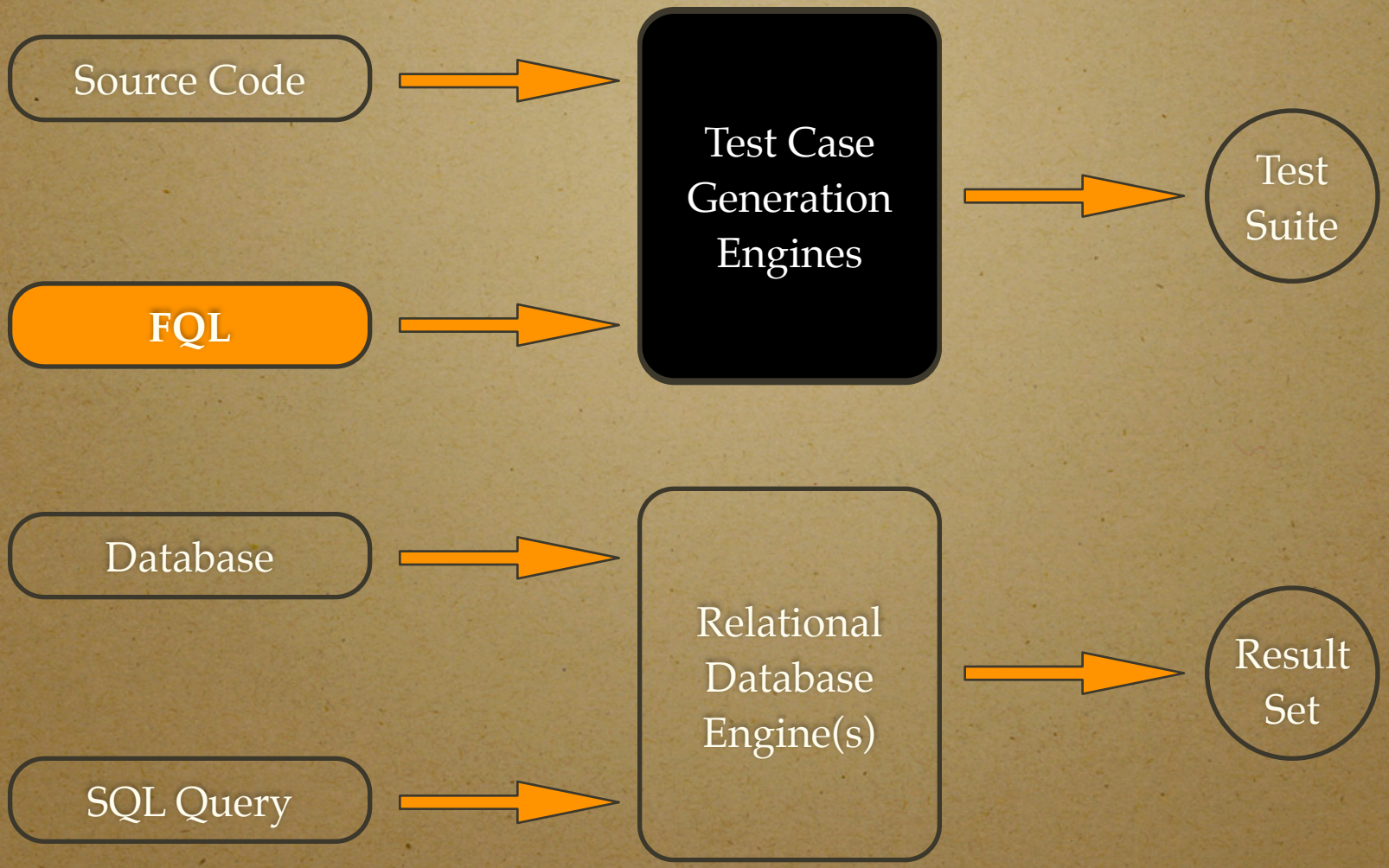
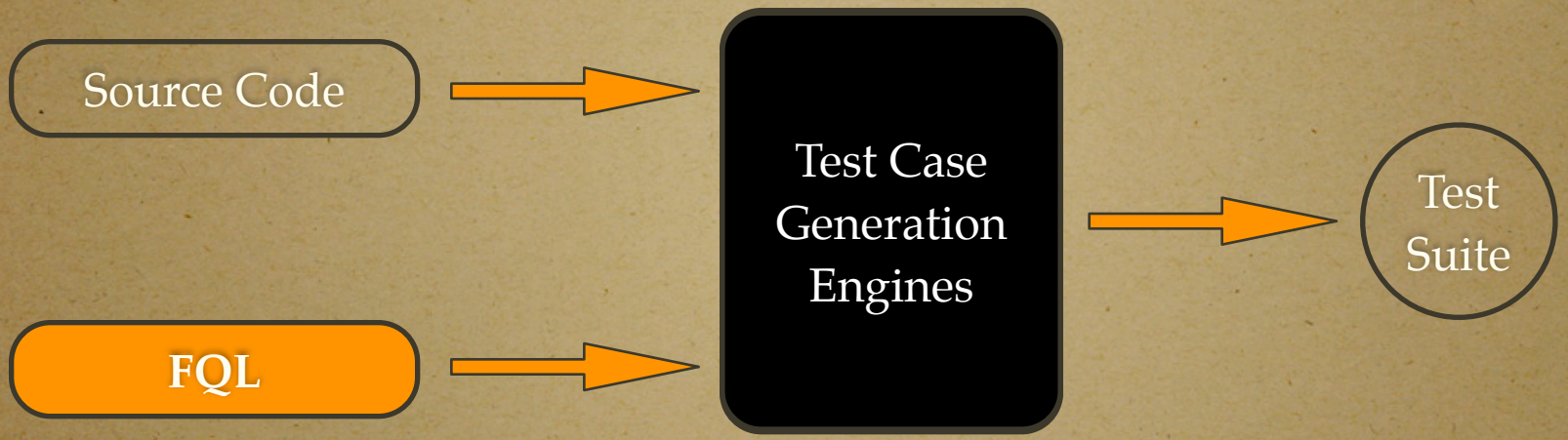
Query-Driven Program Testing



Query-Driven Program Testing

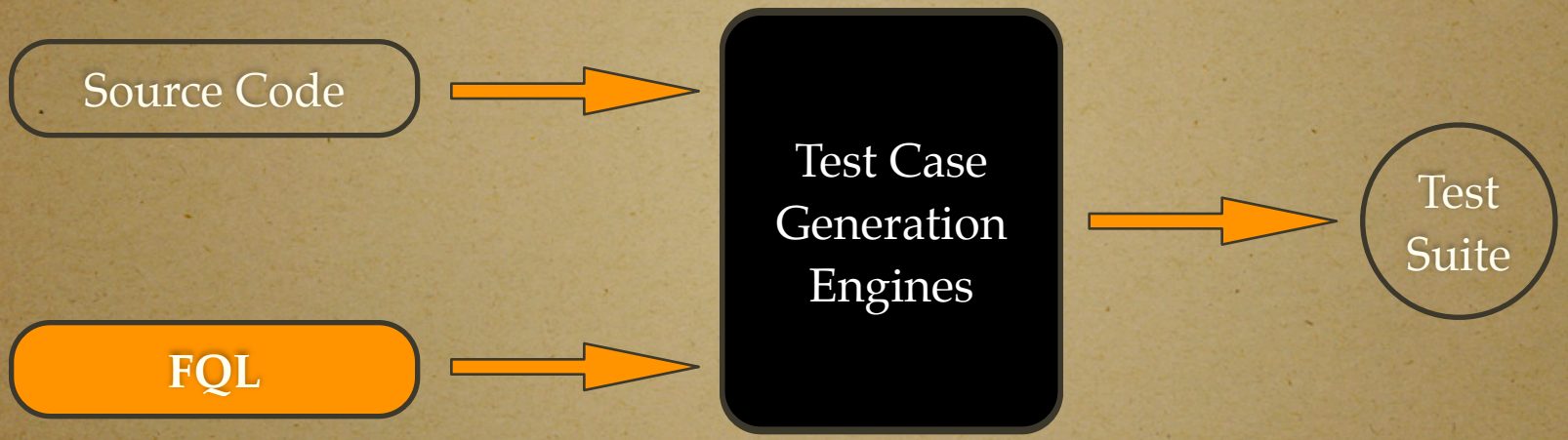


Query-Driven Program Testing



- Algorithmic approach presented at CAV'08, VMCAI'09
- Two engines already exist
  - FShell: Based on CBMC (C Bounded Model Checker)
  - FlleSh: Uses CPAchecker (Configurable Program Analysis)

Query-Driven Program Testing



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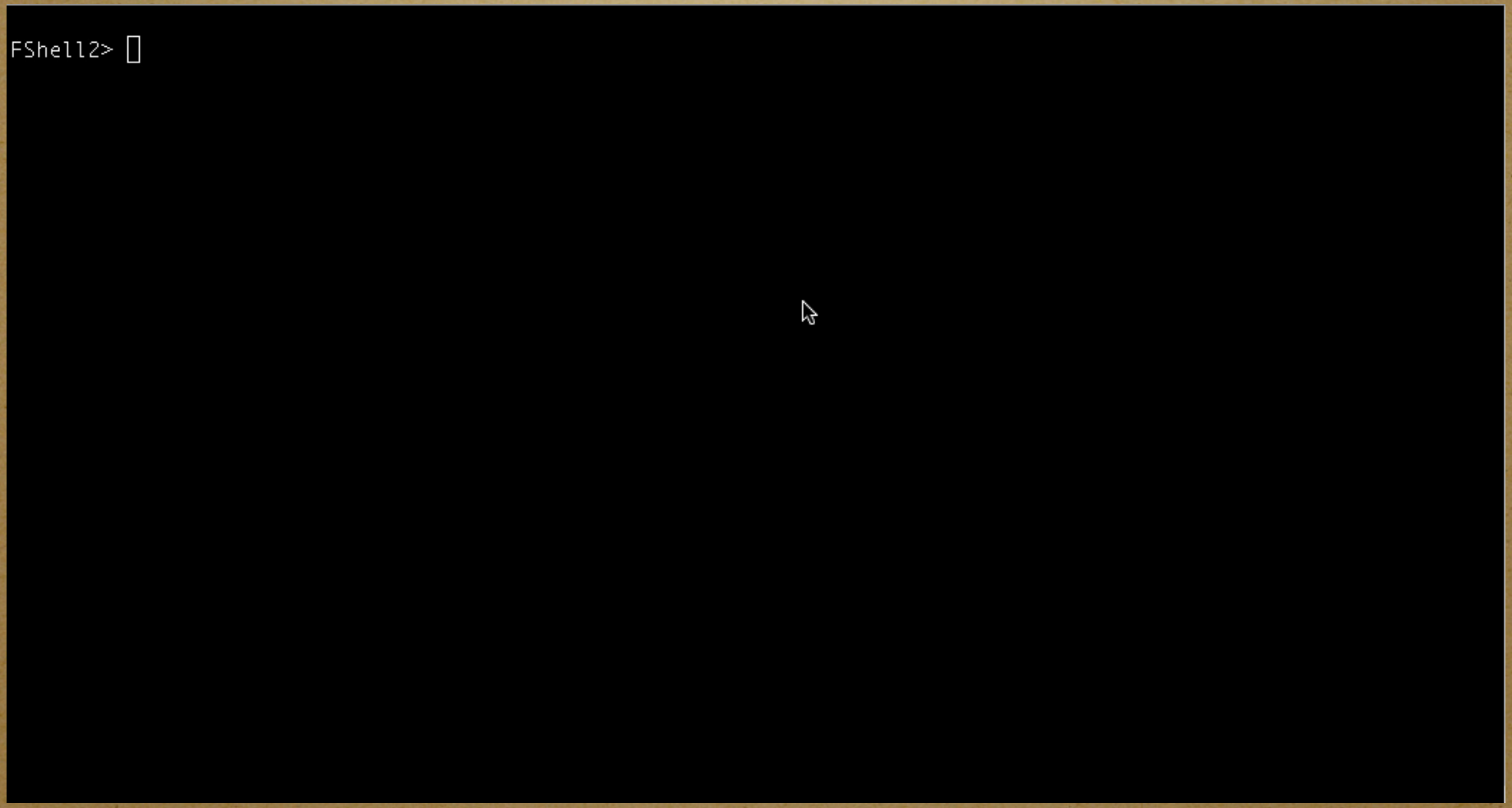
http://code.forsyte.de/fshell

Using FShell to Compute a Test Suite



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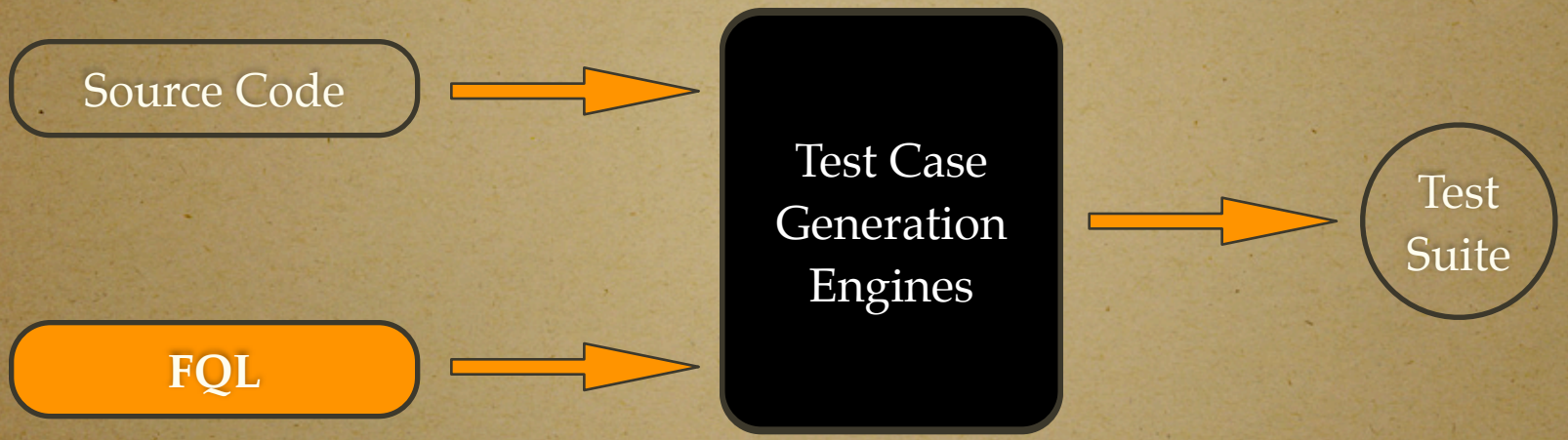
Applications of FQL/FShell



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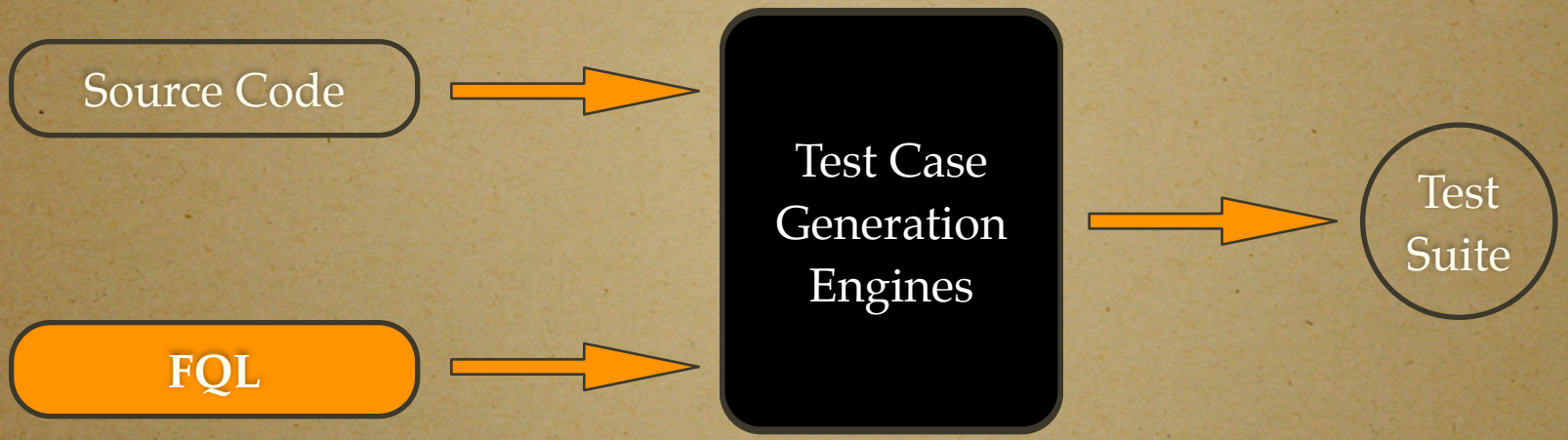


- Test case generation
- Certification
- Requirement-driven testing
- Coverage Evaluation
- Reasoning about test specifications

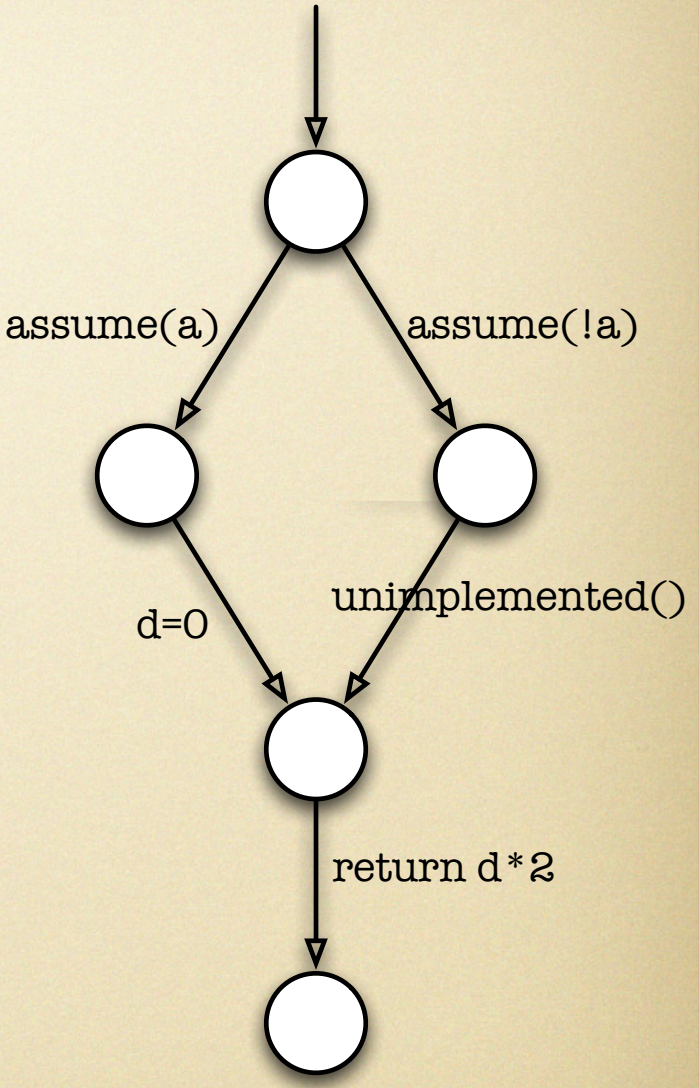
Software Testing using FQL

- Program Representation: Control Flow Automata
- Describing Single Test Cases
- Describing Test Suites

Control Flow Automaton (CFA)

```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

- Henzinger et al. (POPL'02)
- Edges:
  - assume (conditional branches)
  - assignment
  - function call
  - function return
  - skip
- Nodes: locations



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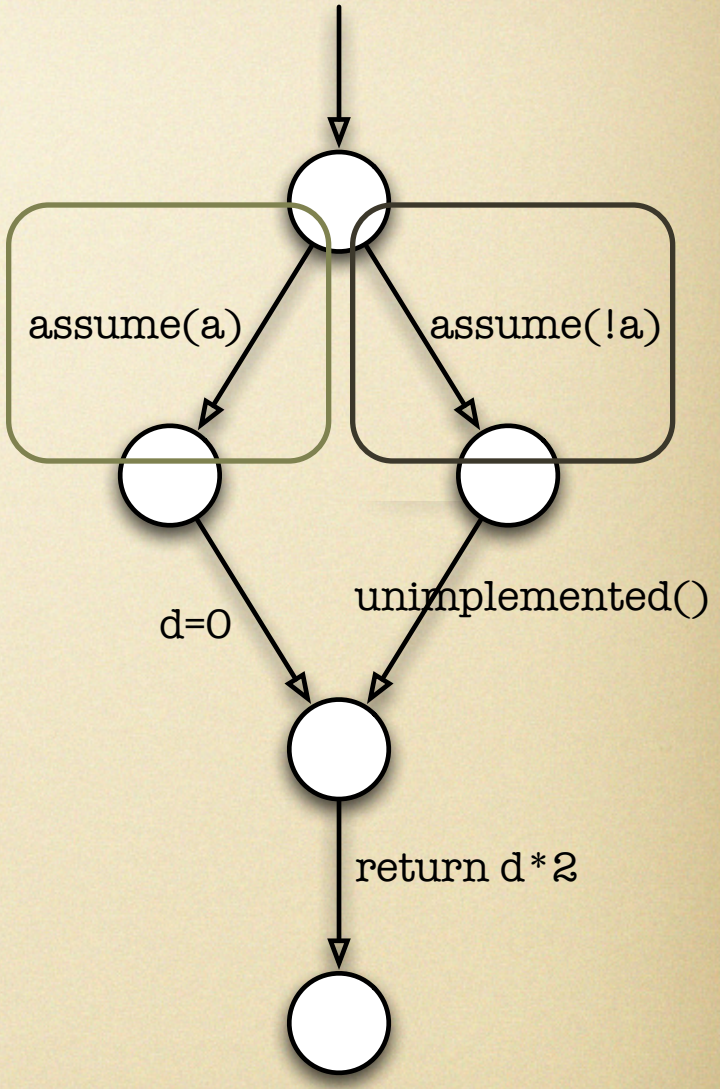

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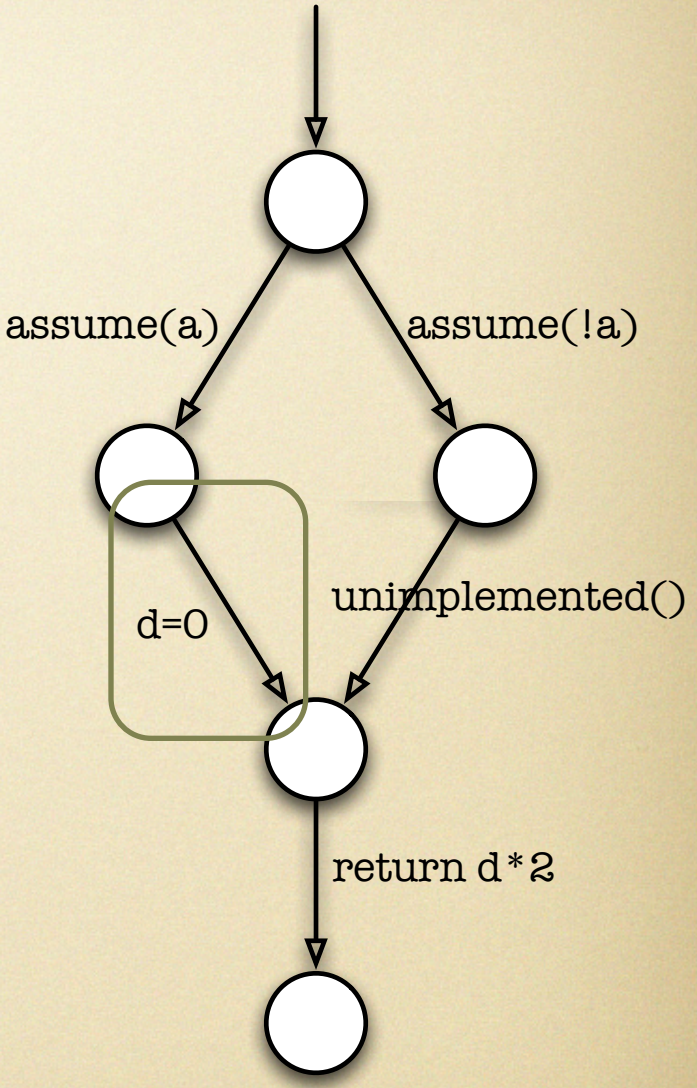

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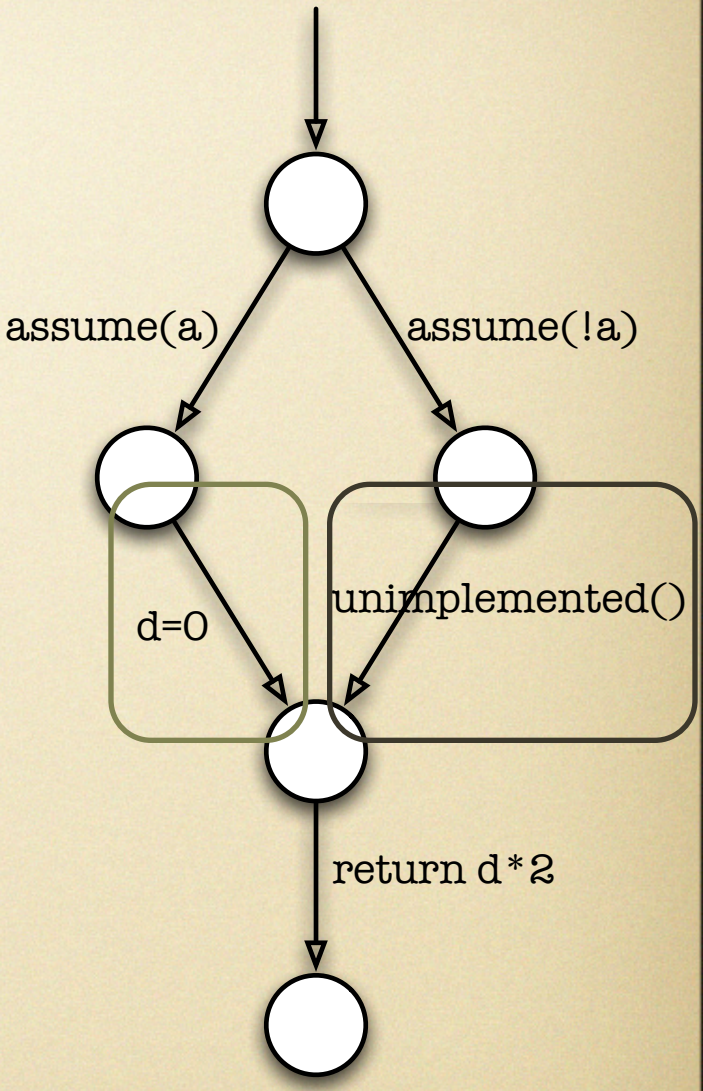

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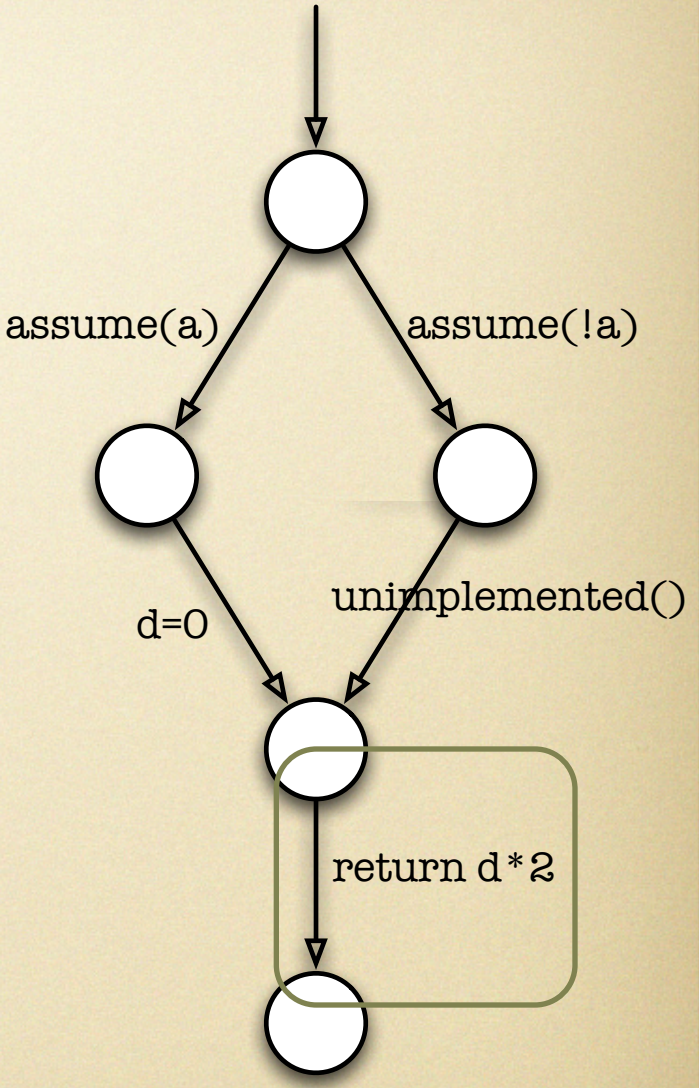

Software Testing using FQL

- ☑ Program Representation: Control Flow Automata
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- Describing Test Suites

Filter Functions

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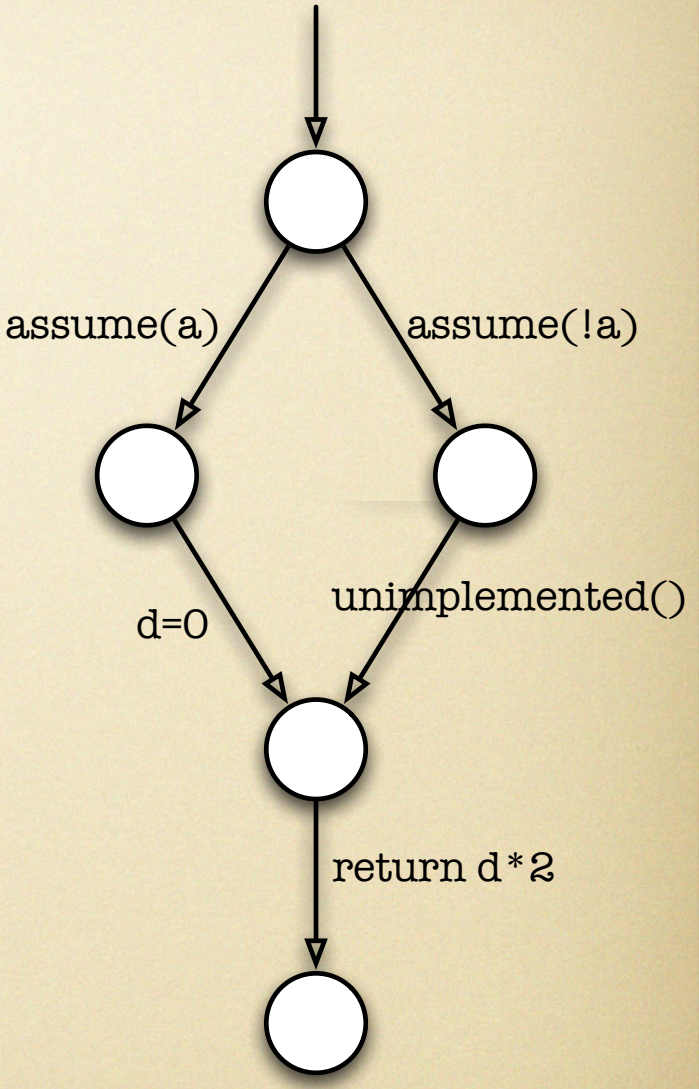

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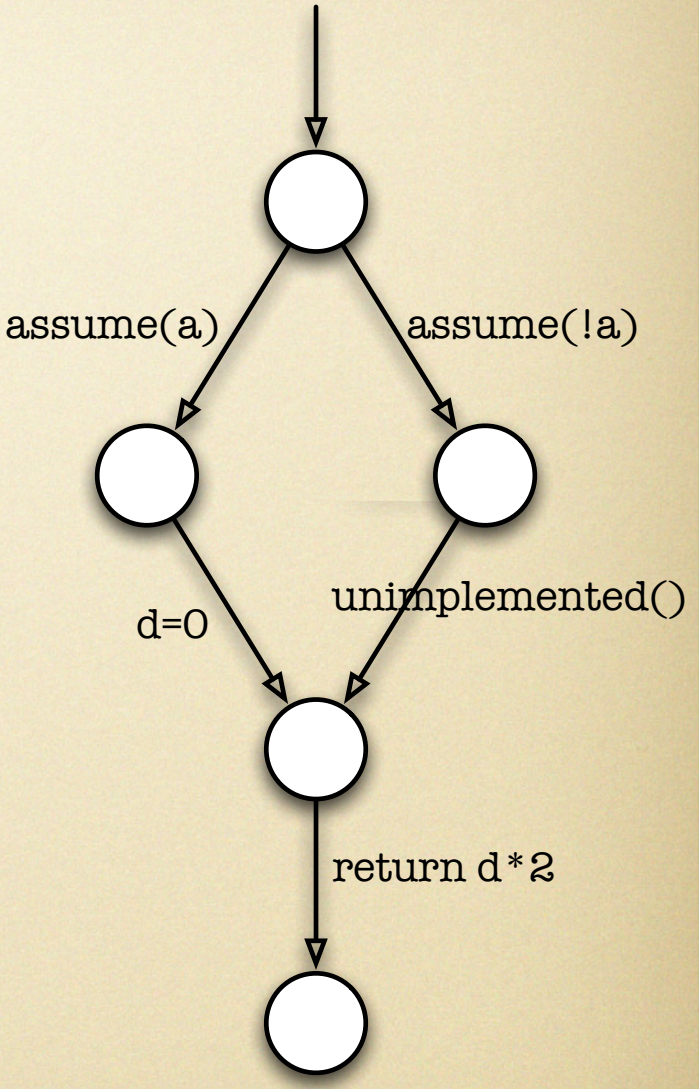

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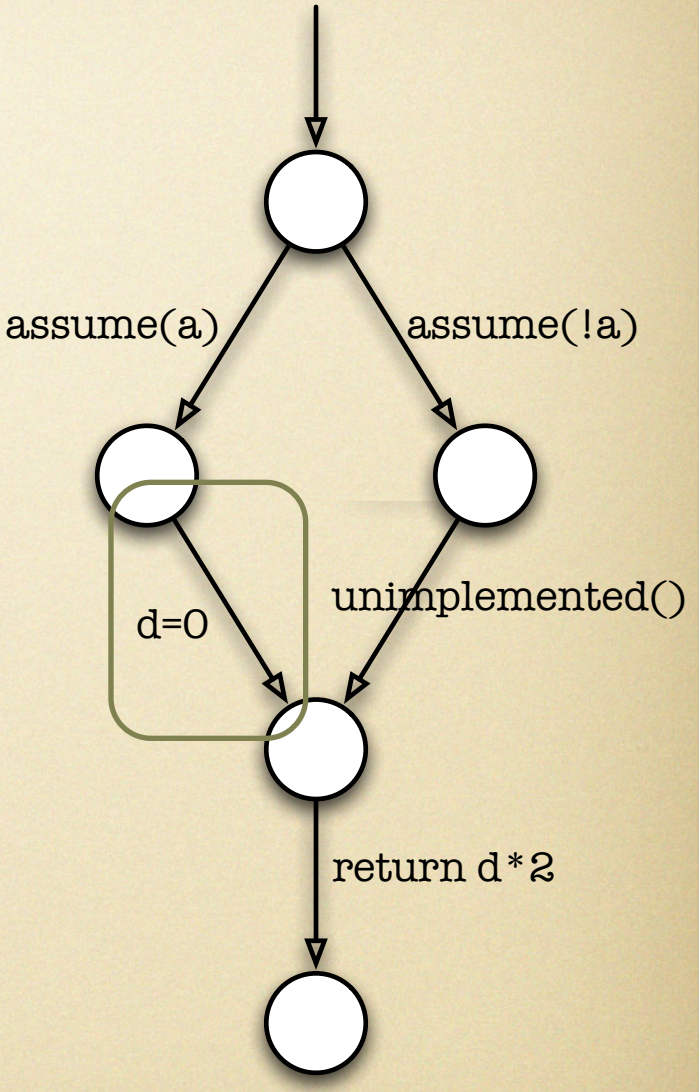

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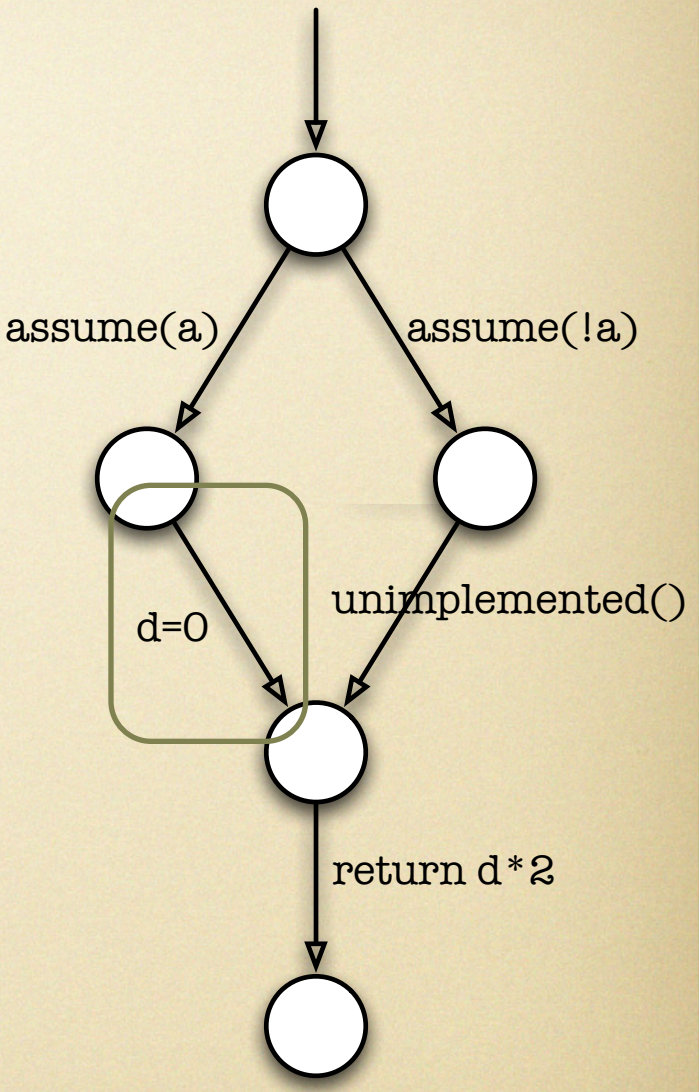
  - **`cover "@4"`**



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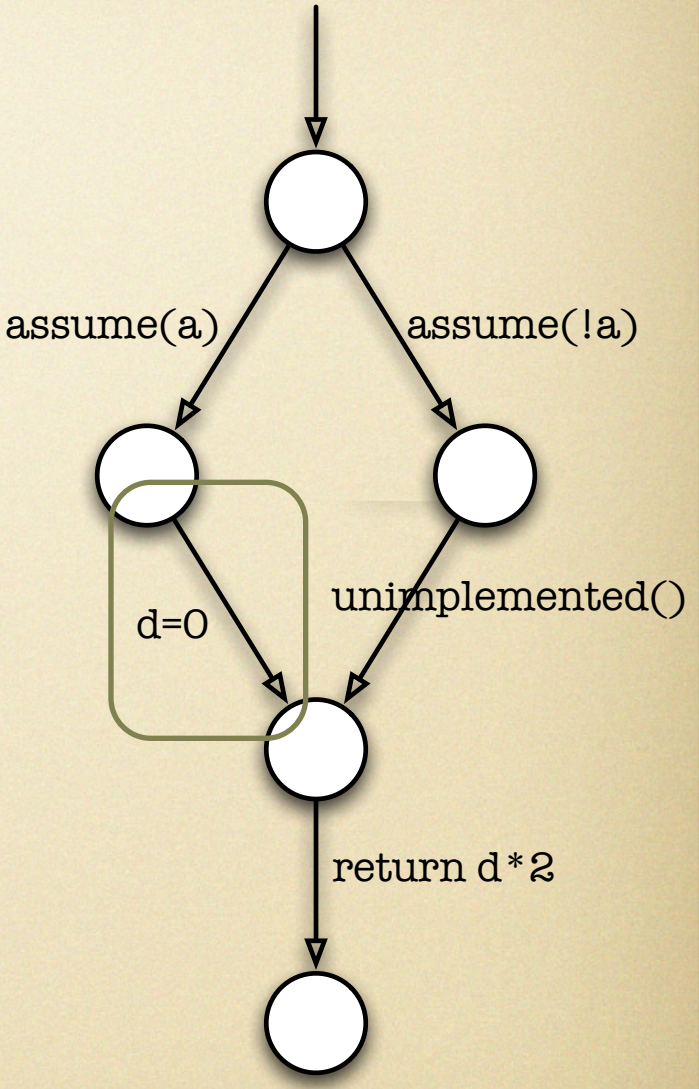
- Cover *line 4*
  - **`cover "@4"`**

    IN:
    a=2
    d=0



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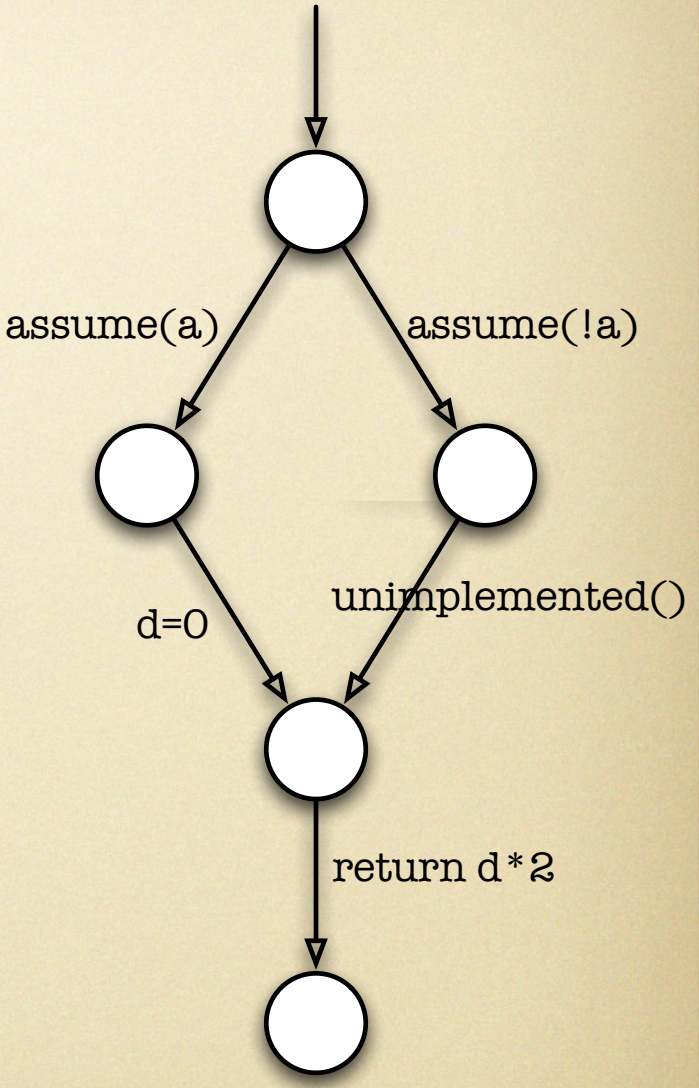
- Cover *line 4*
  - **`cover "@4"`**

    IN:
    a=2
    d=0
- Cover *some statement*



Filter Functions

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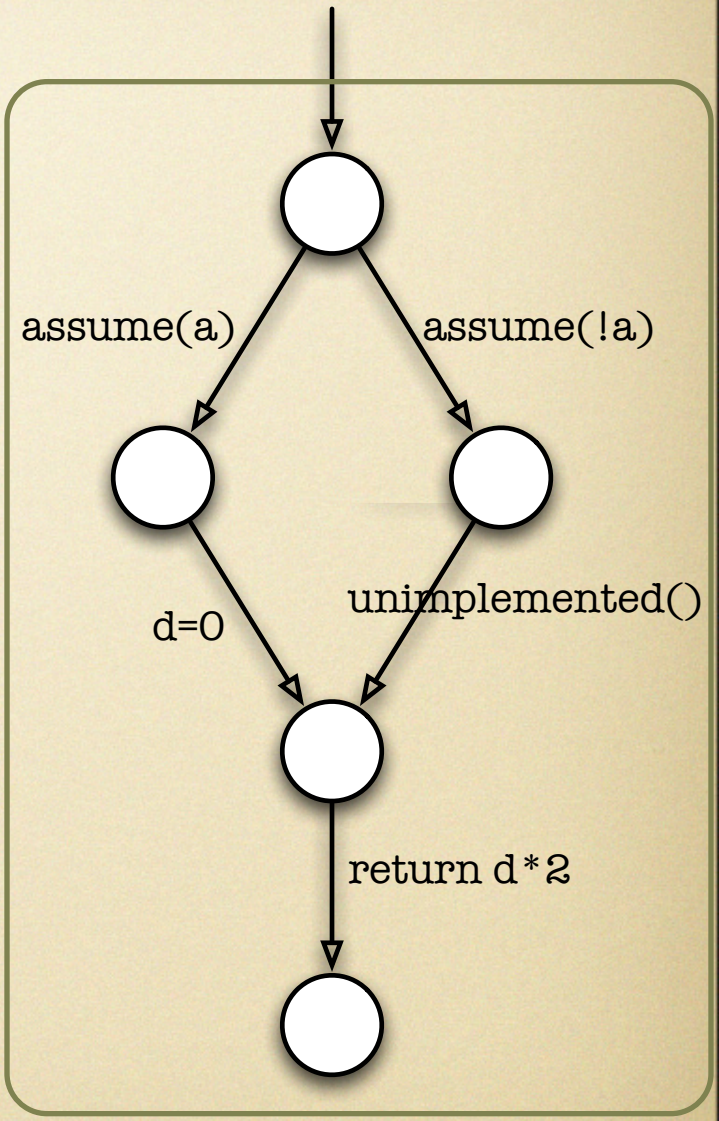
    d=0
- Cover *some statement*

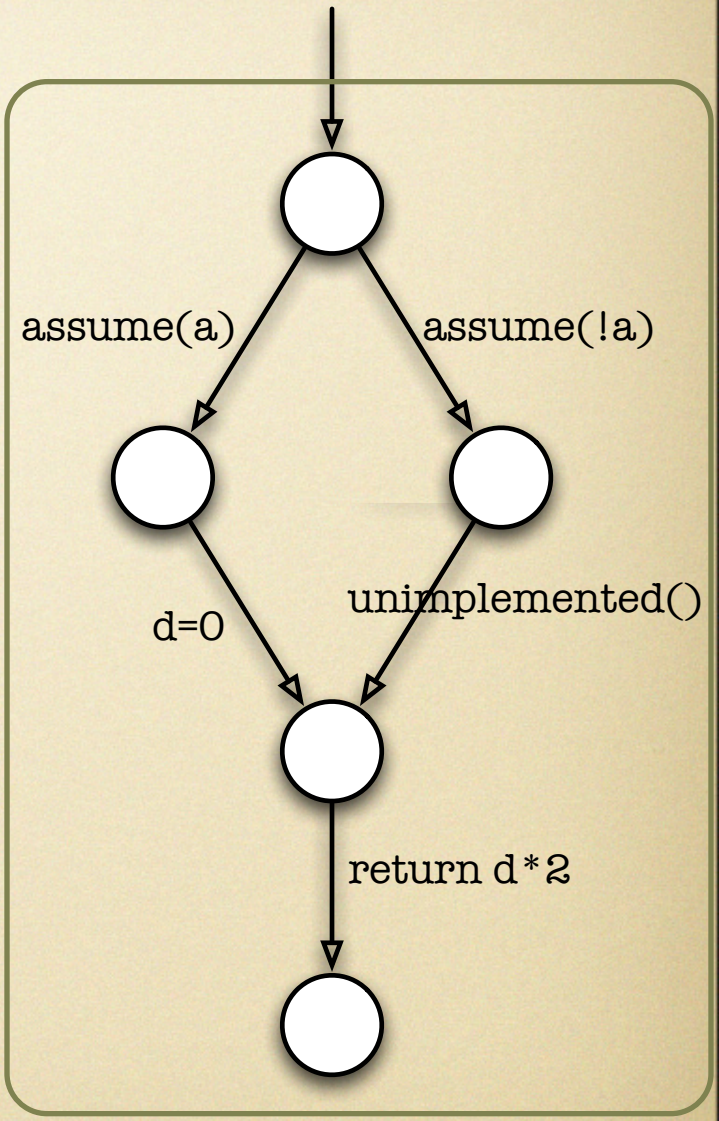


Filter Functions

```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

- Cover *line 4*
  - **`cover "@4"`**

    IN:
    a=2
    d=0
- Cover *some statement*
  - **`cover "ID"`**



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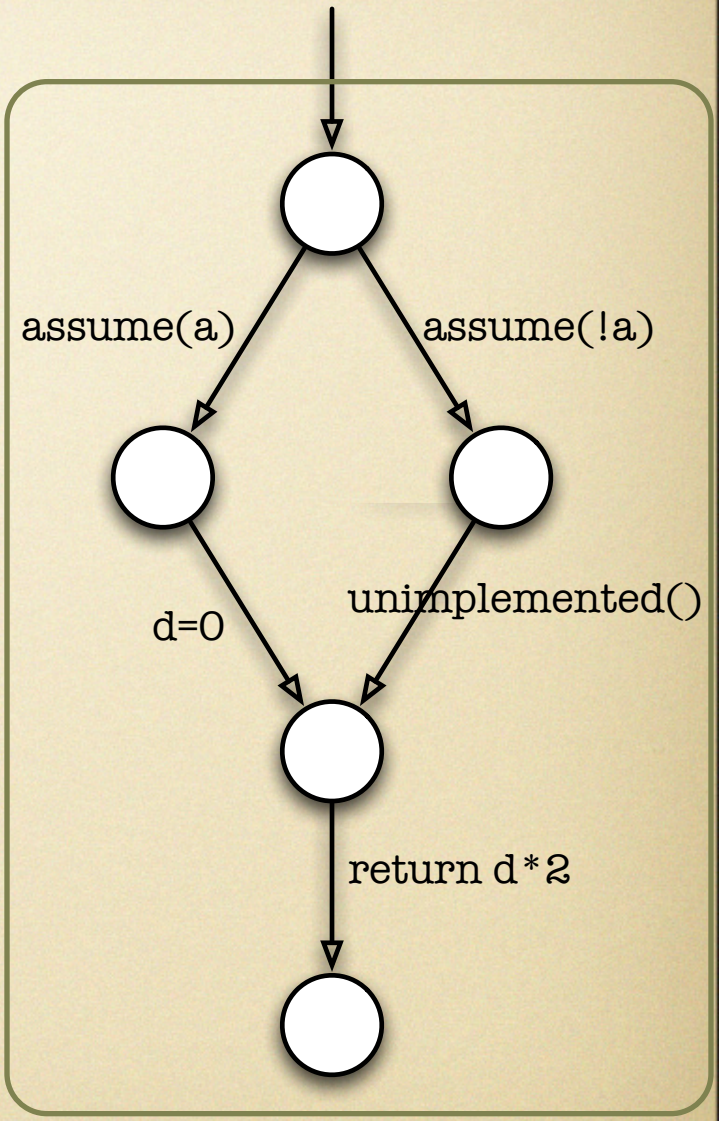
8  }
```

- Cover *line 4*
  - **`cover "@4"`**

    IN:
    a=2
    d=0
- Cover *some statement*
  - **`cover "ID"`**

    IN:
    a=8192
    d=0



Describing Single Test Cases

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1  int example(int a, int d)
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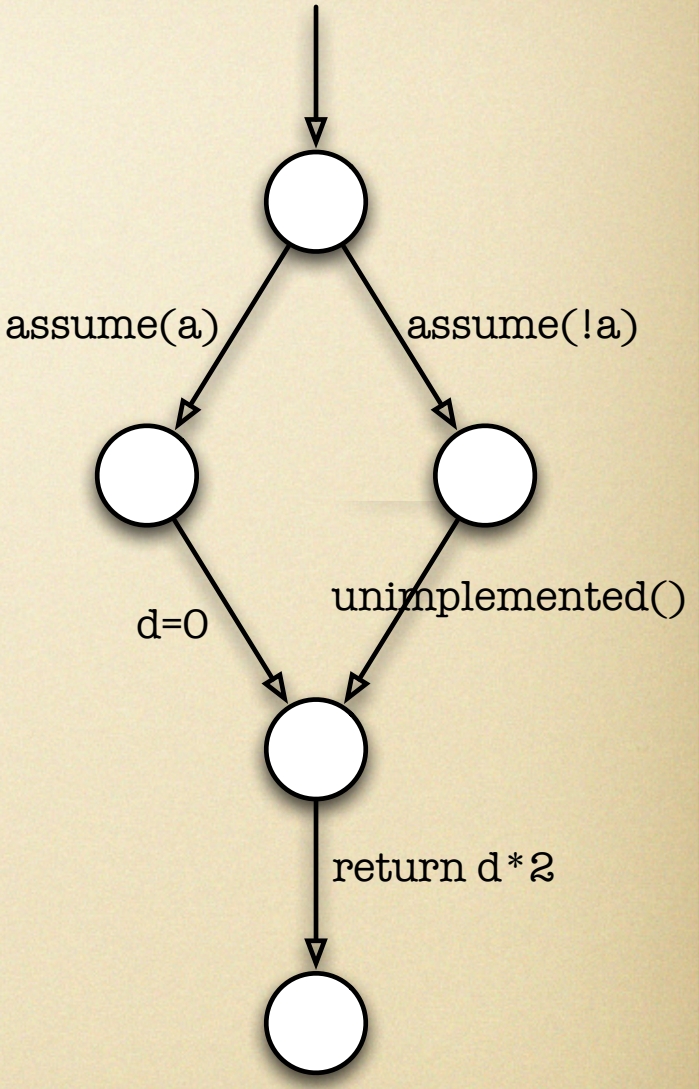

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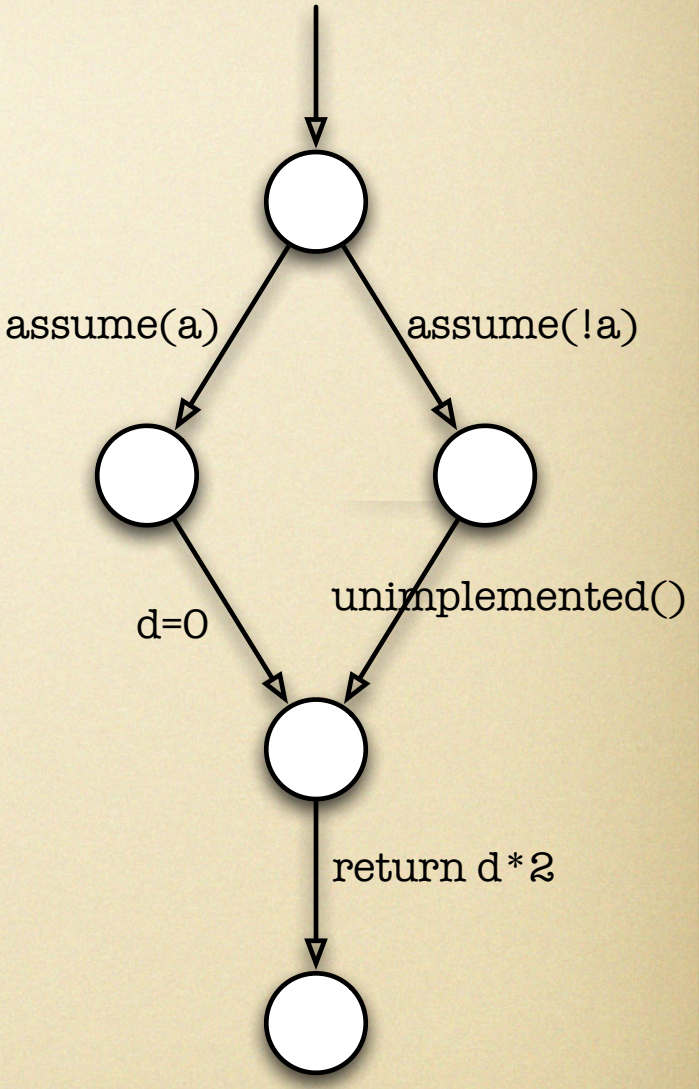
- Cover *line 4 or line 6*



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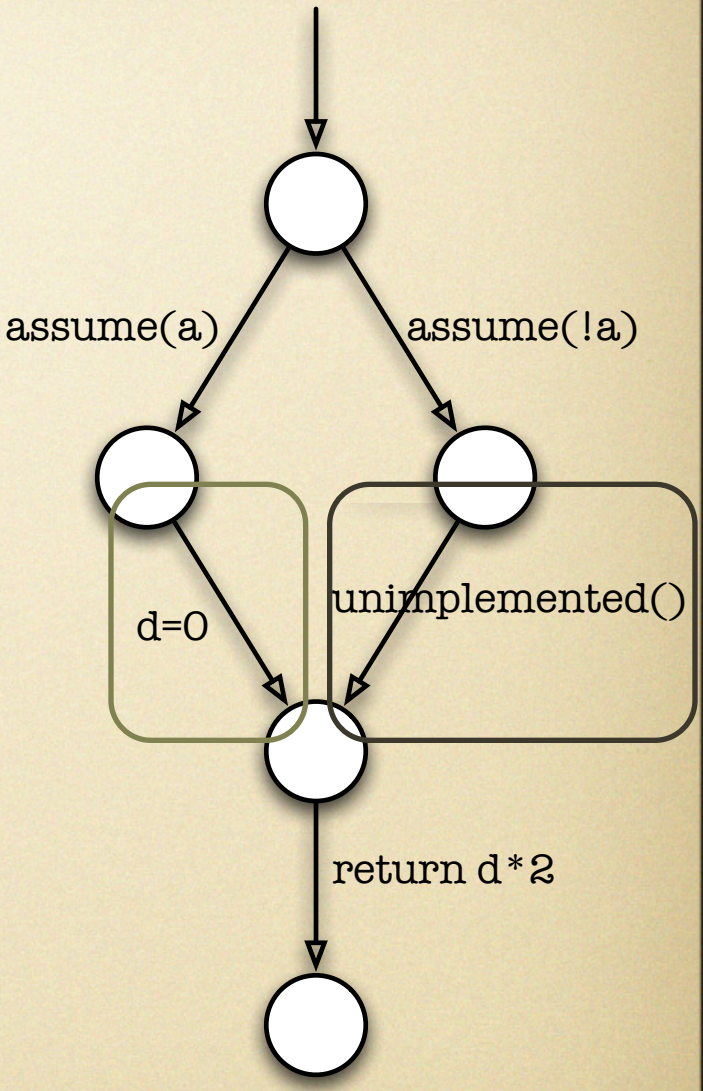
- Cover *line 4 or line 6*



Describing Single Test Cases

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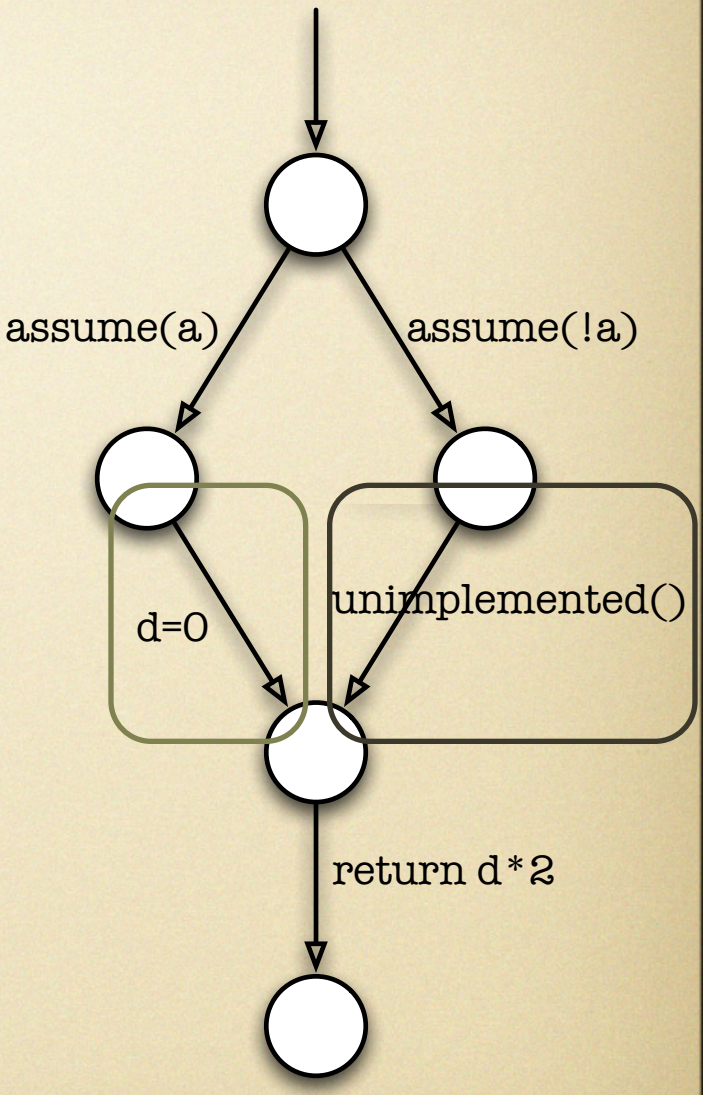
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

- Cover *line 4 or line 6*
  - **`cover "@4+@6"`**



Describing Single Test Cases

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1  int example(int a, int d)
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7    return d*2;
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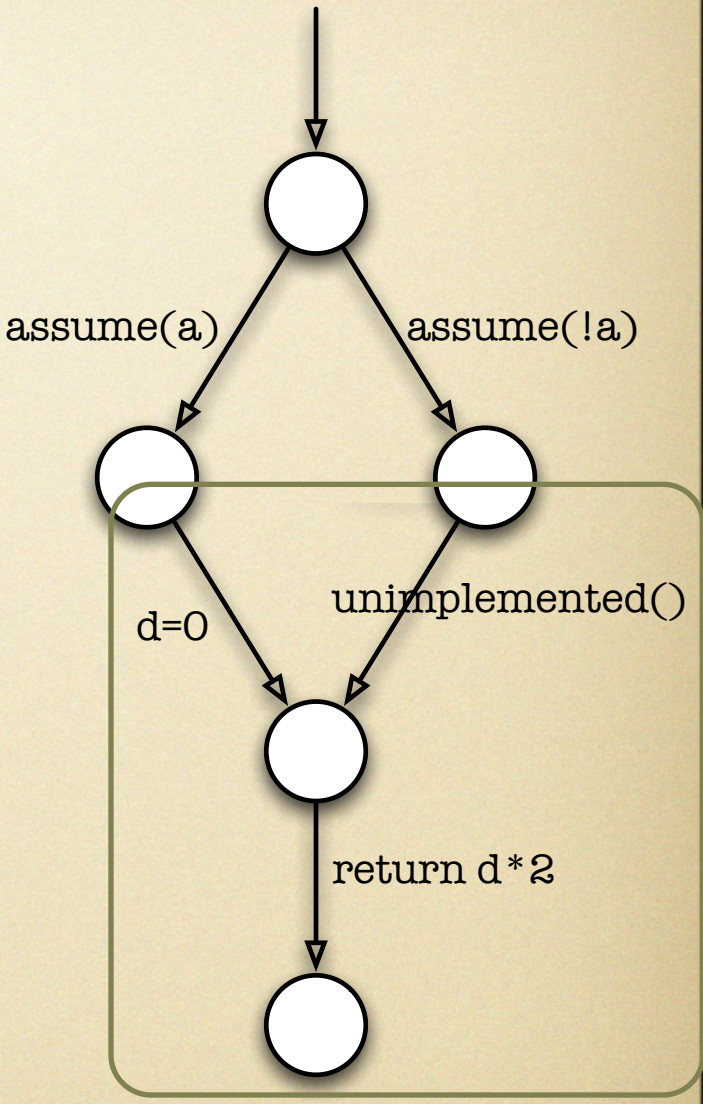
```

- Cover *line 4 or line 6*
  - **`cover "@4+@6"`**
- Cover a *basic block*



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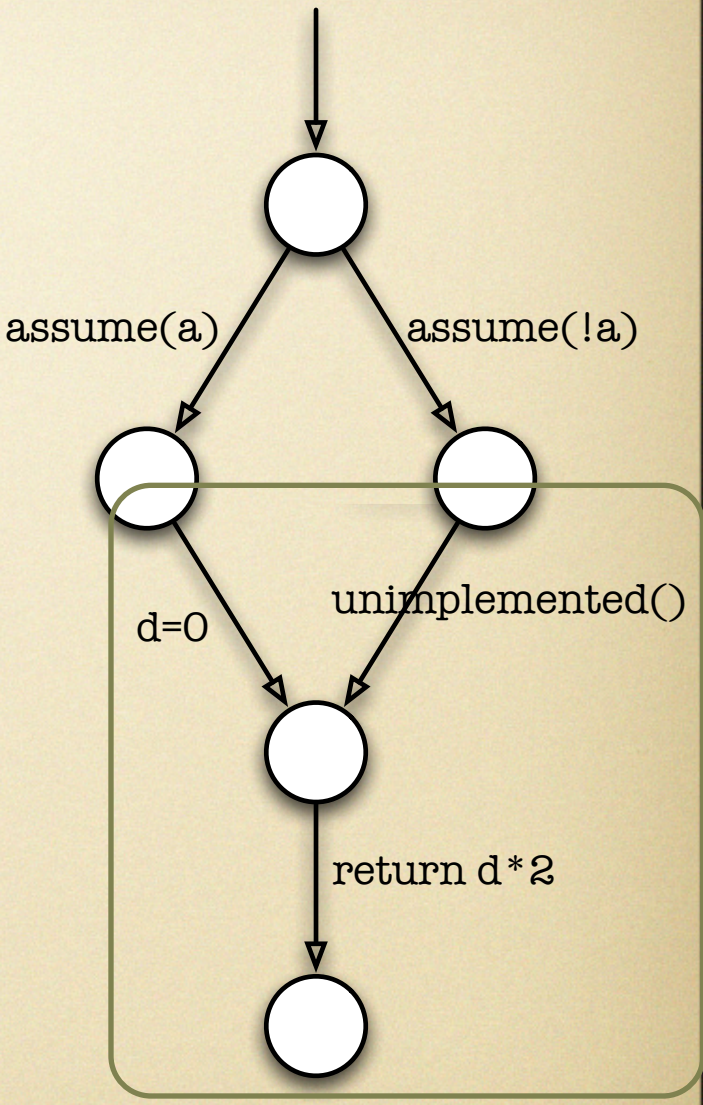

- Cover *line 4 or line 6*
  - **`cover "@4+@6"`**
- Cover a *basic block*
  - **`cover "@basicblockentry"`**

Describing Single Test Cases

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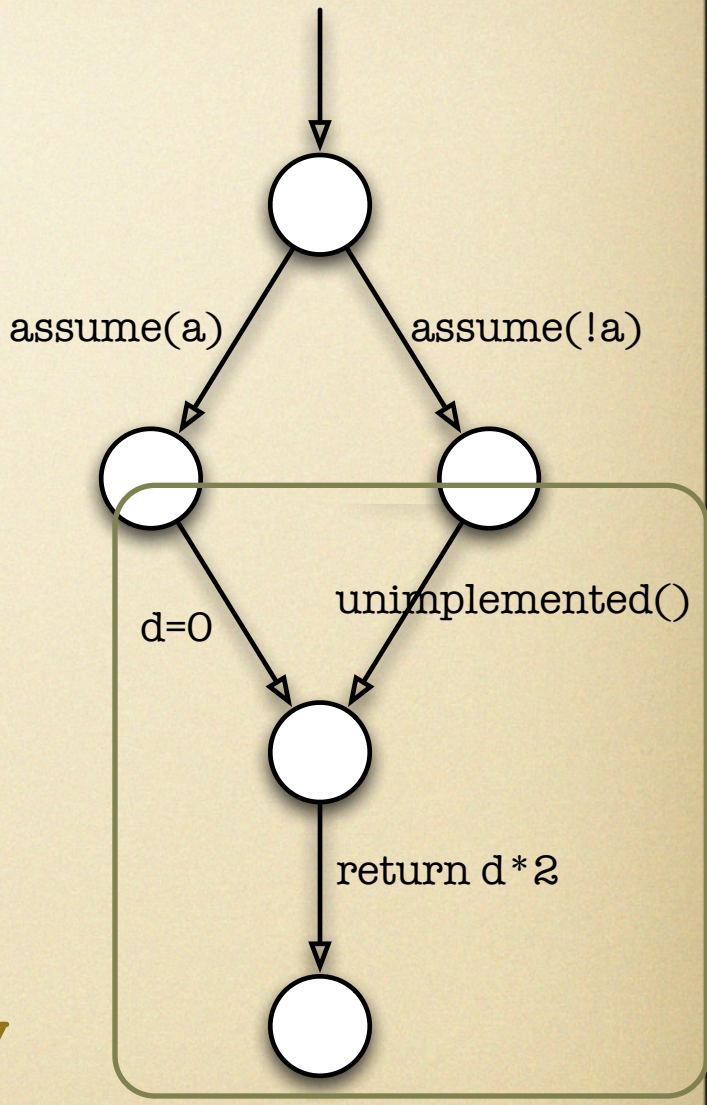
```



- Cover *line 4 or line 6*
  - **`cover "@4+@6"`**
- Cover a *basic block*
  - **`cover "@basicblockentry"`**
- For this example **`@basicblockentry`** is tantamount to **`@4+@6+@7`**

Describing Single Test Cases

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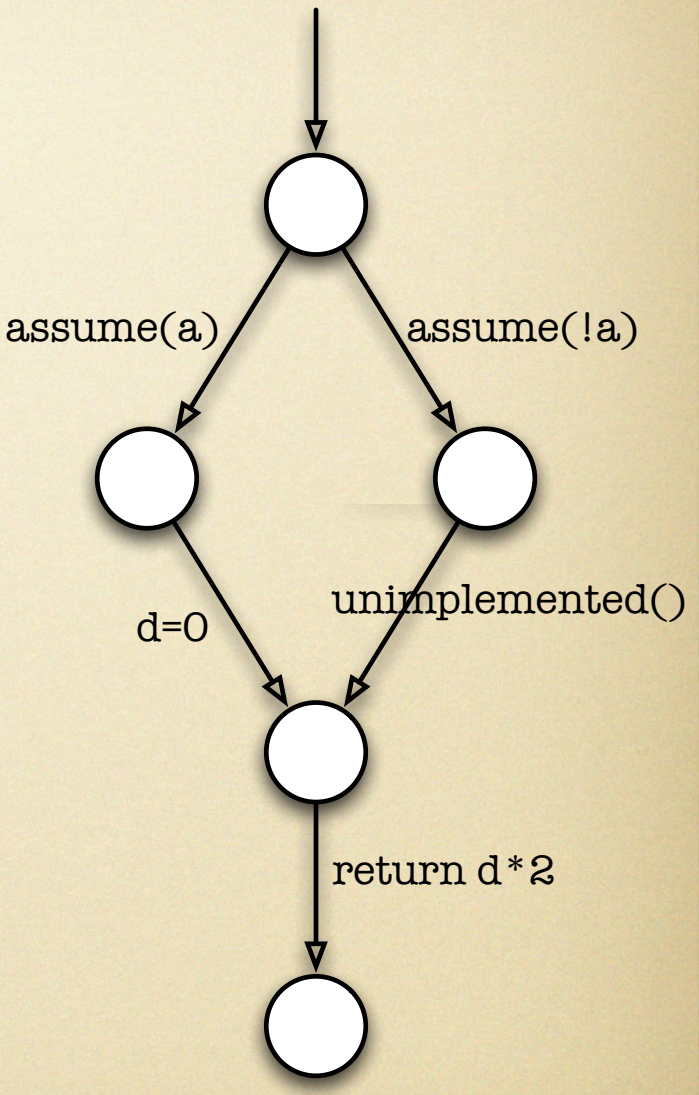

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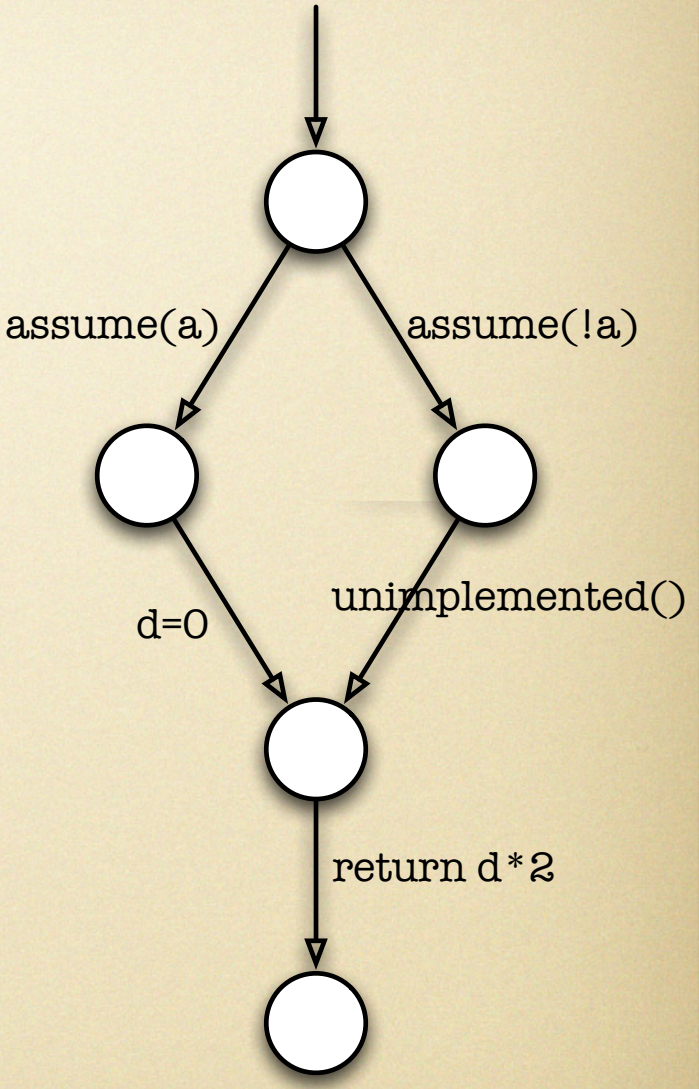
- Test case is execution (program path)



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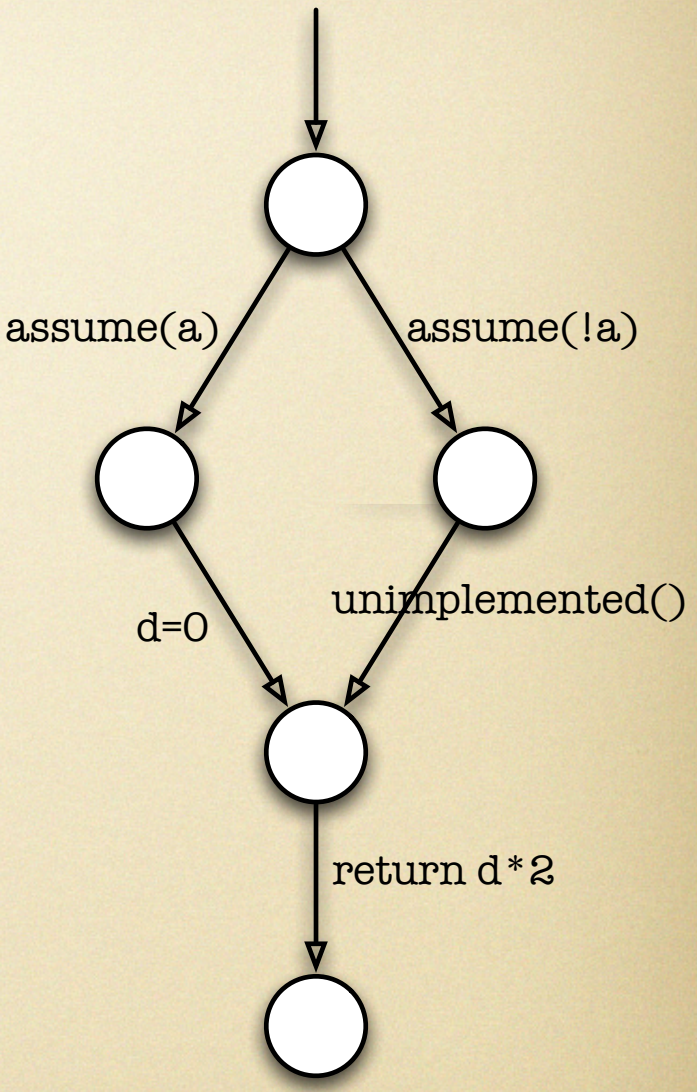

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- Test case is execution (program path)
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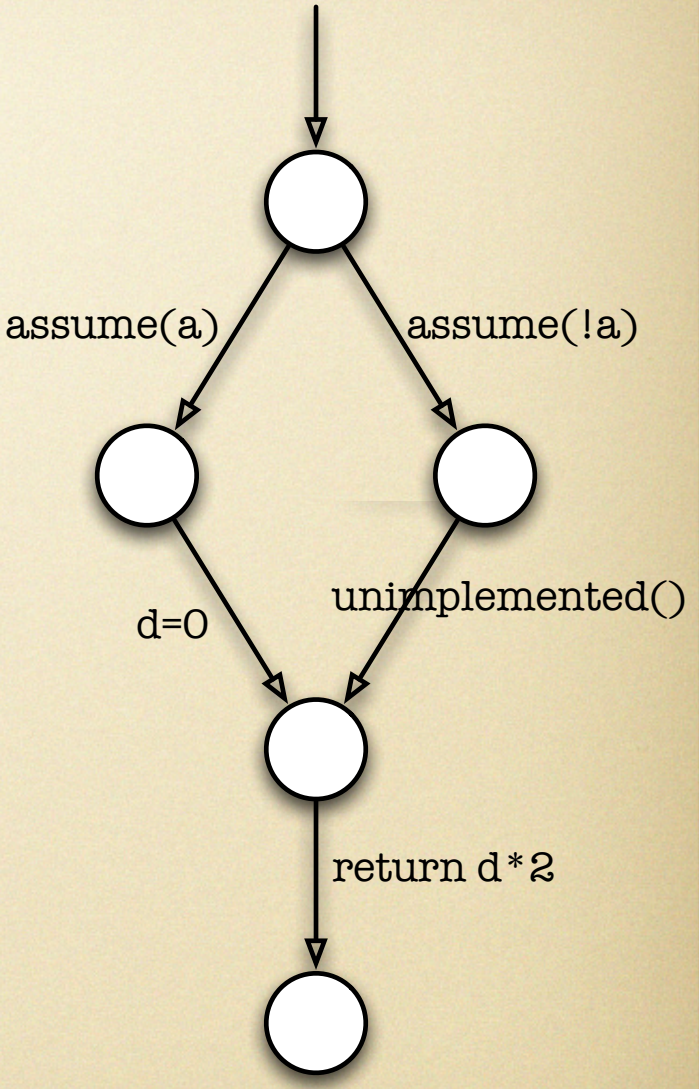
  - Execute some statement(s)



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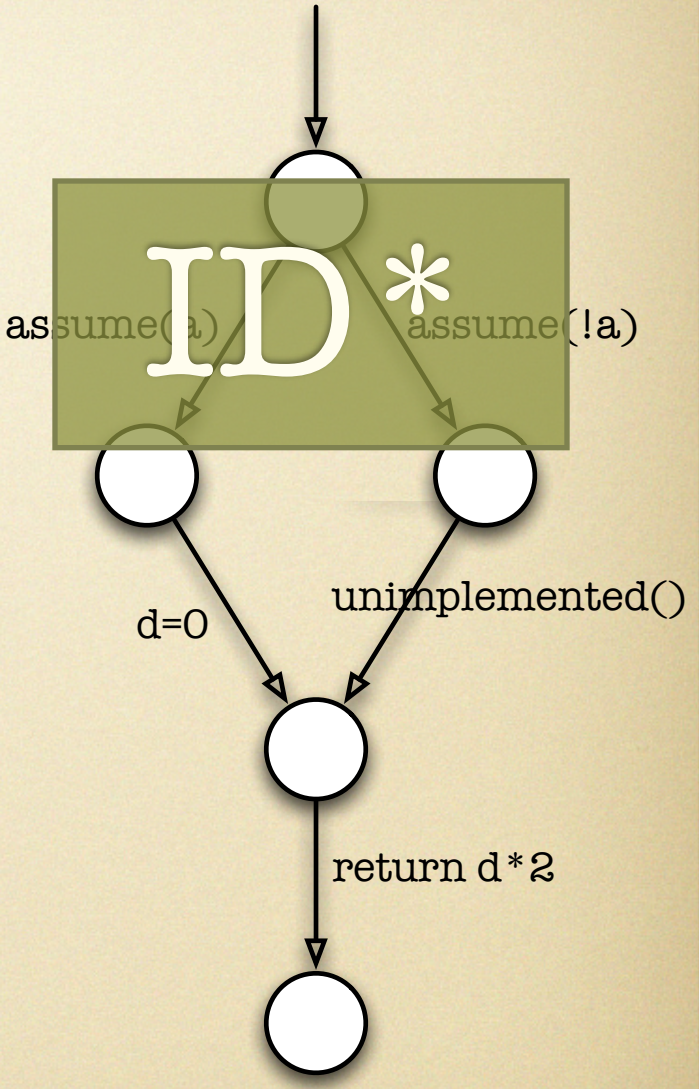

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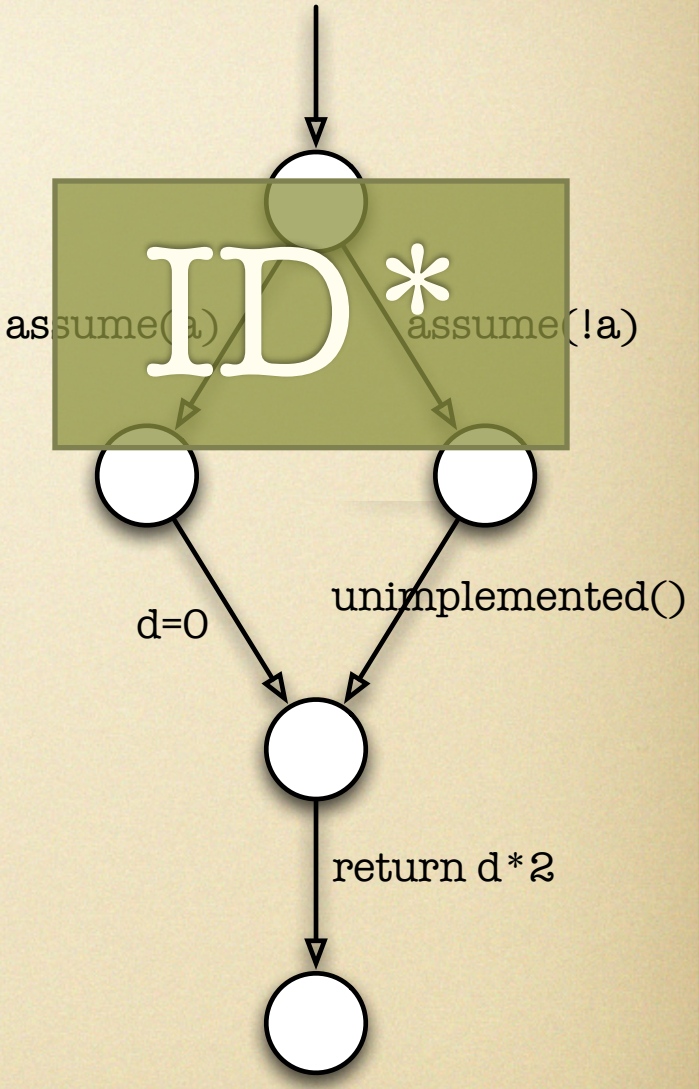
- Test case is execution (program path)
- Intuitively: “cover line 4” =
  - Execute some statement(s)
  - Reach line 4



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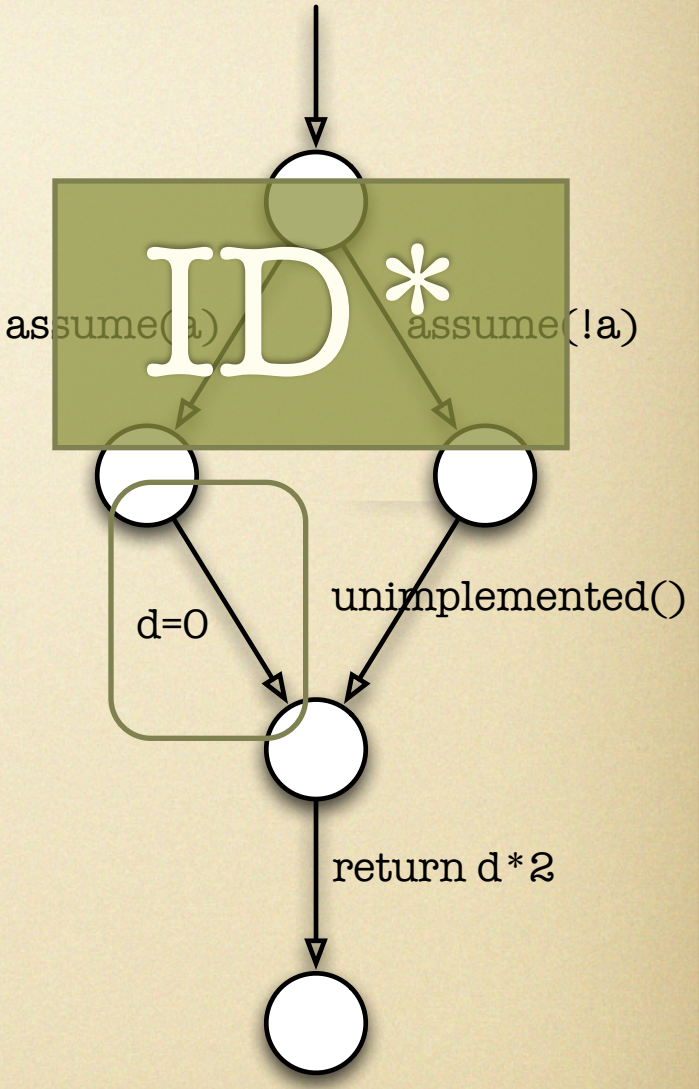

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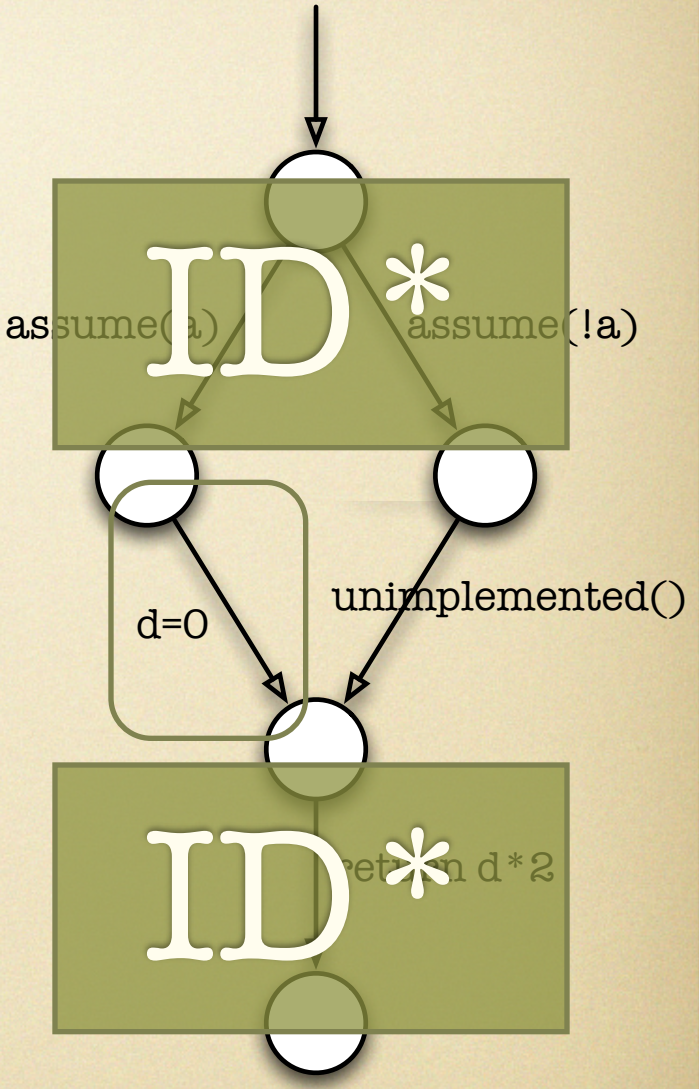
- Test case is execution (program path)
- Intuitively: “cover line 4” =
  - Execute some statement(s)
  - Reach line 4
  - More statements until program exit



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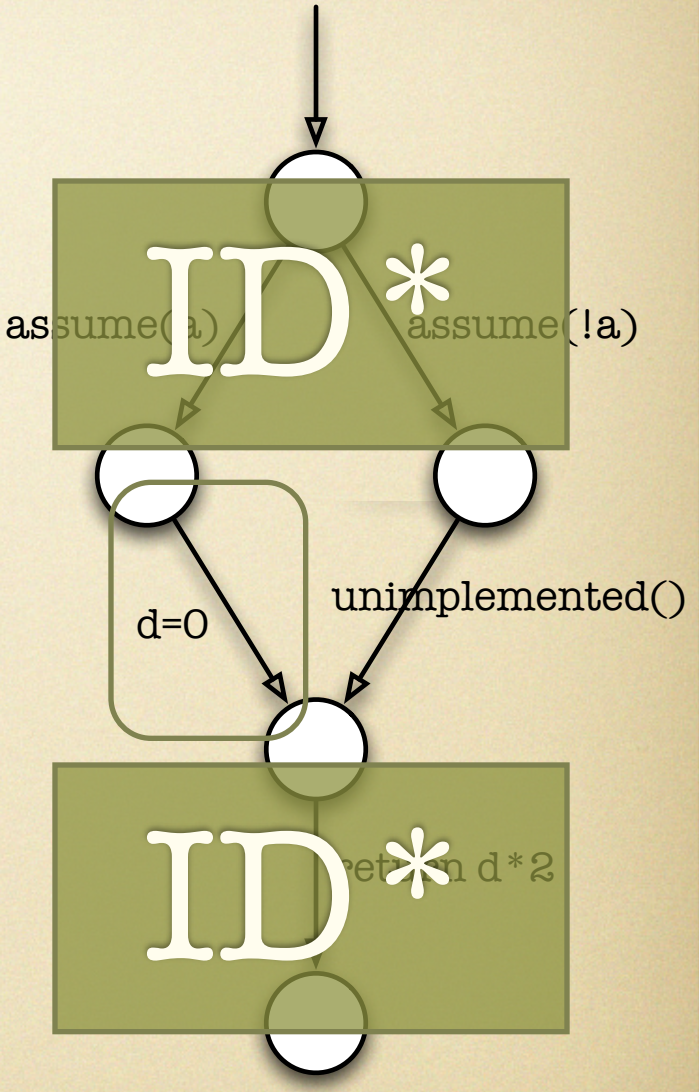
  - **`cover "ID*.@4.ID*"`**



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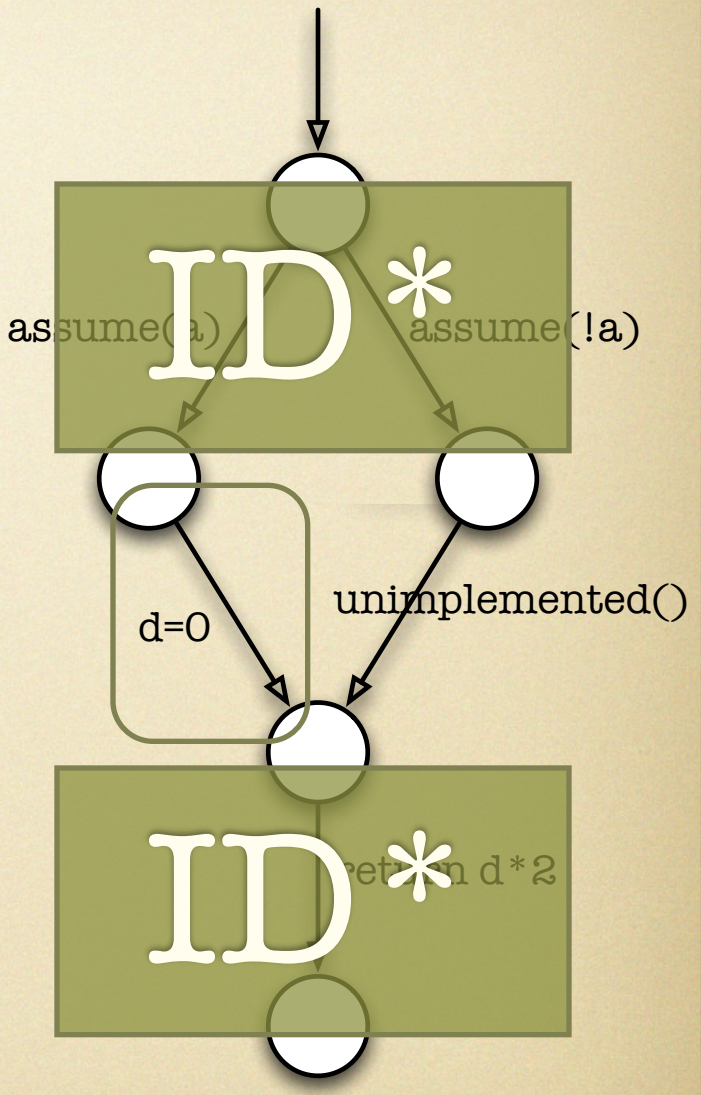
  - **`cover "ID*.@4.ID*"`**

    IN:

    a=2
    d=0



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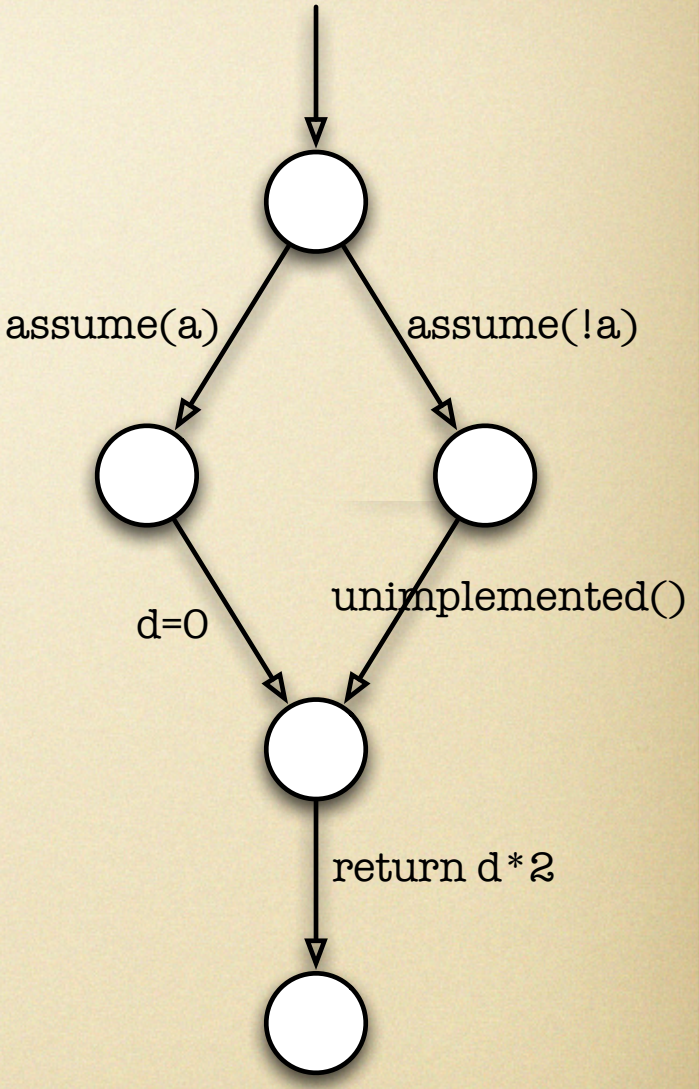

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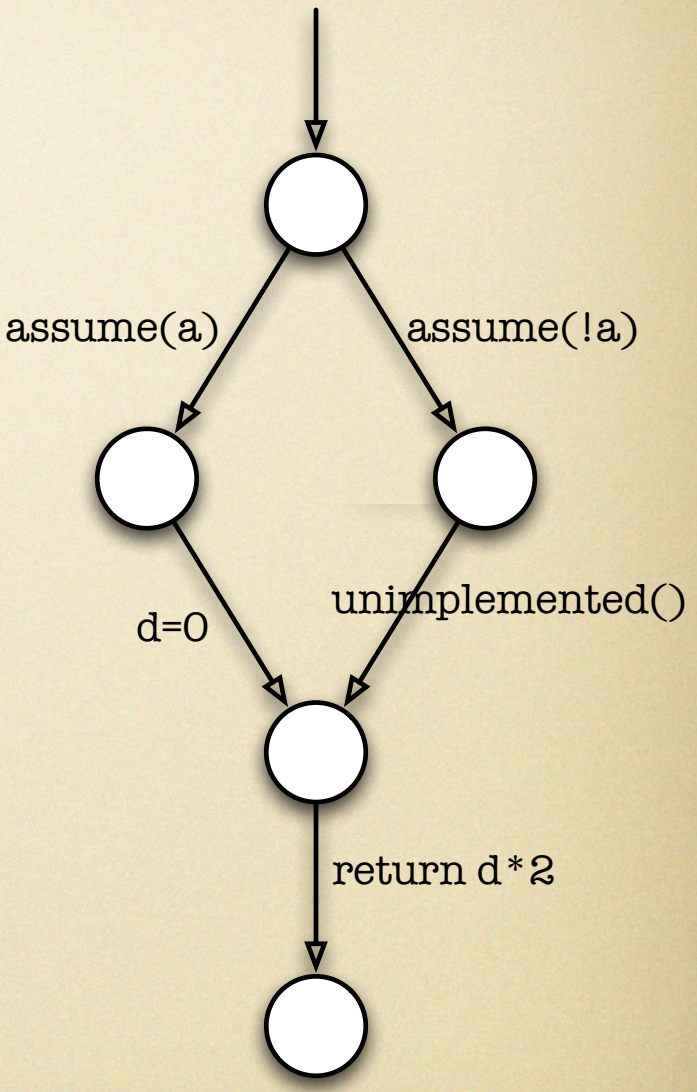
- `cover "ID* . @4 . ID* + ID* . @6 . ID*"`



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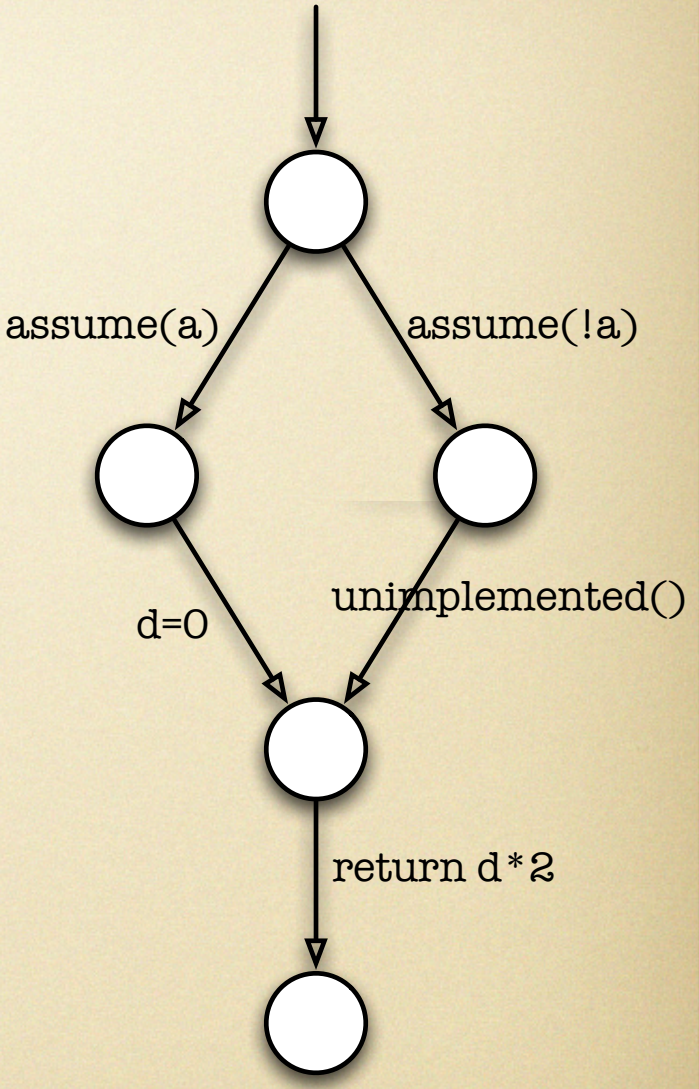
- **`cover "ID* . @4 . ID* + ID* . @6 . ID*"`**
- Path patterns are regular expressions:



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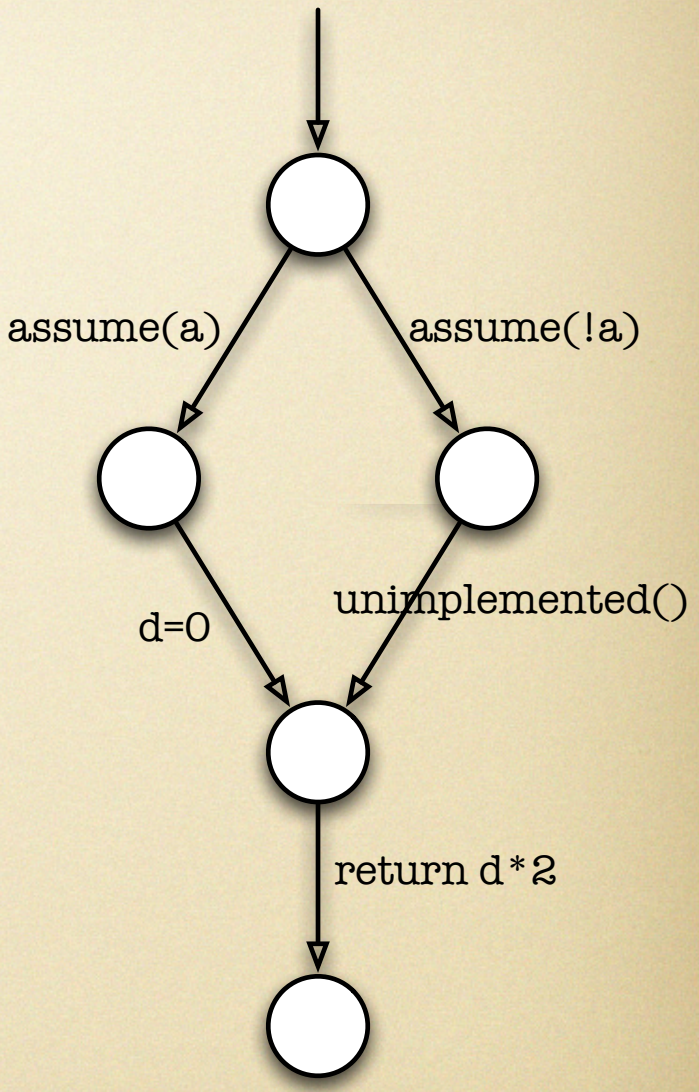

- **`cover "ID* . @4 . ID* + ID* . @6 . ID*"`**
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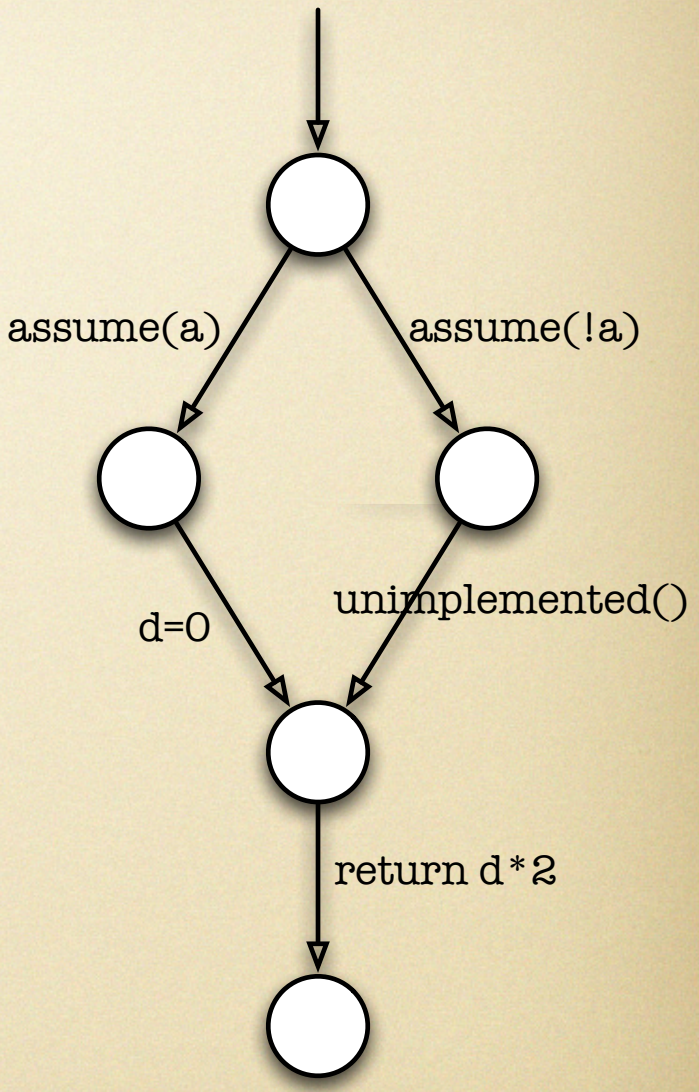

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Path Patterns

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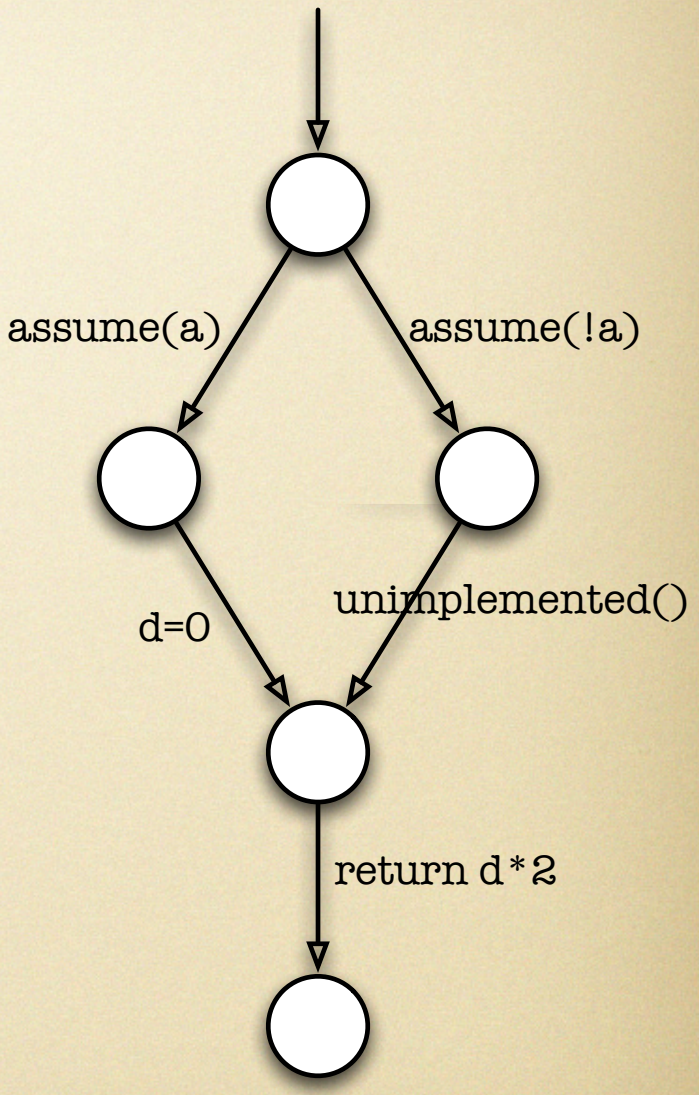

- **`cover "ID* . @4 . ID* + ID* . @6 . ID*"`**
- Path patterns are regular expressions:
  - Kleene star (*)
  - Concatenation (.)
  - Alternative/Union (+)

Alphabet of Path Patterns

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- Further filter functions

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- CFA transformers

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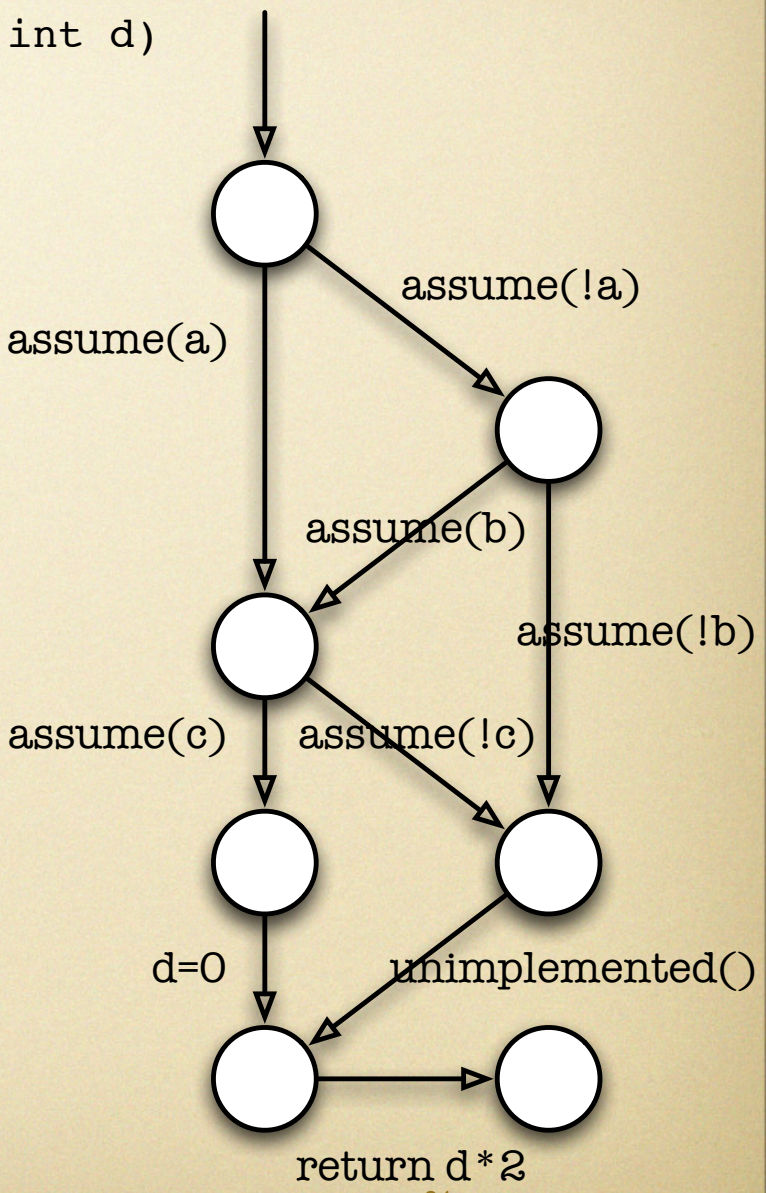
- Predicates over program variables

Alphabet of Path Patterns

- Further filter functions
- CFA transformers
- Predicates over program variables
- Beyond CFA edges (statements)

Further Filter Functions

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```



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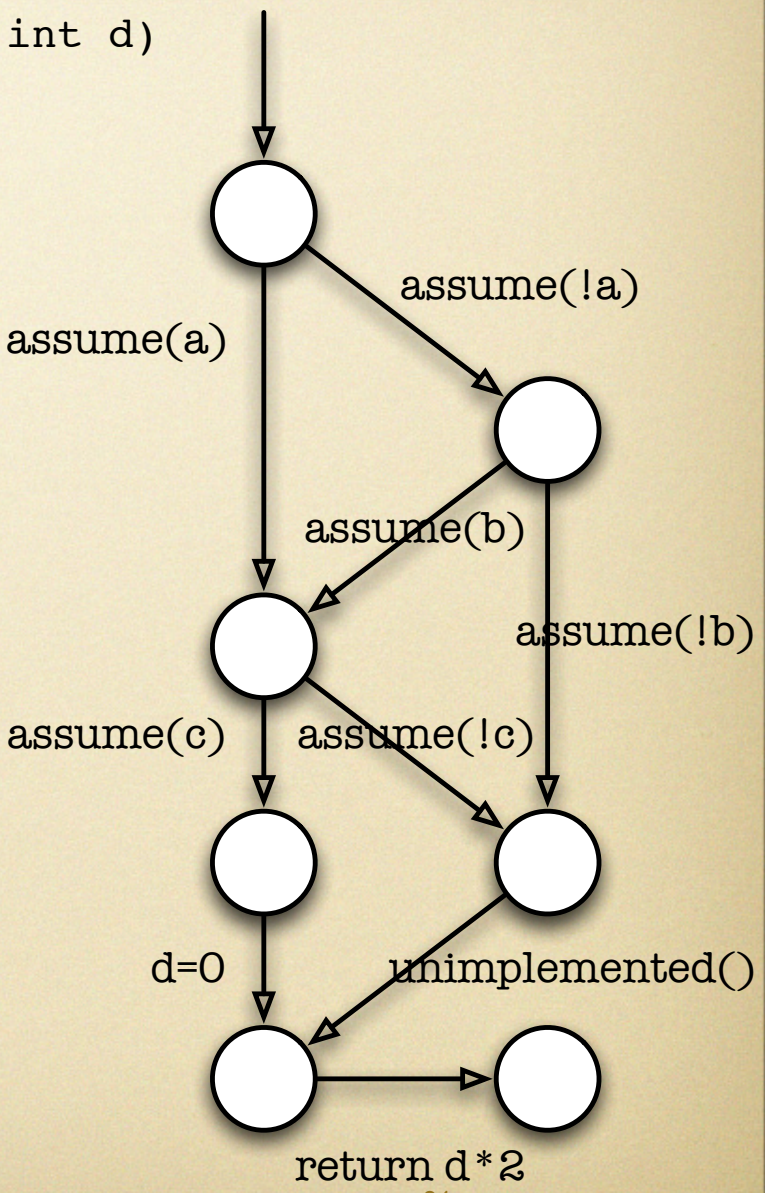
```

- `cover "@conditionedge"`



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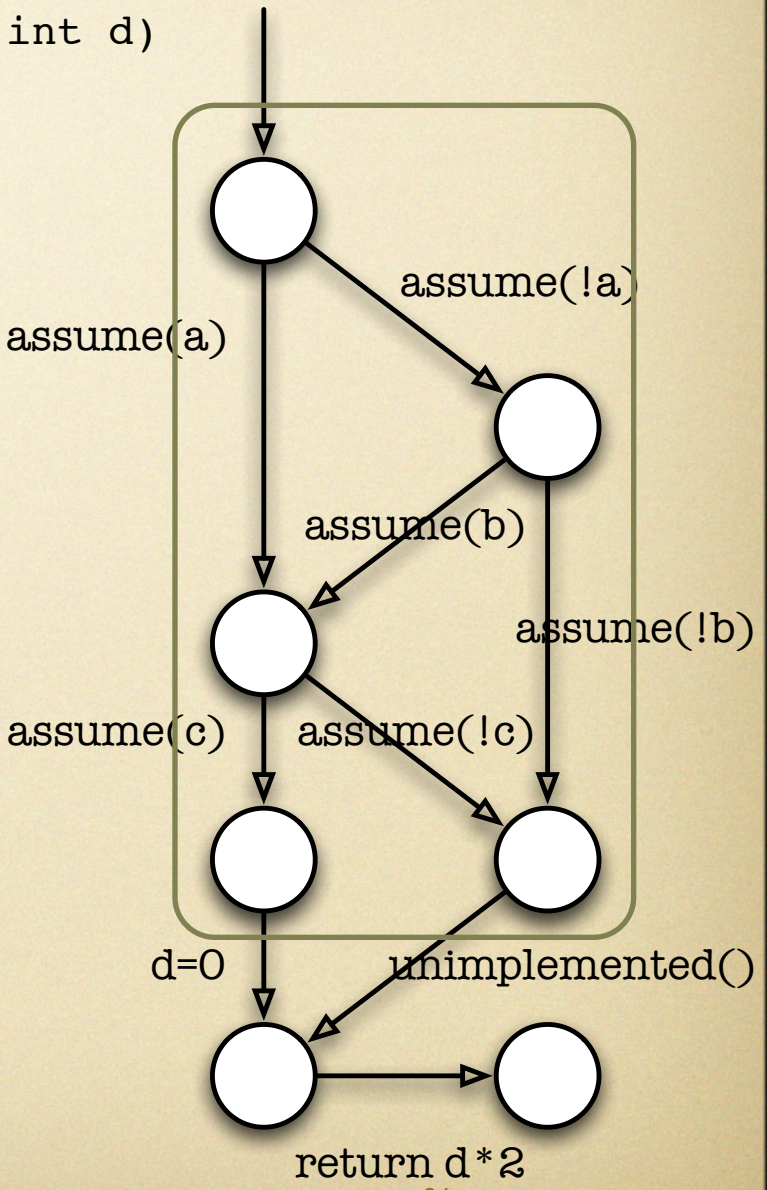
- cover "@conditionedge"



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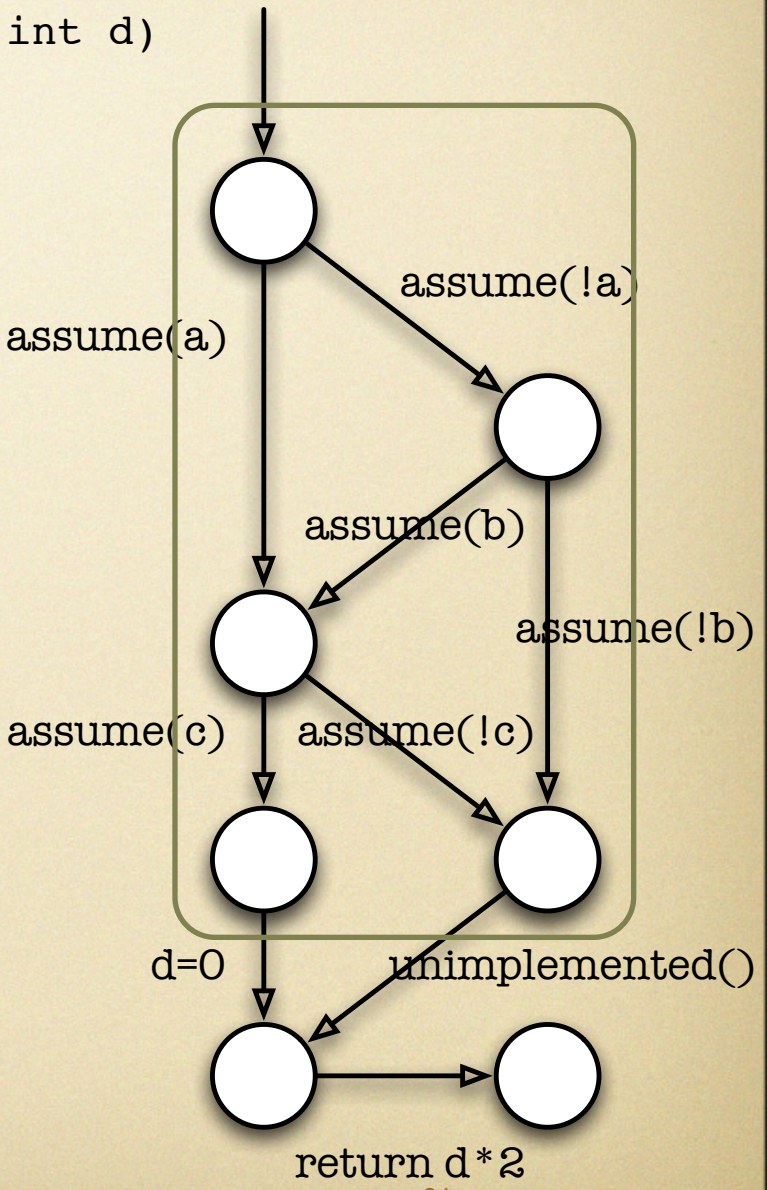
```

- cover "@conditionedge"
- cover "@conditiongraph"



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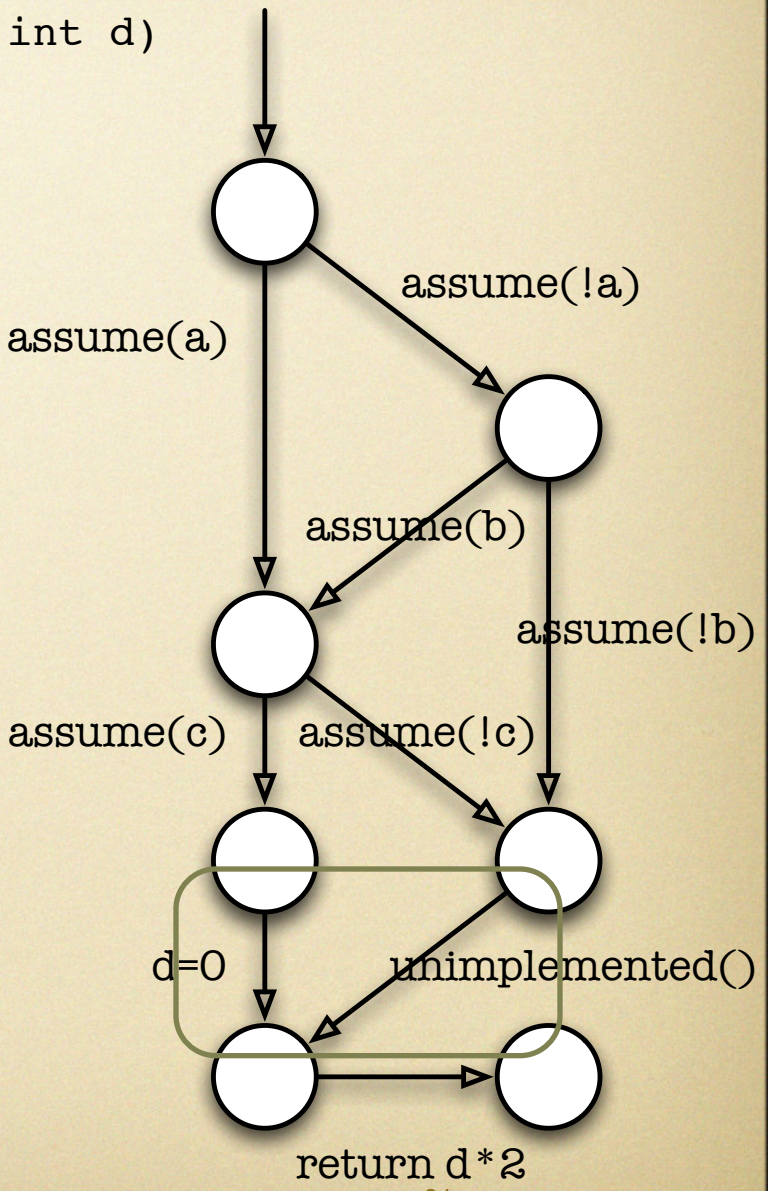
```

- cover "@conditionedge"
- cover "@conditiongraph"
- cover "@decisionedge"



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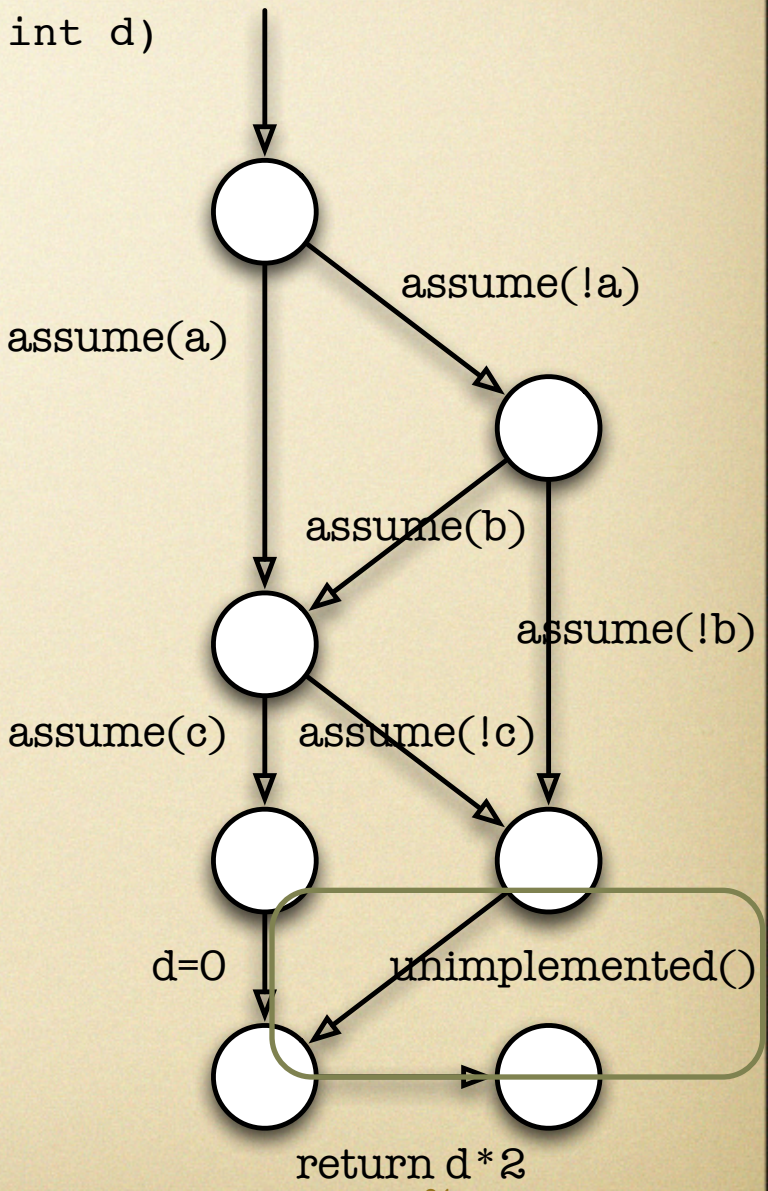
```

- cover "@conditionedge"
- cover "@conditiongraph"
- cover "@decisionedge"
- cover "@calls"



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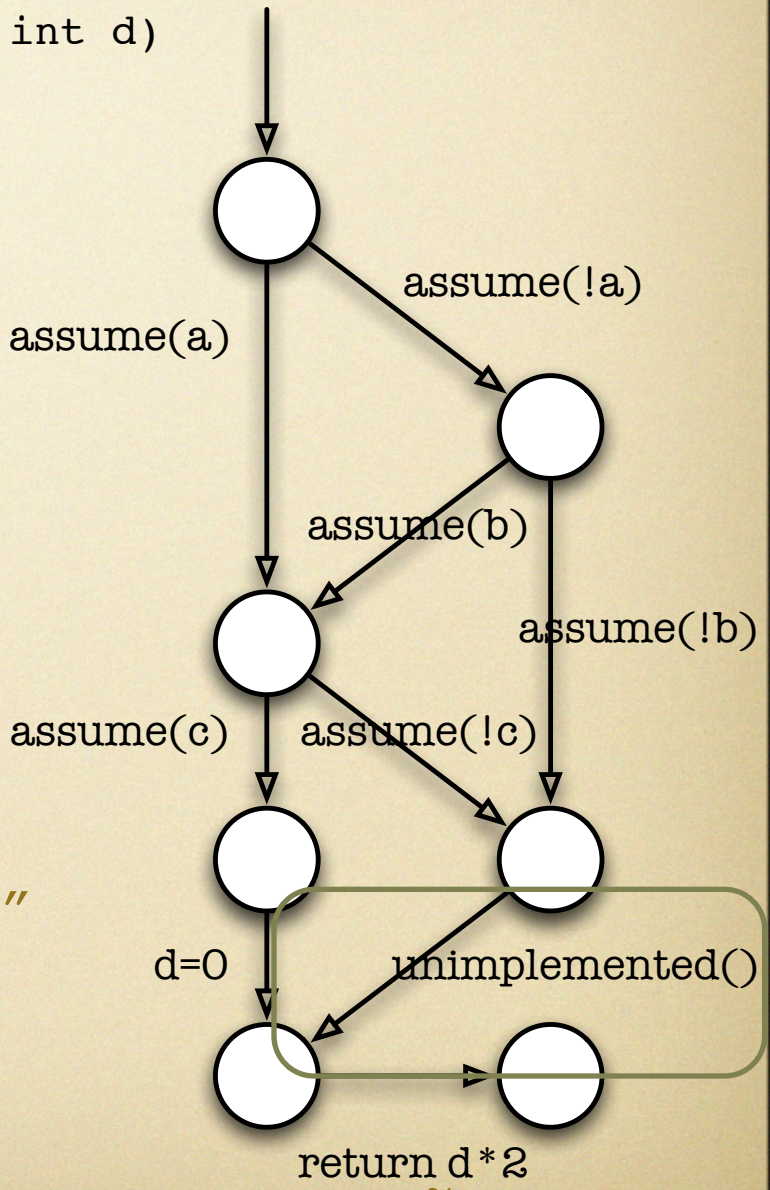
- cover "@conditionedge"
- cover "@conditiongraph"
- cover "@decisionedge"
- cover "@calls"
- cover "@call(unimplemented)"



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- cover "@conditionedge"
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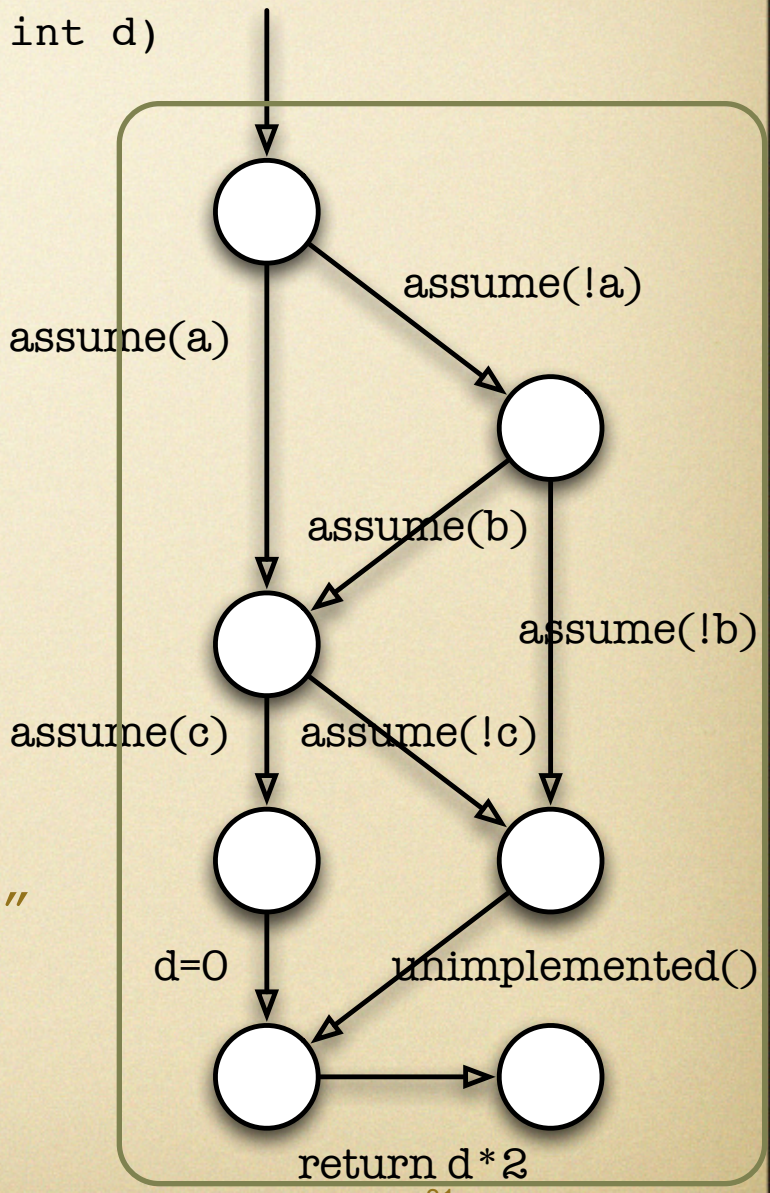
- cover "@decisionedge"
- cover "@calls"
- cover "@call(unimplemented)"
- cover "@func(example)"



CFA Transformers

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
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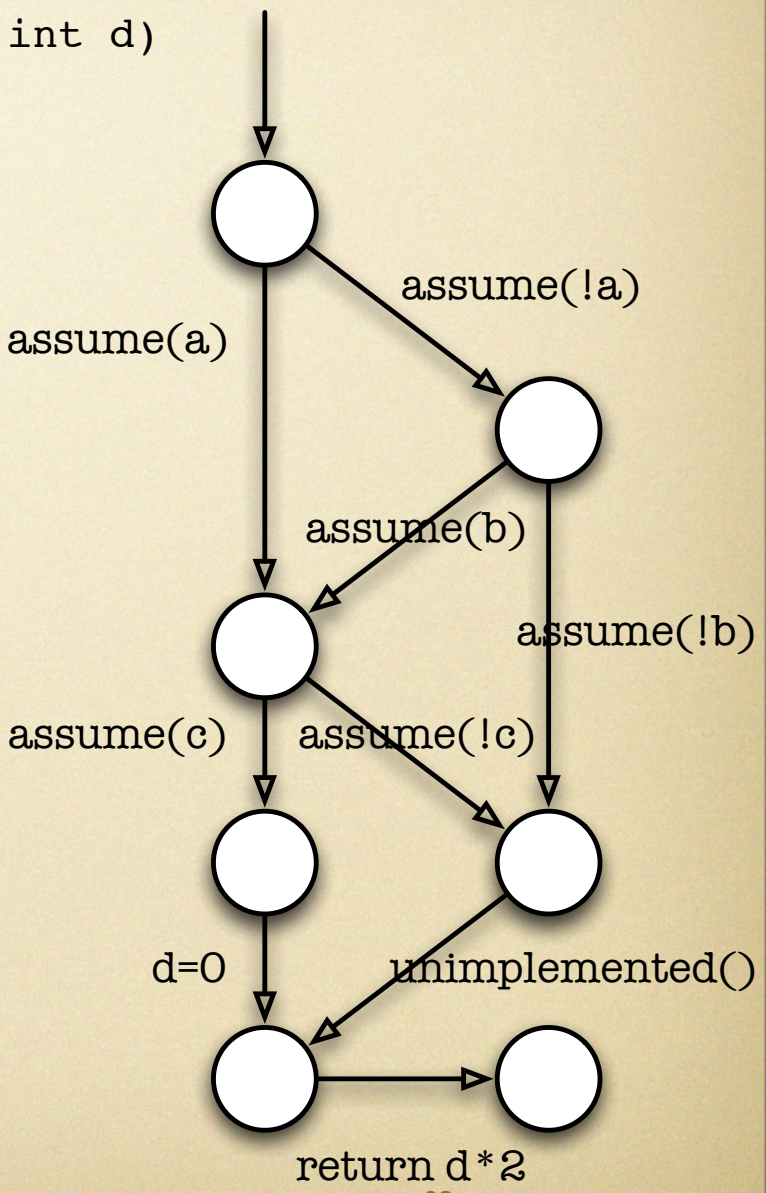

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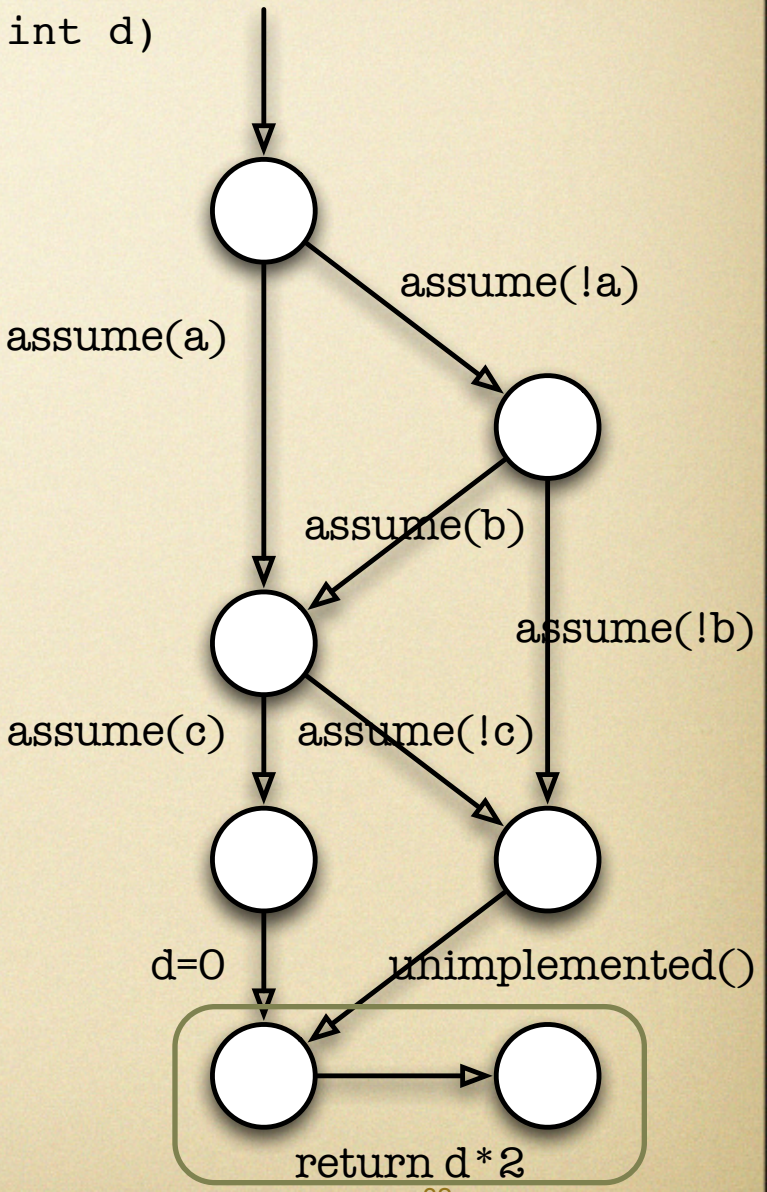

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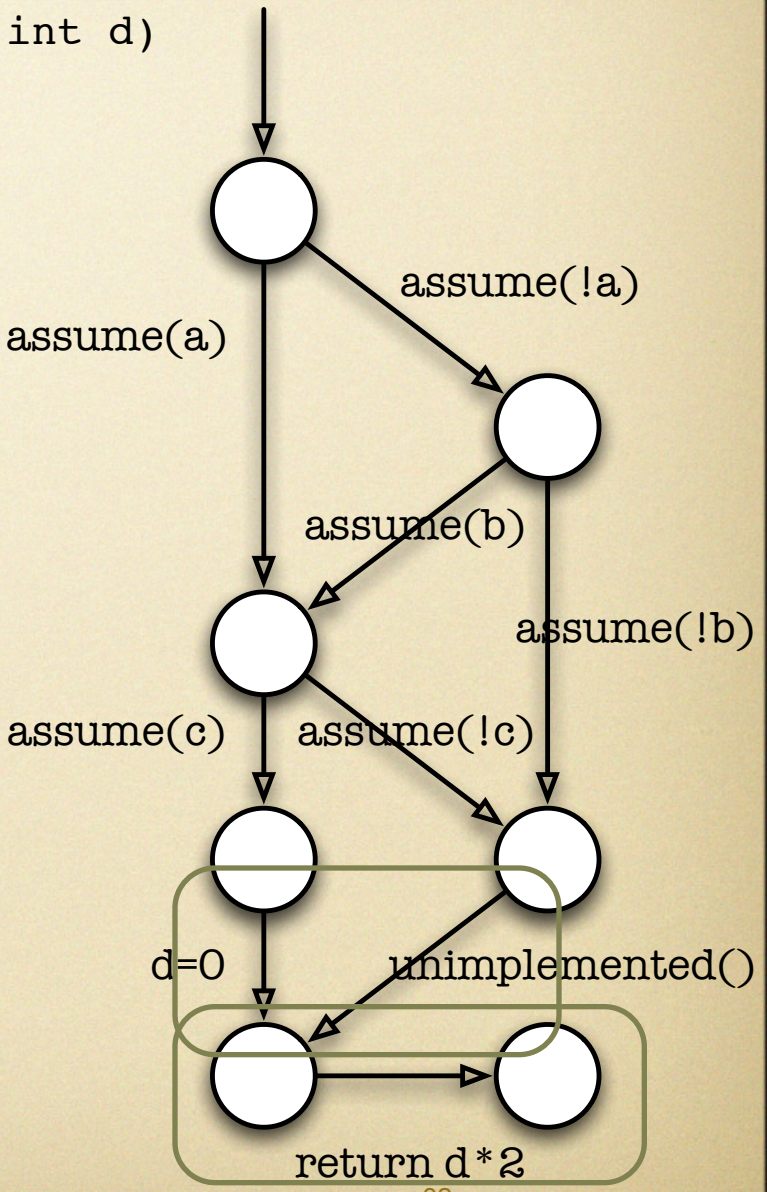

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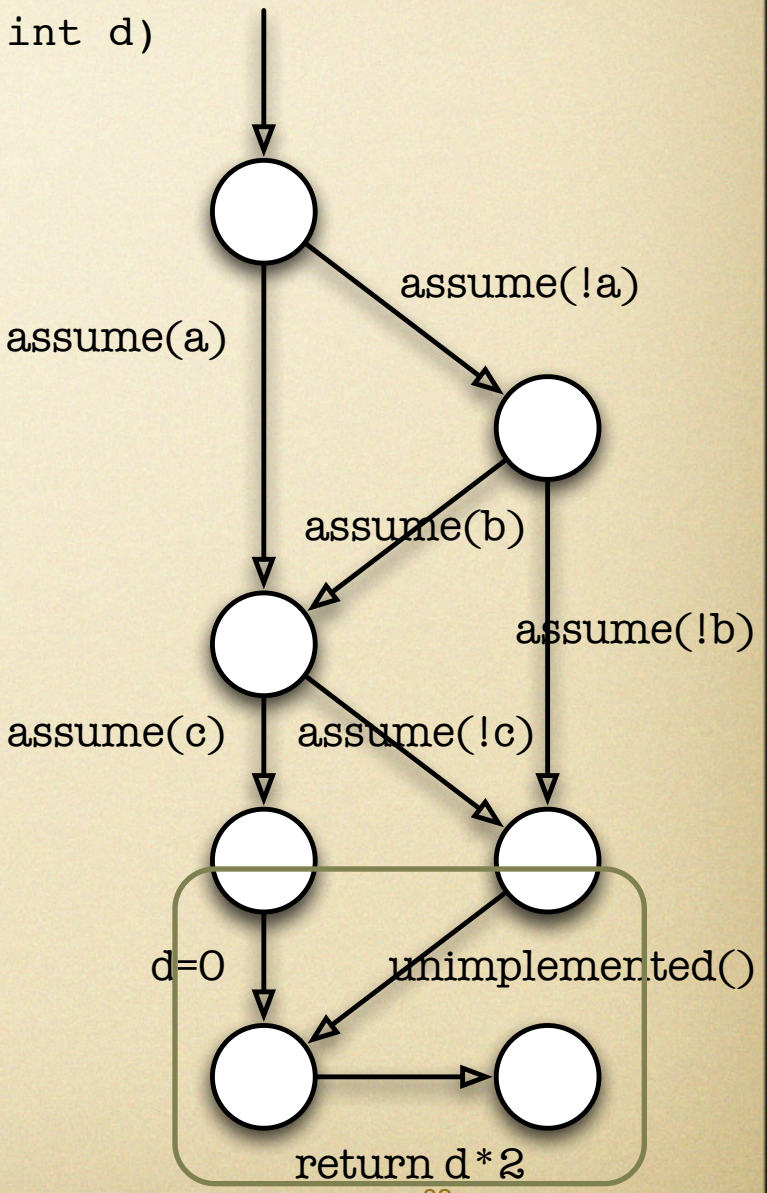
- `cover "@7 | @decisionedge"`



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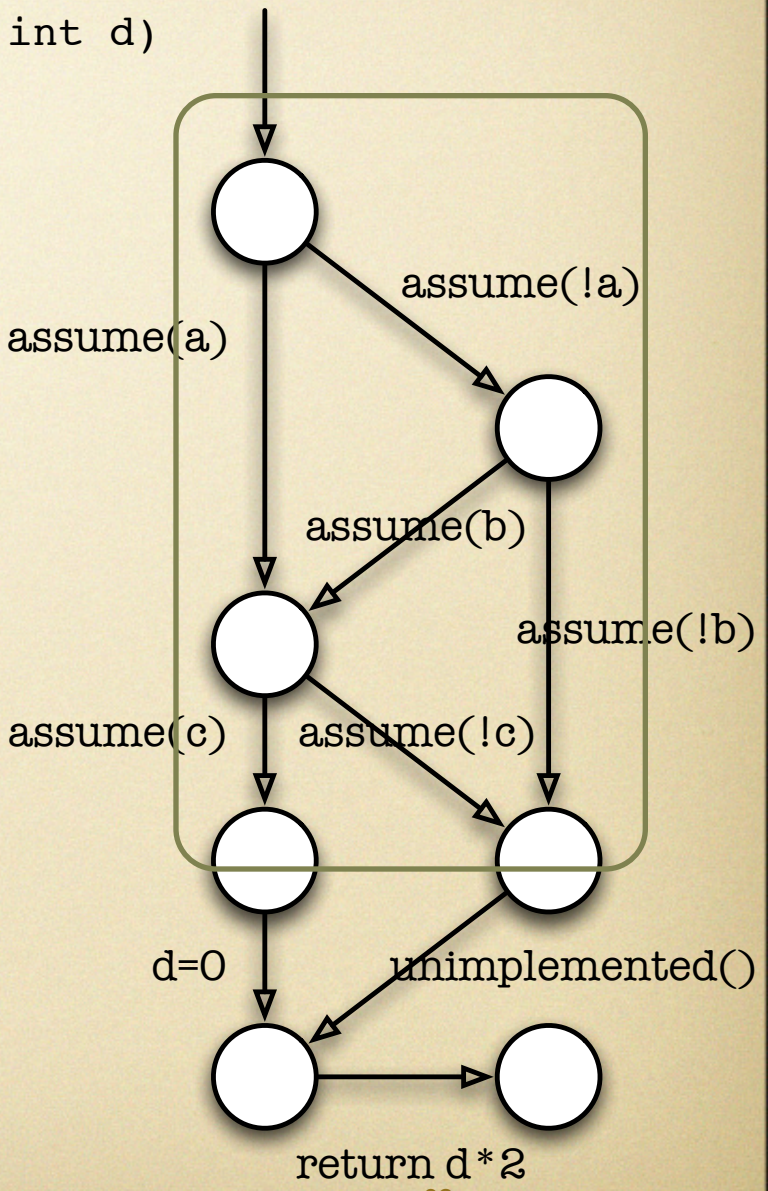

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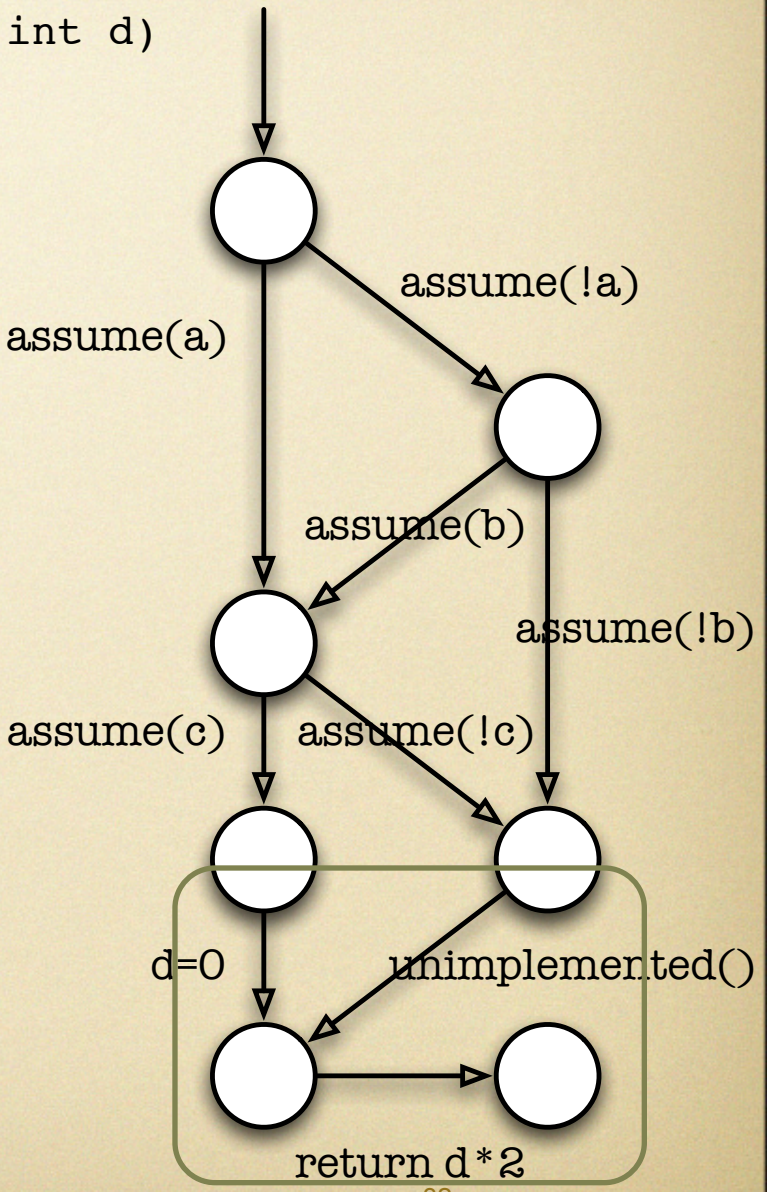
- `cover "not(@3)"`



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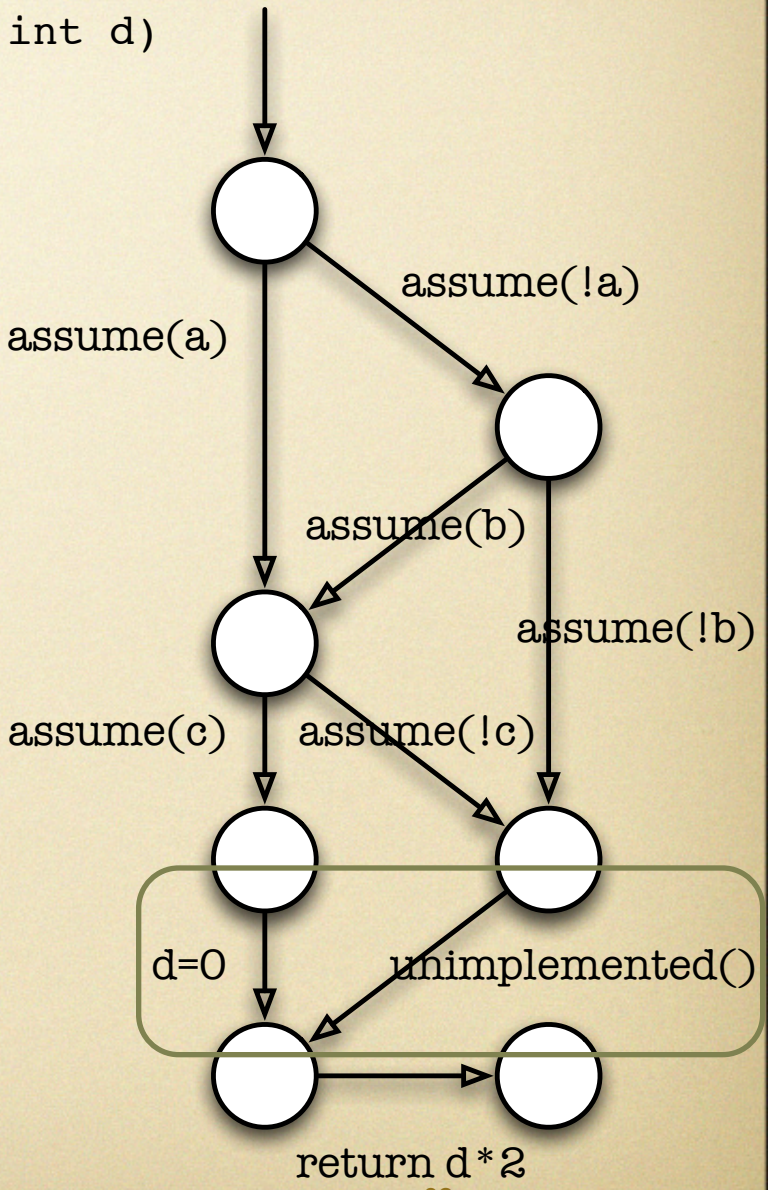

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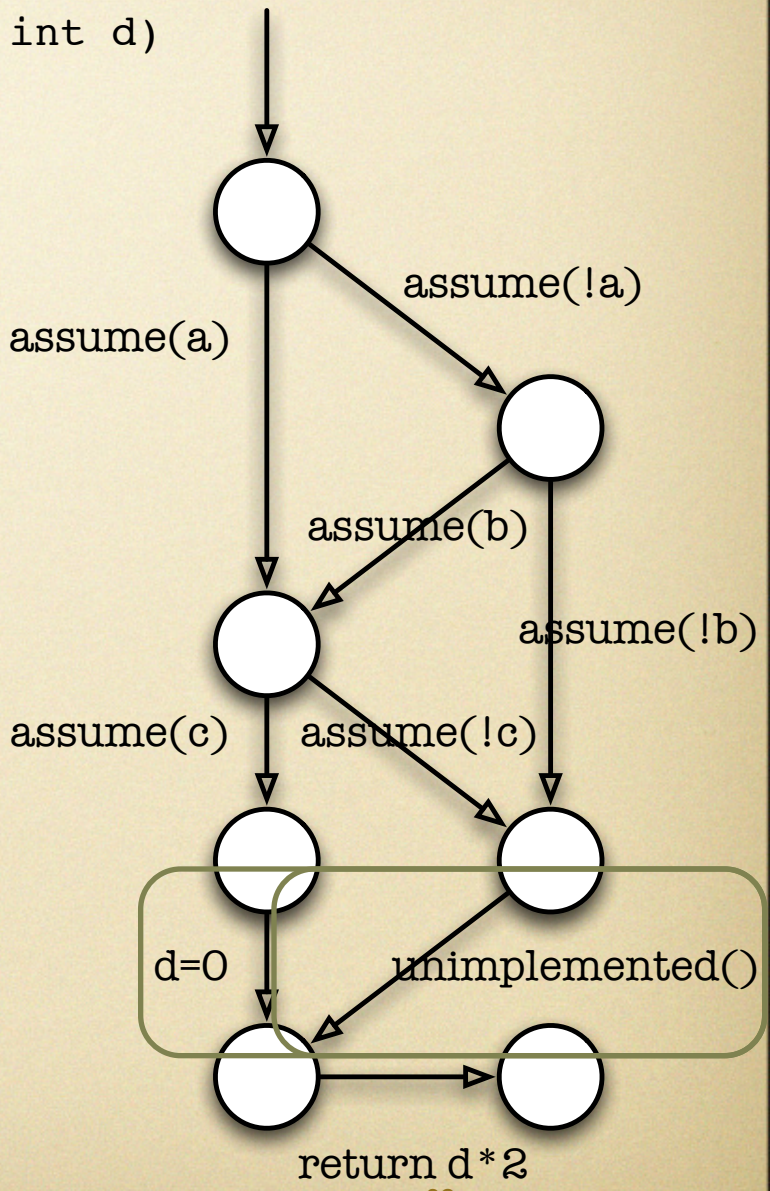

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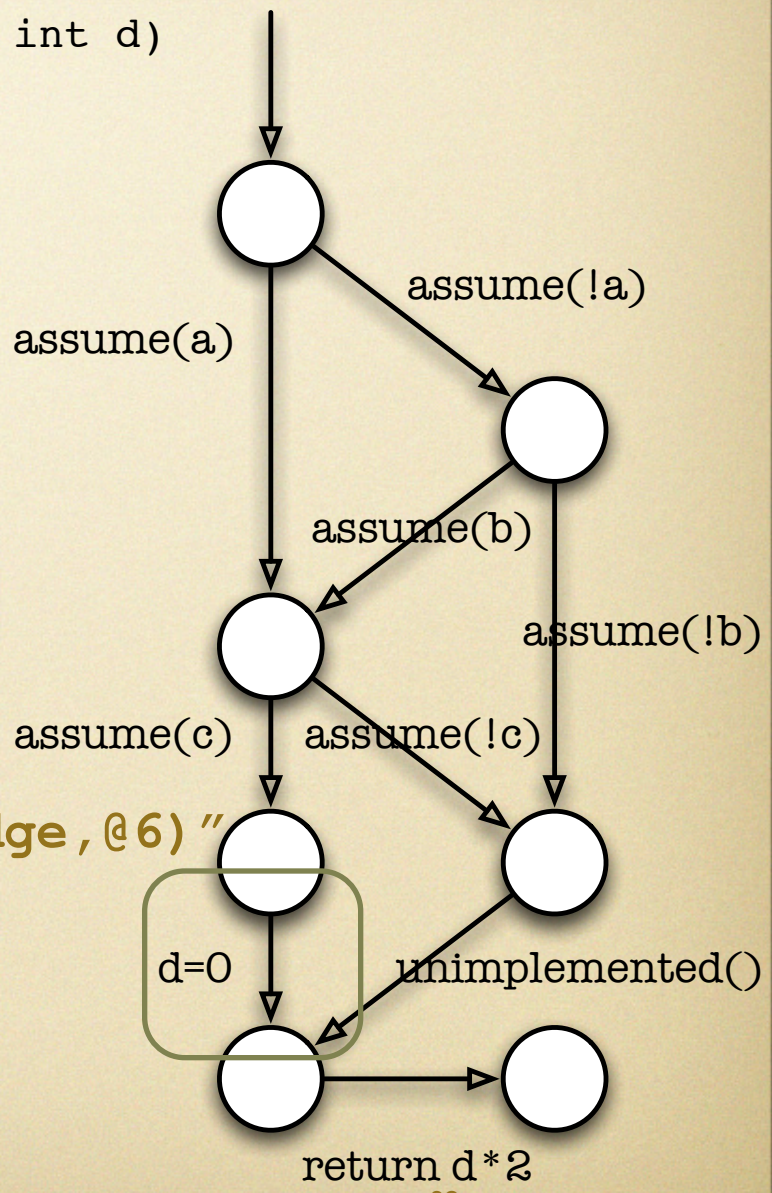

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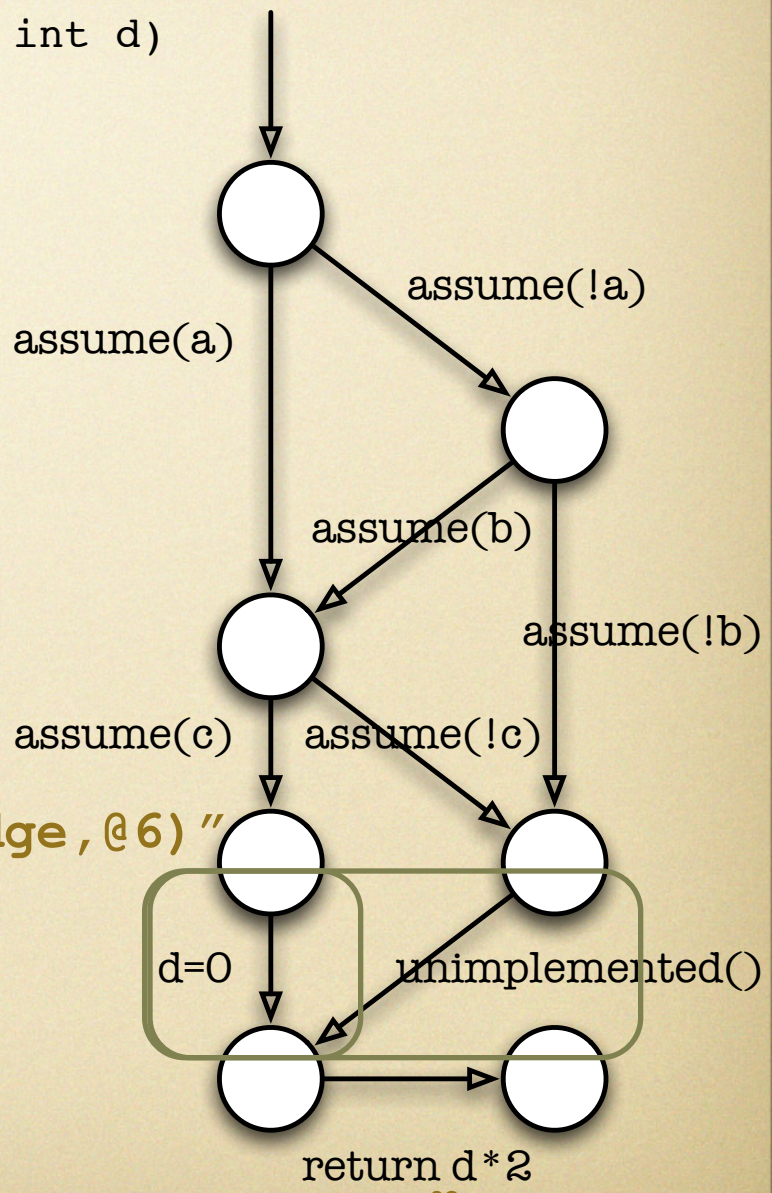

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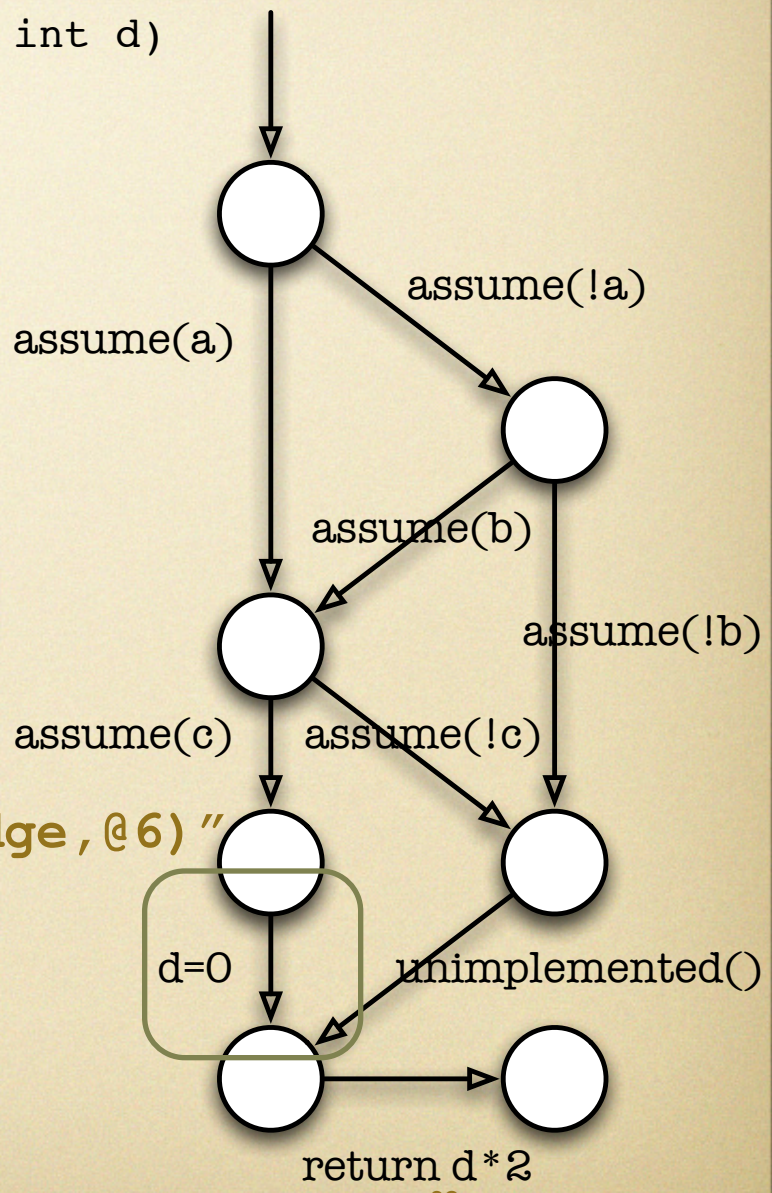

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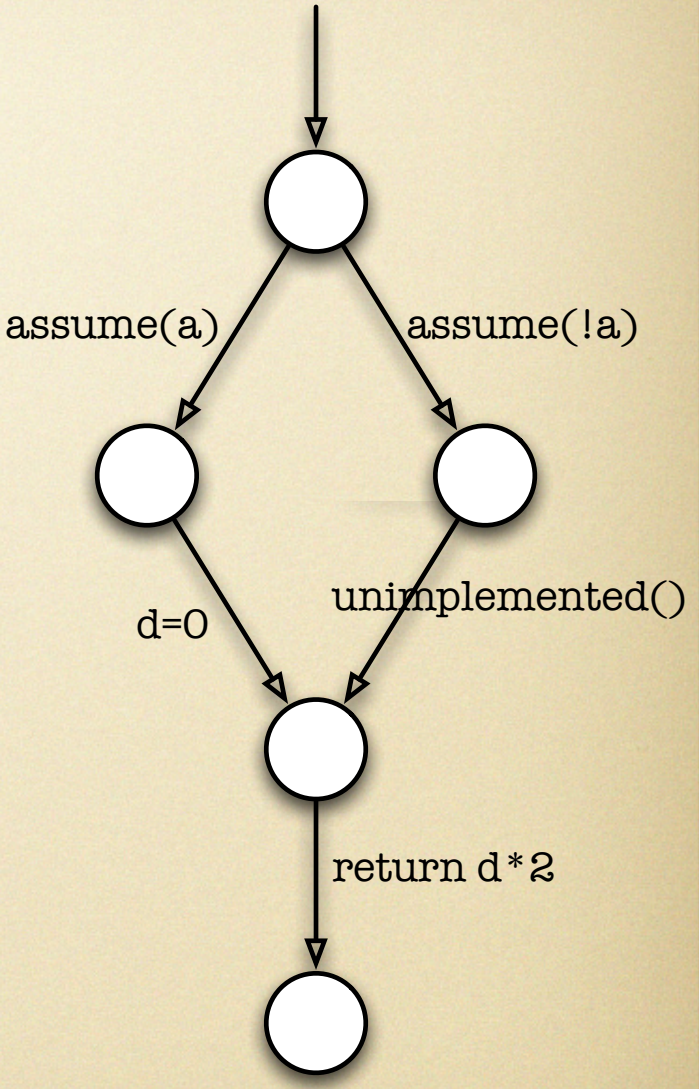

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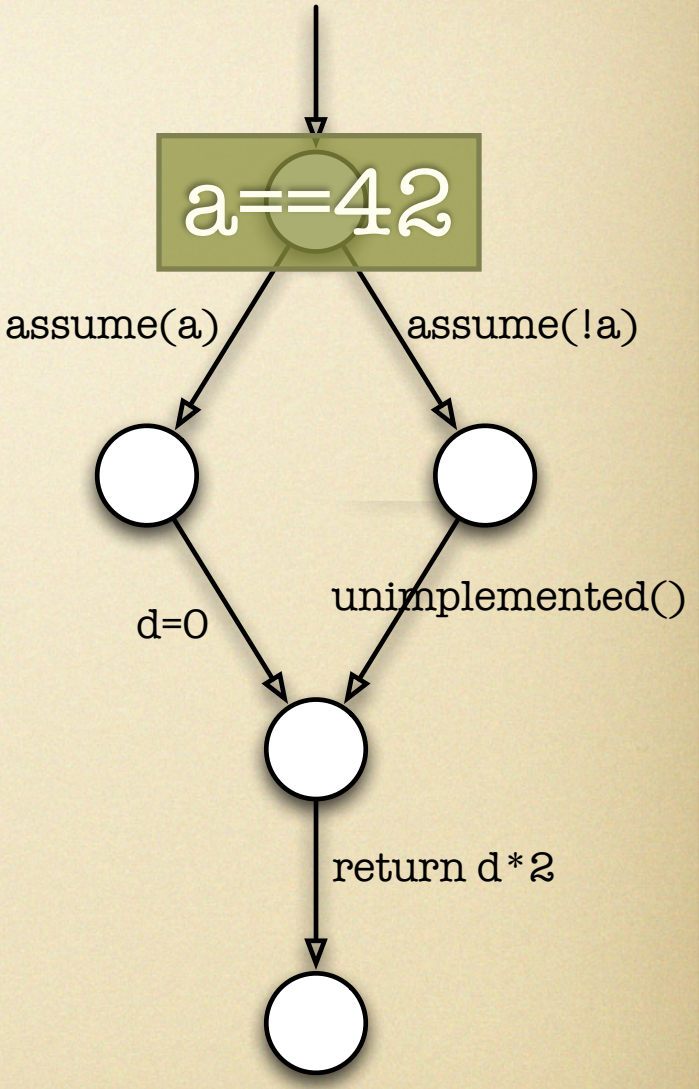

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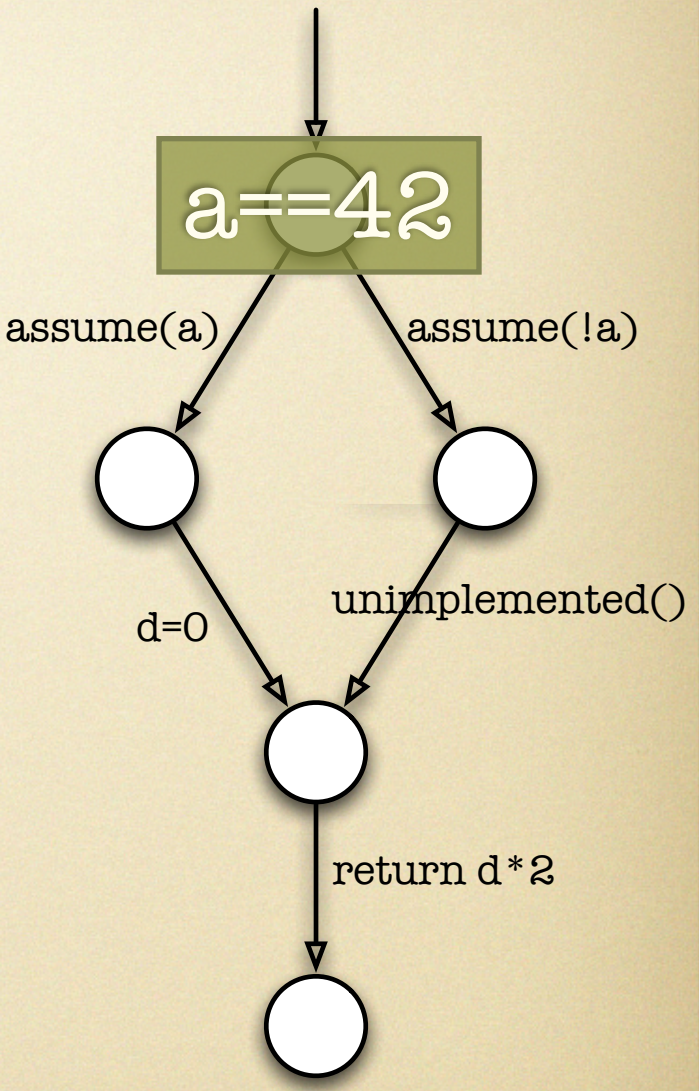
- **cover "{a==42}.@3"**

  IN:

  a=42
  d=0



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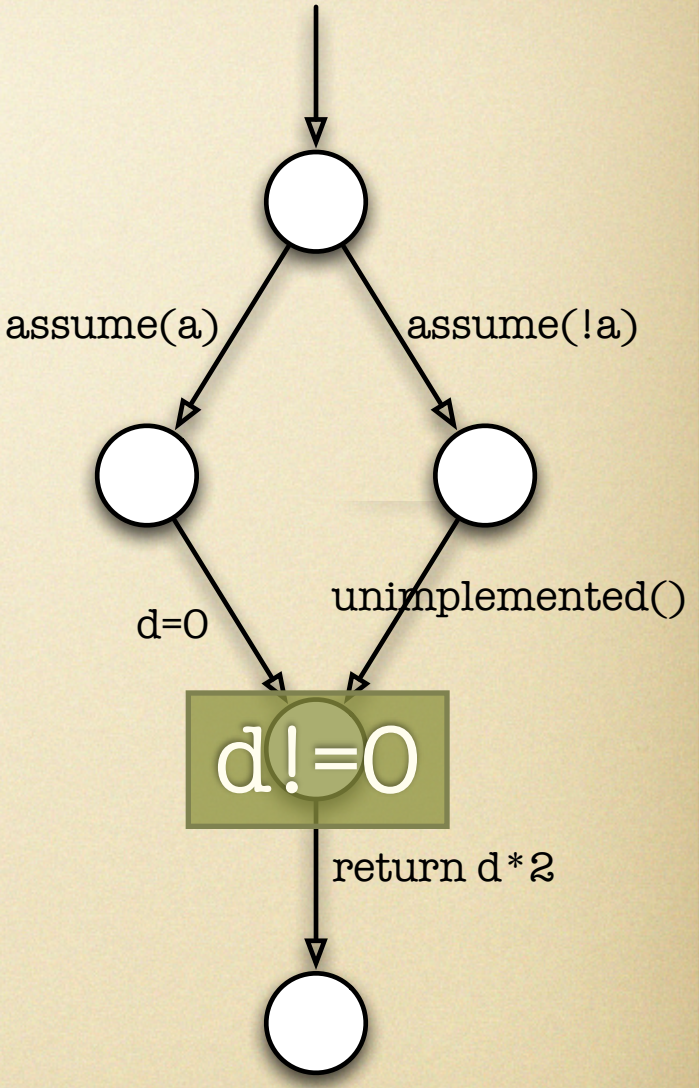

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- **cover "{a==42}.@3"**

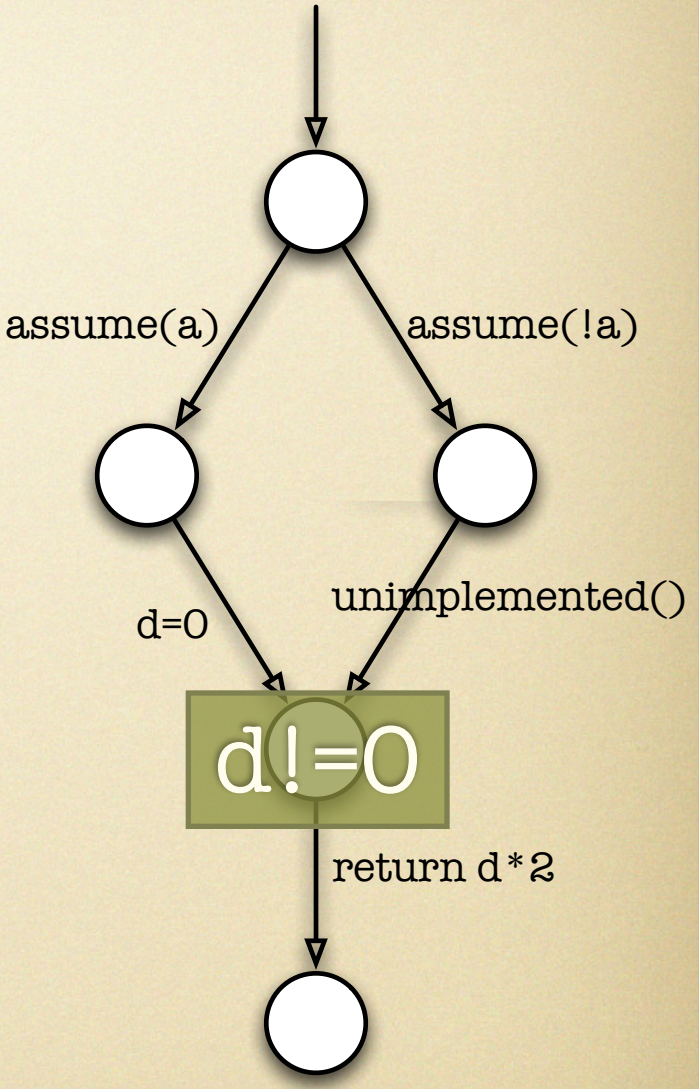
  IN:

  a=42
  d=0

- **cover "(@4+@6).{d!=0}"**

  IN:

  a=0
  d=65536



Software Testing using FQL

- ☑ Program Representation: Control Flow Automata
- ☑ Describing Single Test Cases
- **Describing Test Suites**

Coverage Patterns

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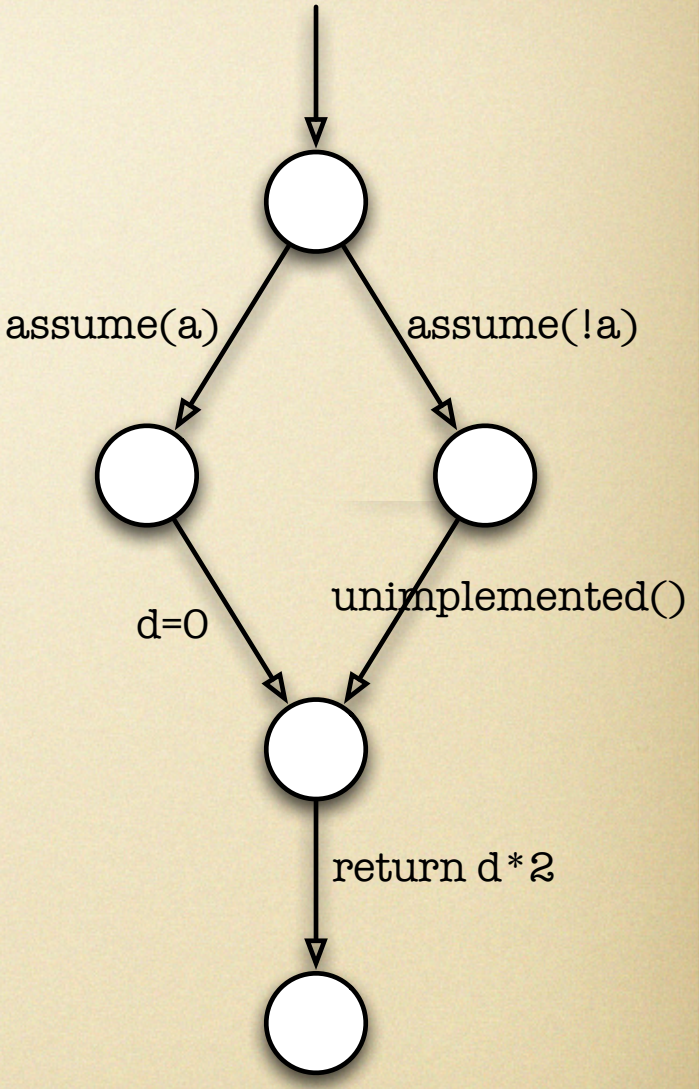

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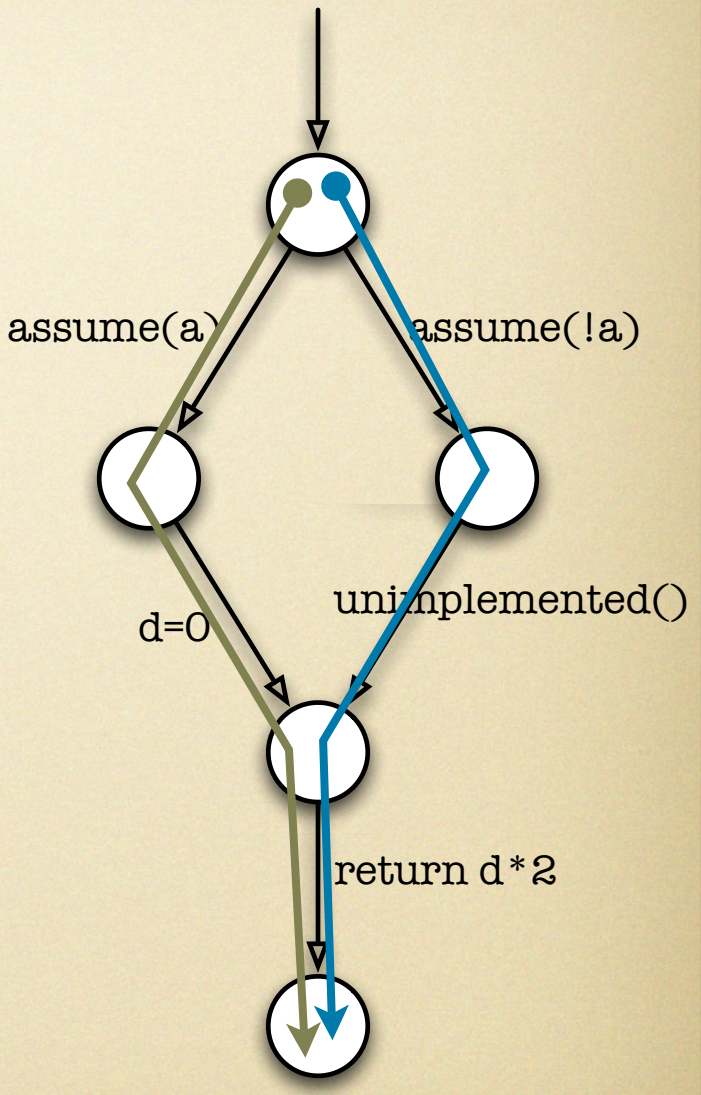

- Cover if **and** else branch ?

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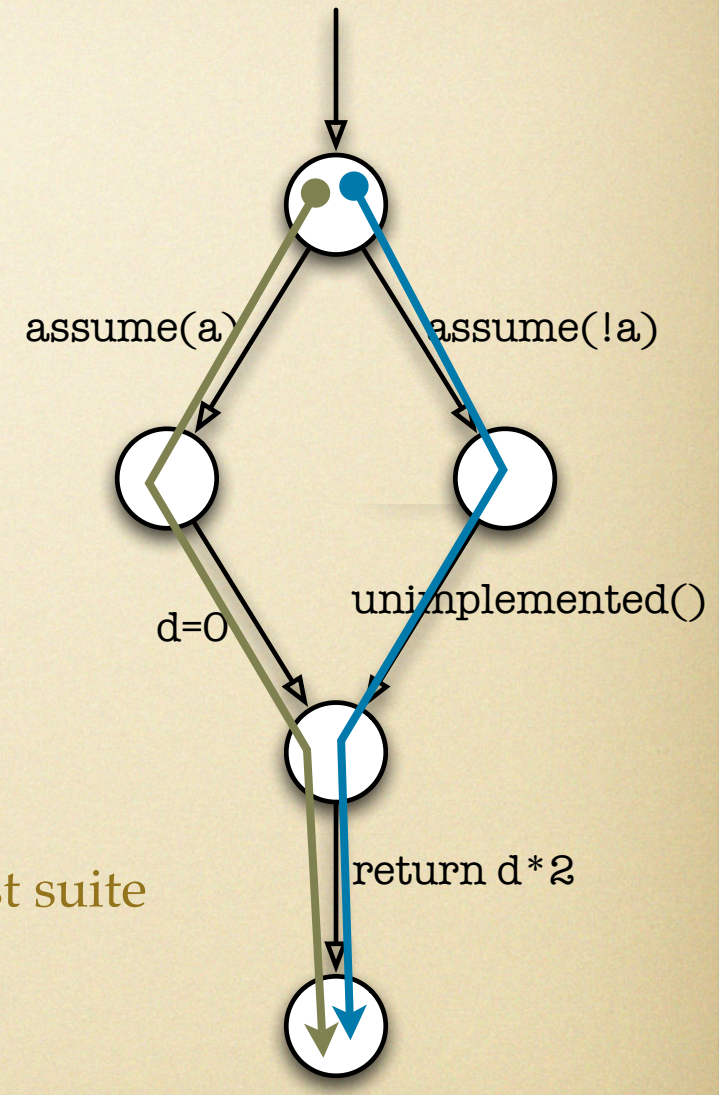

- Cover if **and** else branch ?
- We need more than one test case - a test suite

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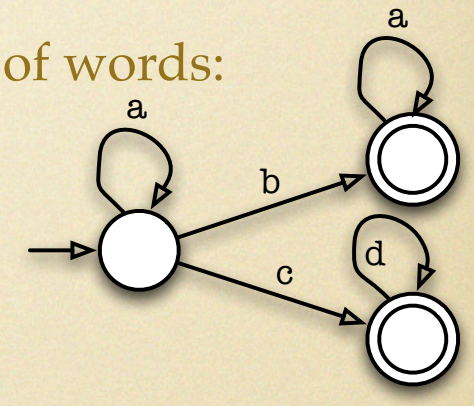

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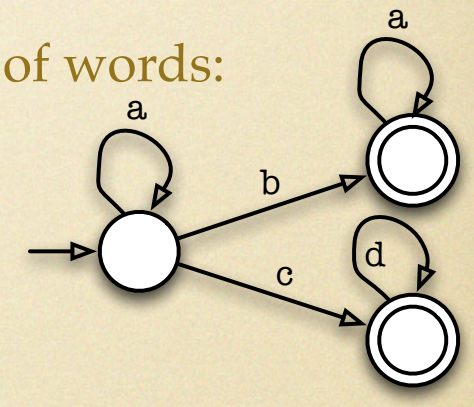

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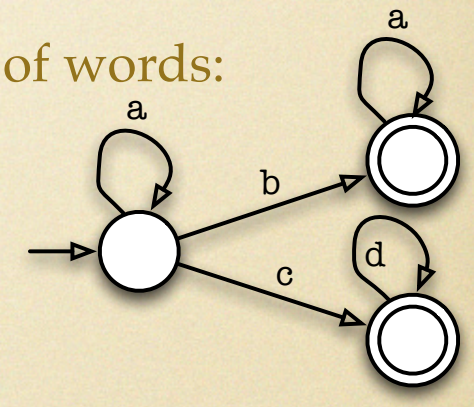

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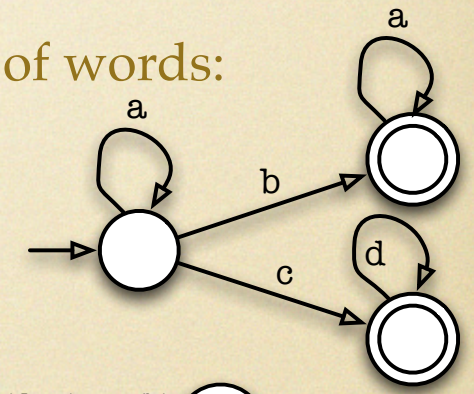

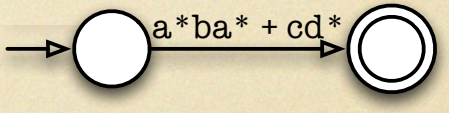

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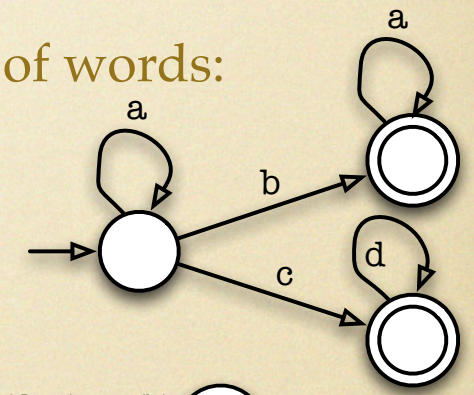

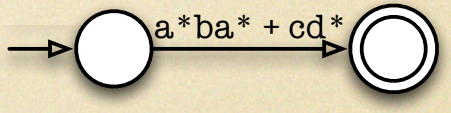

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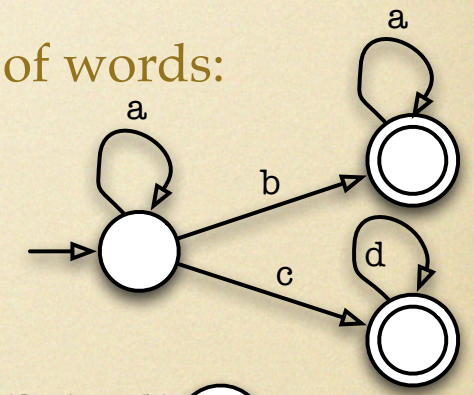

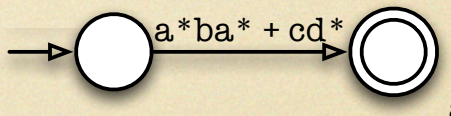

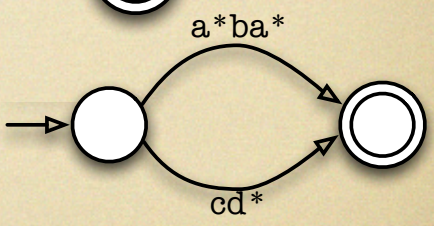

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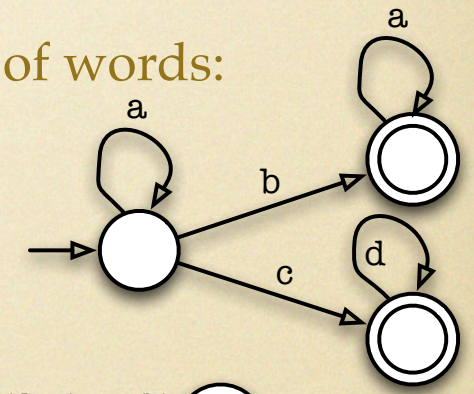

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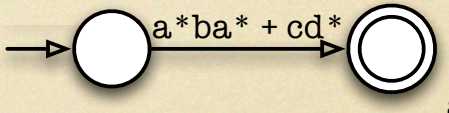

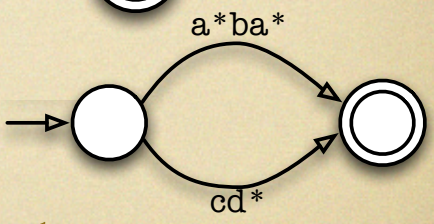

- In coverage patterns: Kleene star only within quotes

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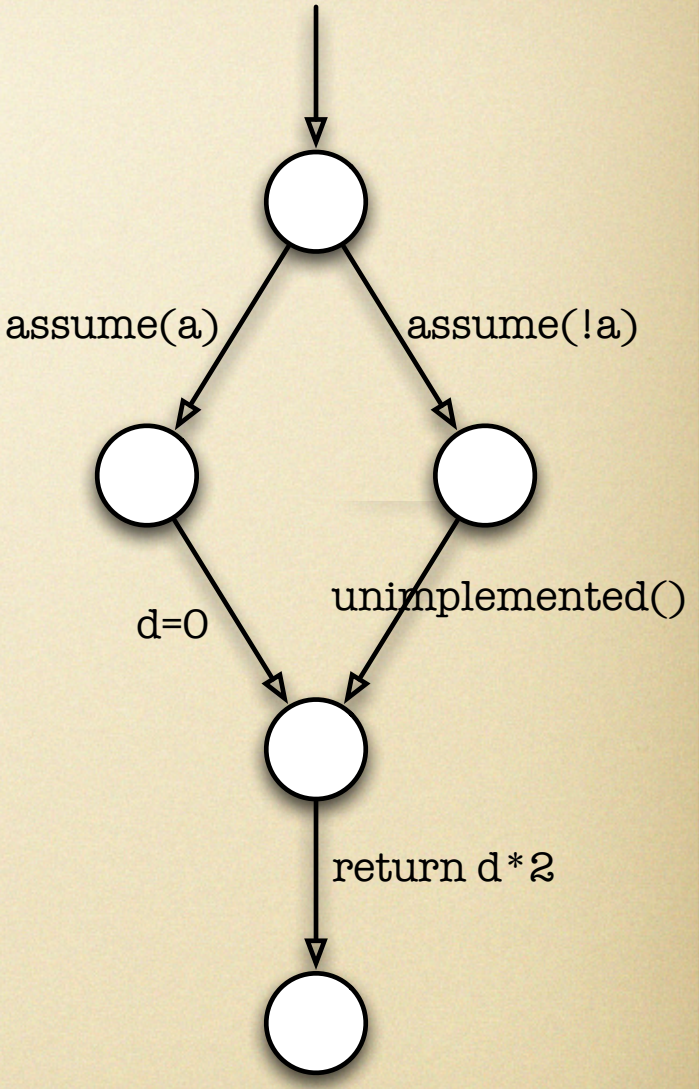

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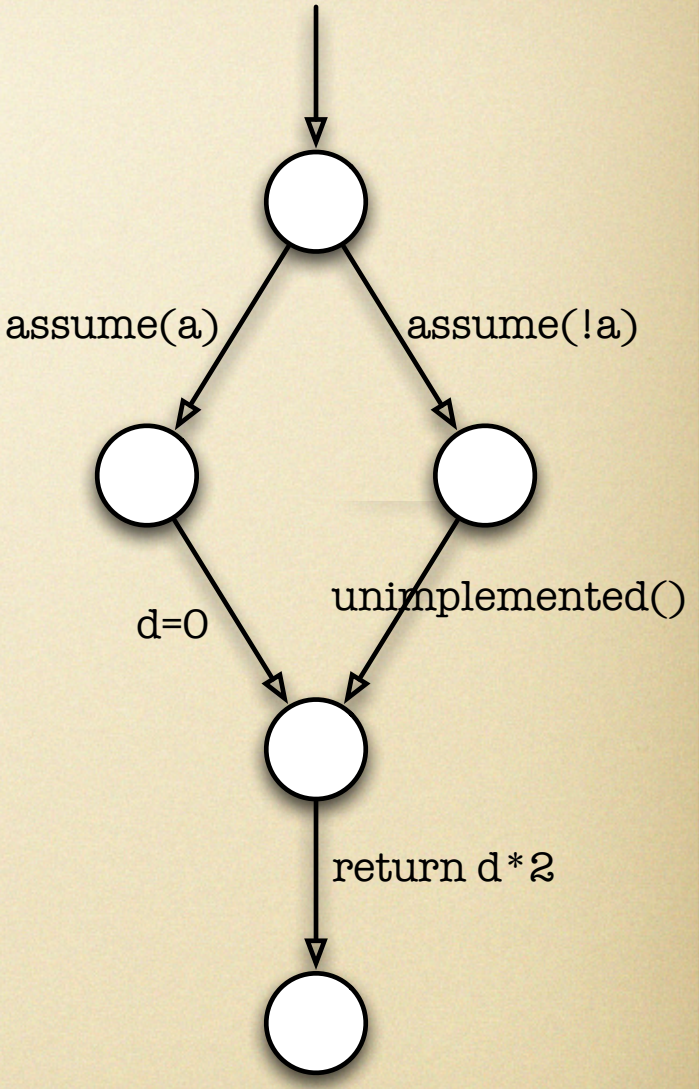

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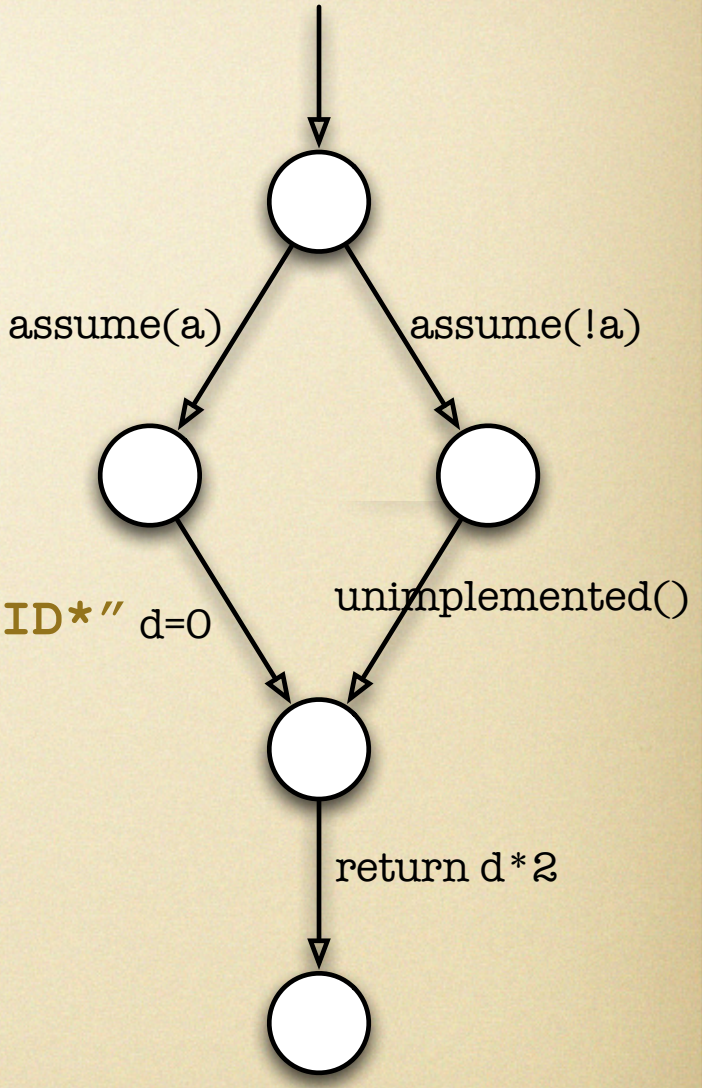
- Cover if **and** else branch
- `cover "ID*.@4.ID*" + "ID*.@6.ID*"`



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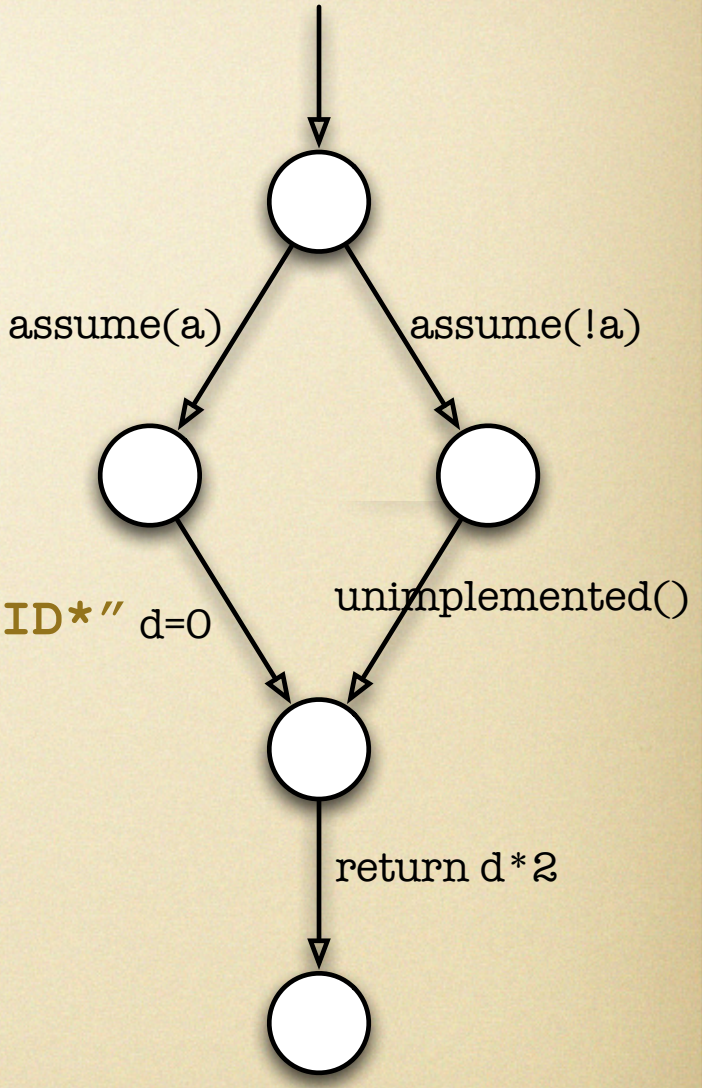
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

- Cover if **and** else branch
- `cover "ID*.@4.ID*" + "ID*.@6.ID*"`
- 2 words - 2 test goals



Coverage Patterns

```
1  int example(int a, int d)
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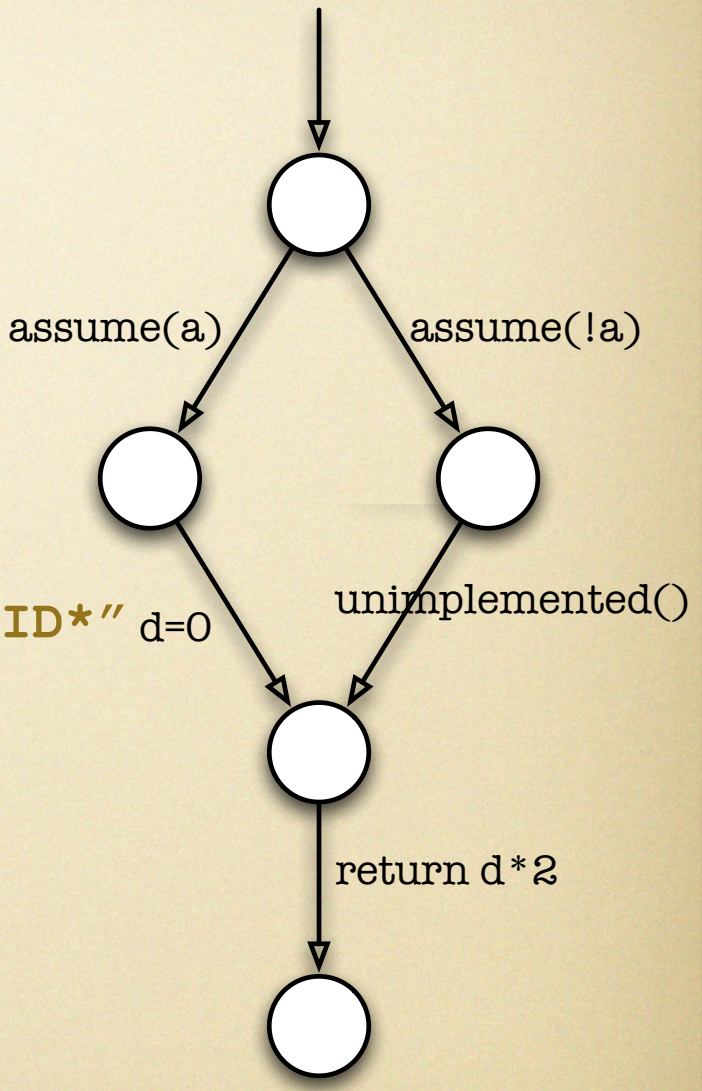

- Cover if **and** else branch
- **`cover "ID*.@4.ID*" + "ID*.@6.ID*"`**
- 2 words - 2 test goals

IN:

a=2
d=0

IN:

a=0
d=0

Coverage Patterns

```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
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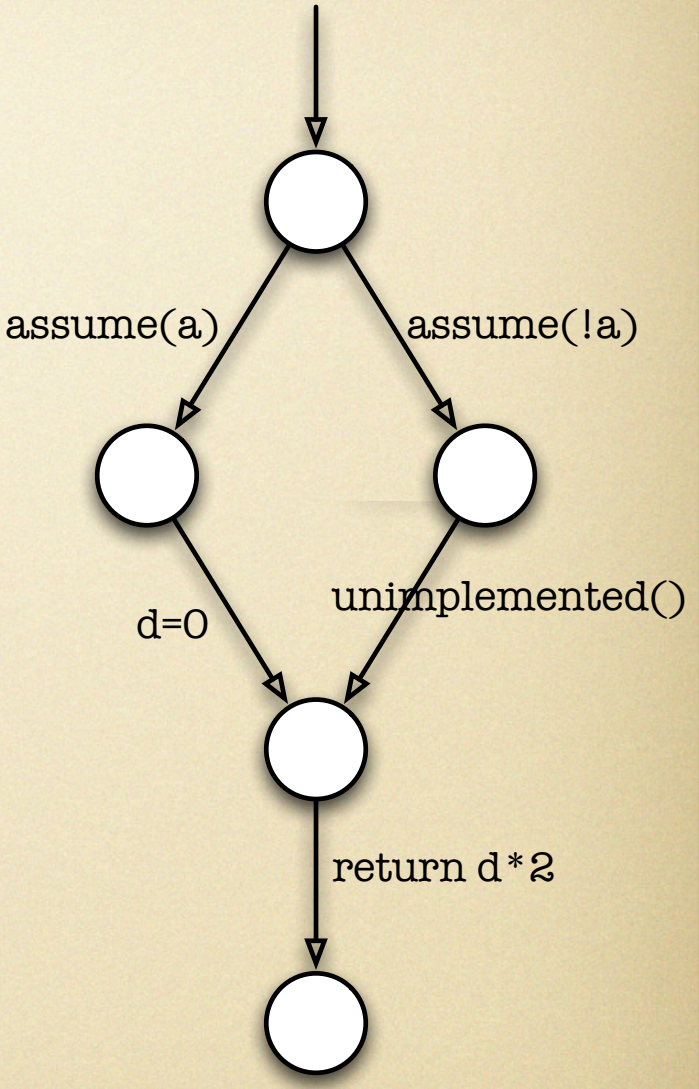

Coverage Patterns

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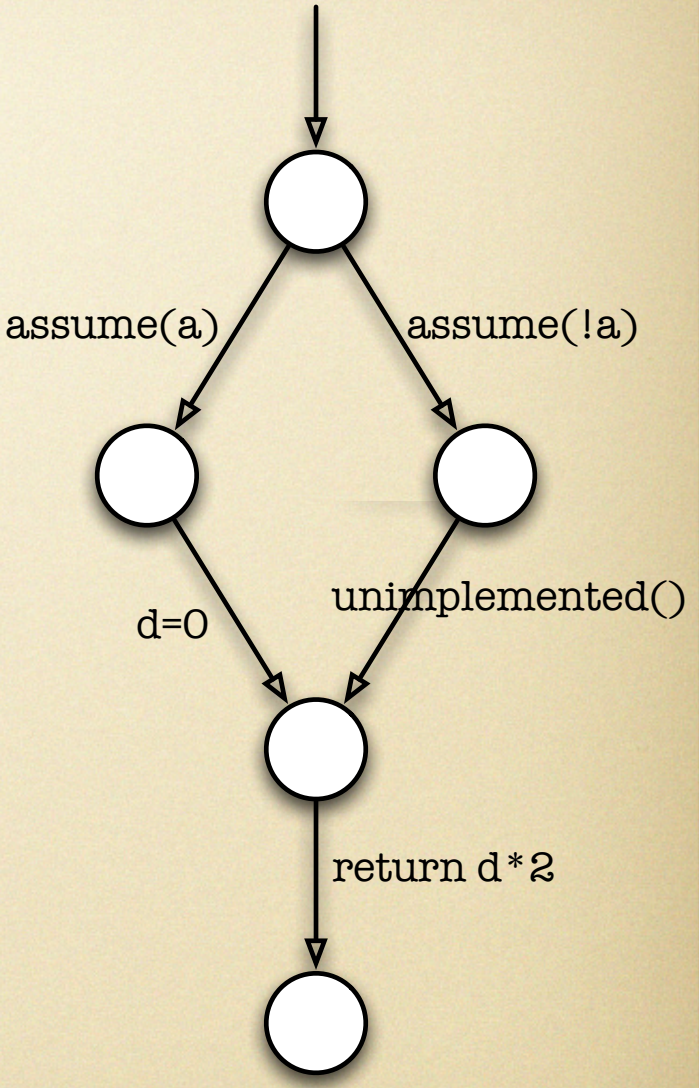
- Can we cover pairs of lines?



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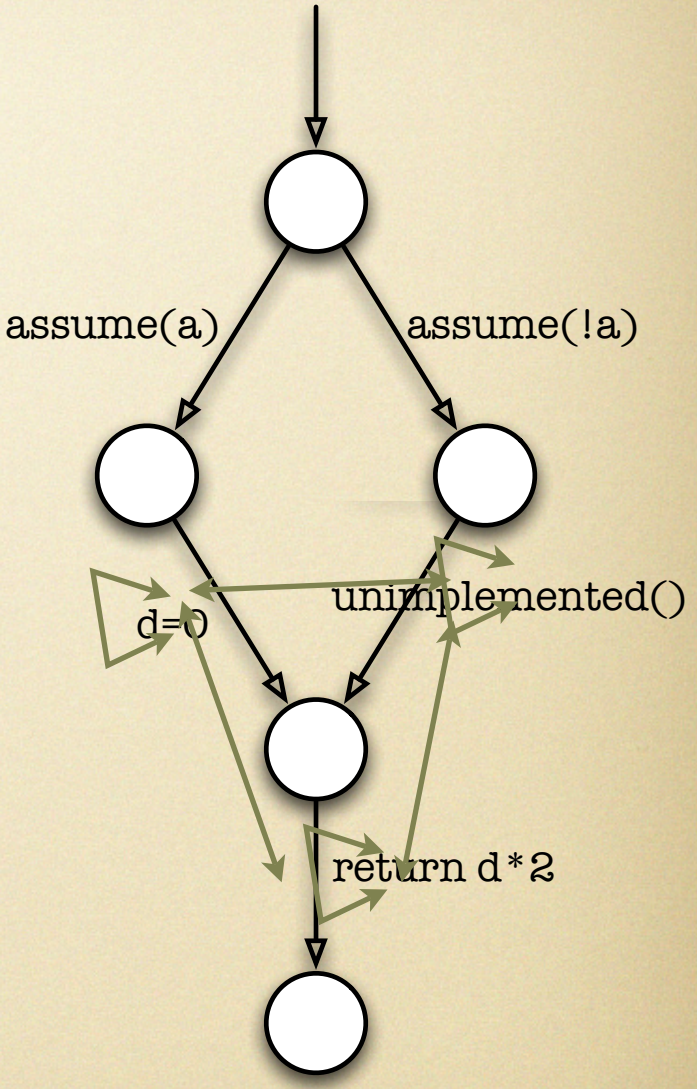

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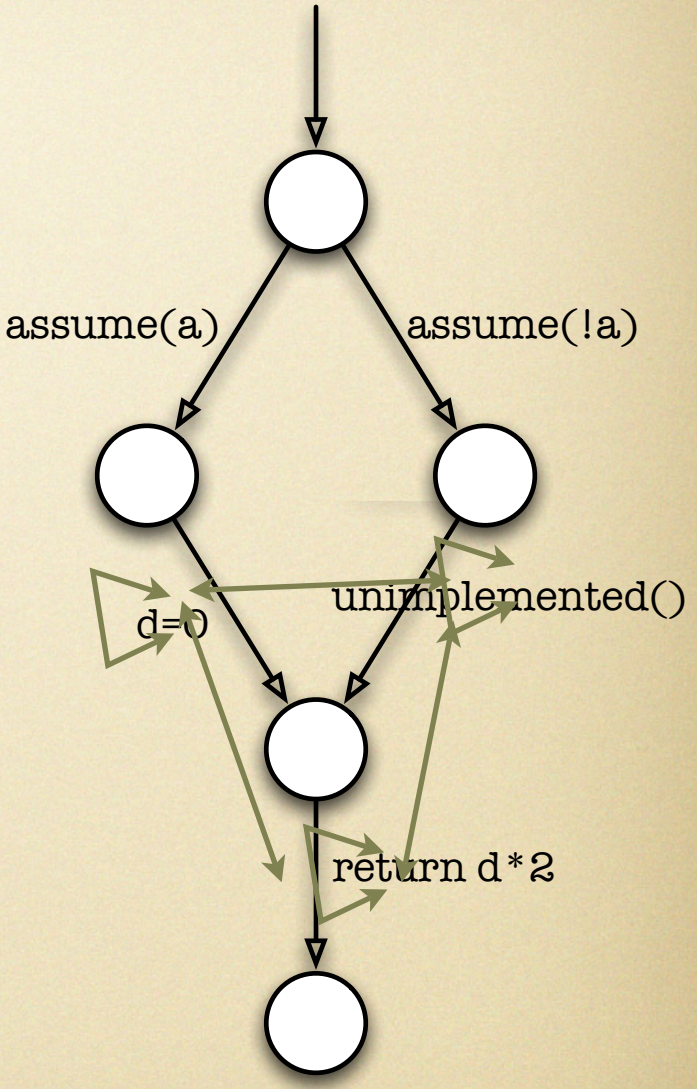
- Can we cover pairs of lines?
- **`cover "ID*".(@4+@6+@7)."ID*".(@4+@6+@7)."ID*"`**



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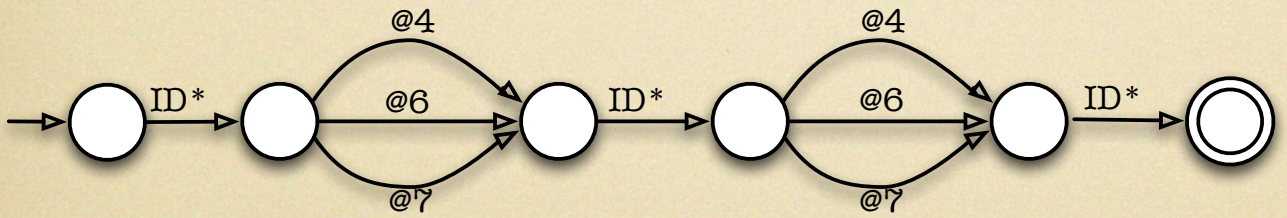

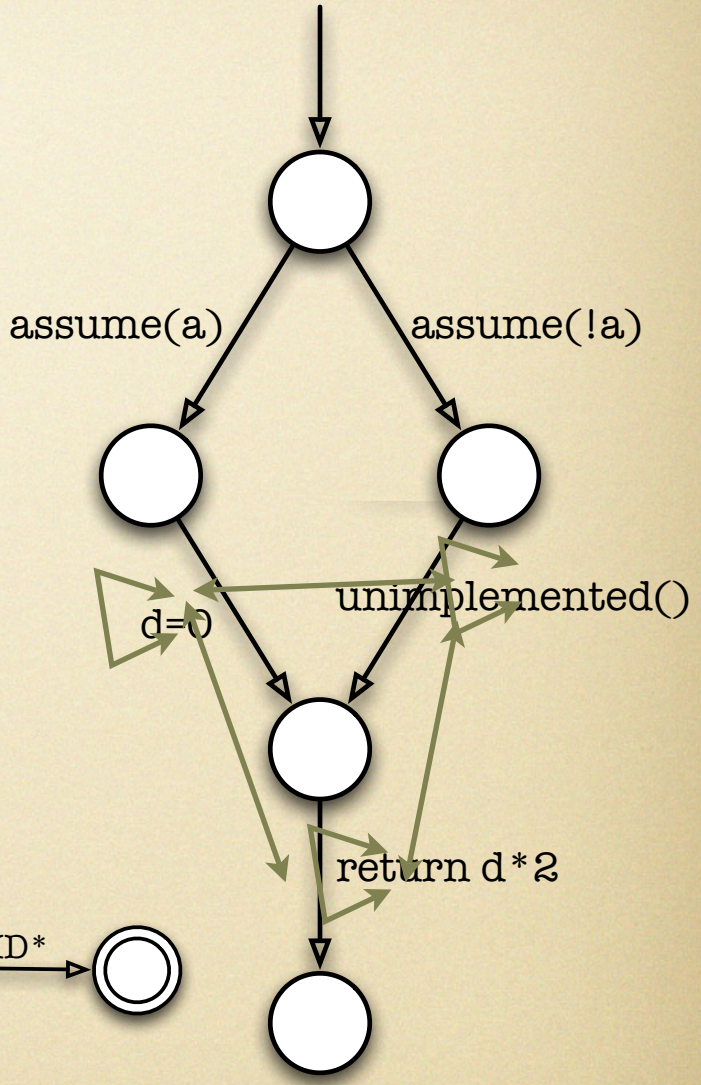

Coverage Patterns

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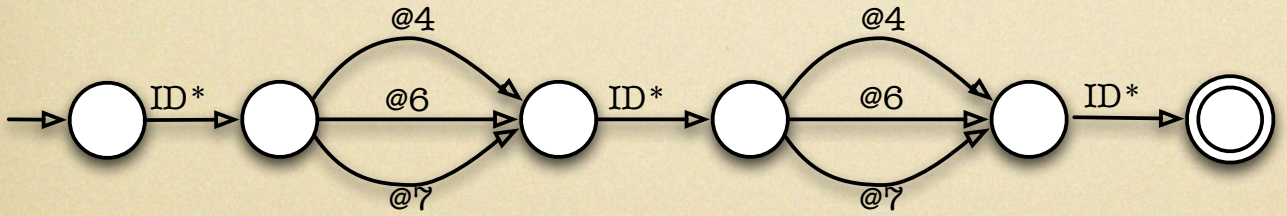
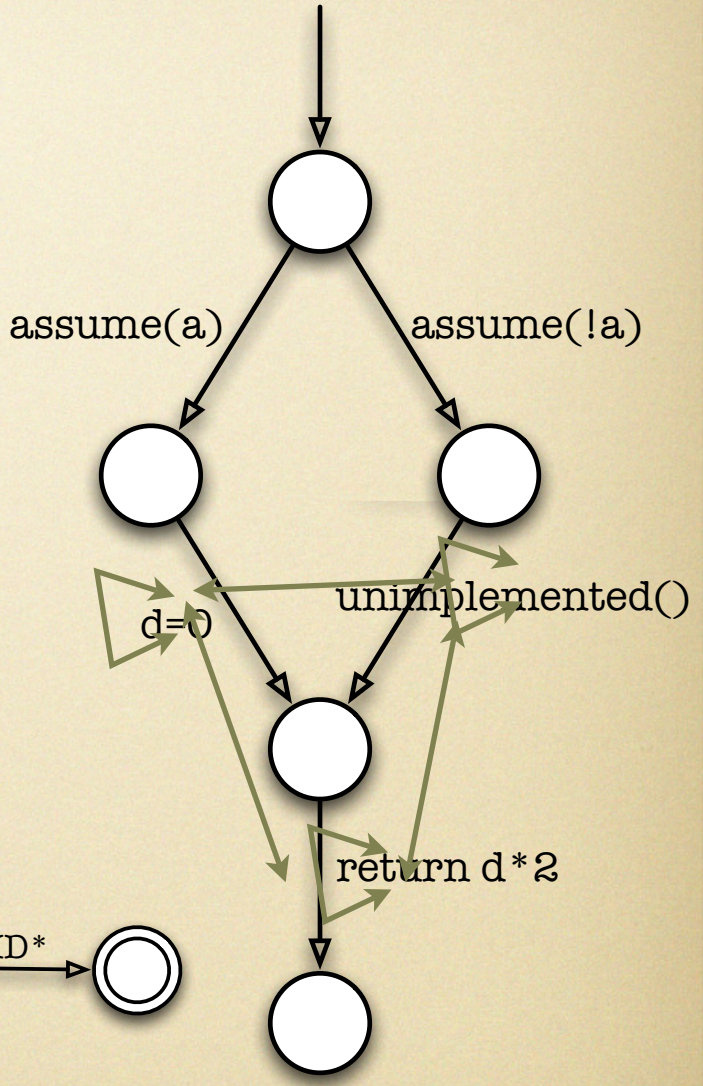
- Can we cover pairs of lines?
- **`cover "ID*".(@4+@6+@7)."ID*".(@4+@6+@7)."ID*"`**
- Coverage pattern describes 9 test goals





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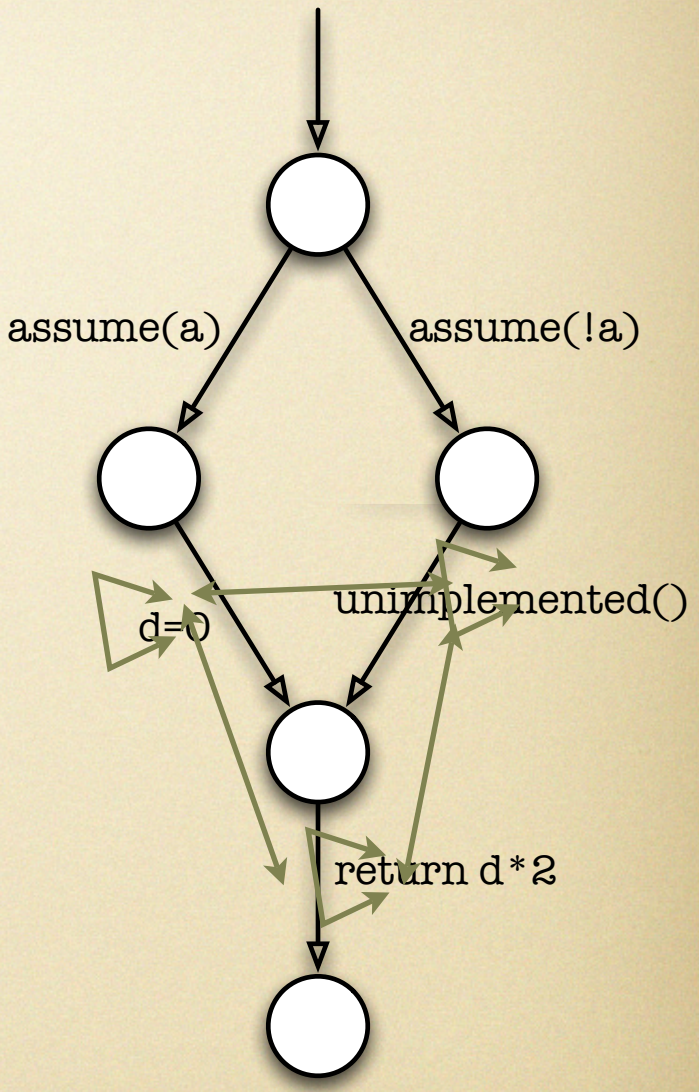

- Can we cover pairs of lines?
- **`cover "ID*".(@4+@6+@7)."ID*".(@4+@6+@7)."ID*"`**
- Coverage pattern describes 9 test goals

```
IN:
  a=67108864
  d=0
IN:
  a=0
  d=0
```

Coverage Patterns

```
1  int example(int a, int d)
2  {
3    if (a)
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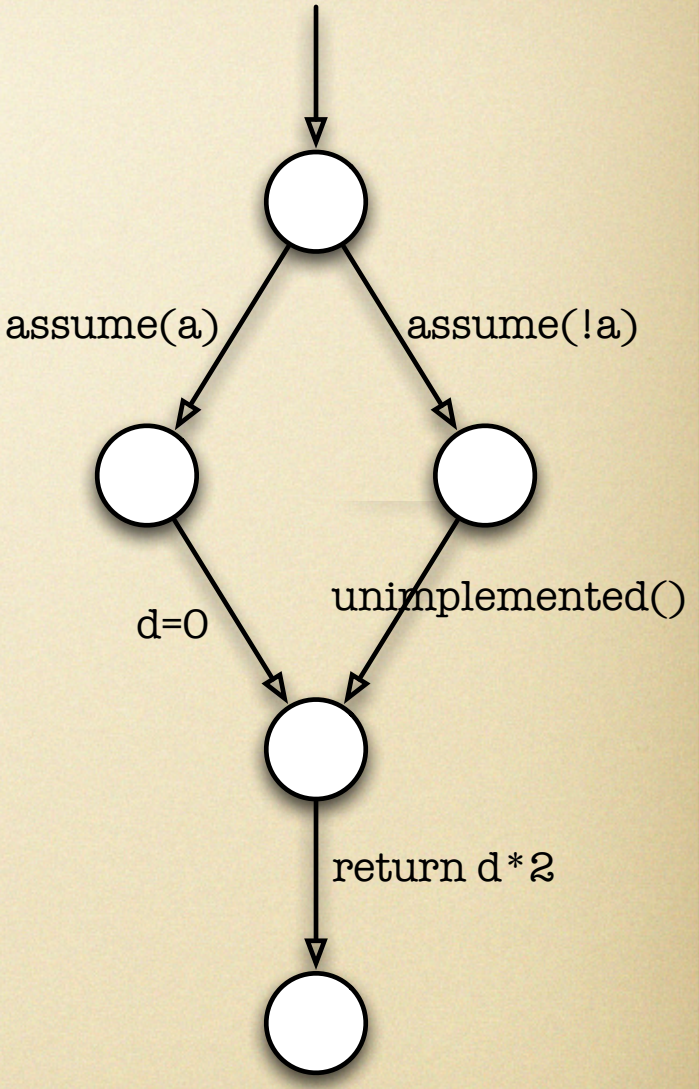

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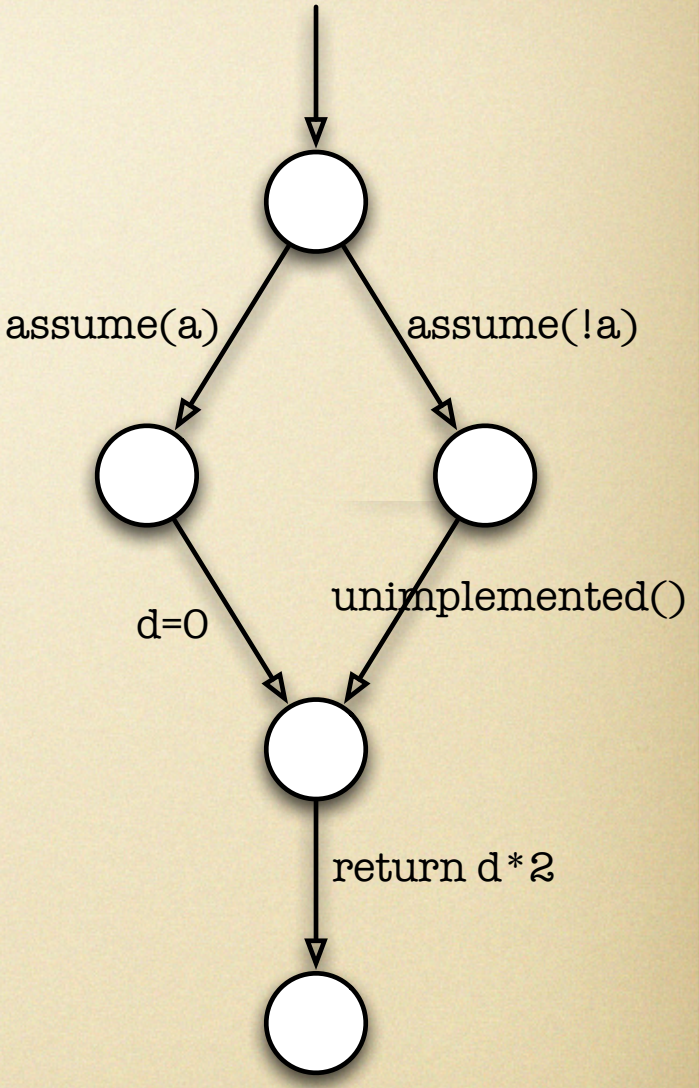
- Earlier: *"For this example* ***@basicblockentry*** *is tantamount to* ***@4+@6+@7"***



Coverage Patterns

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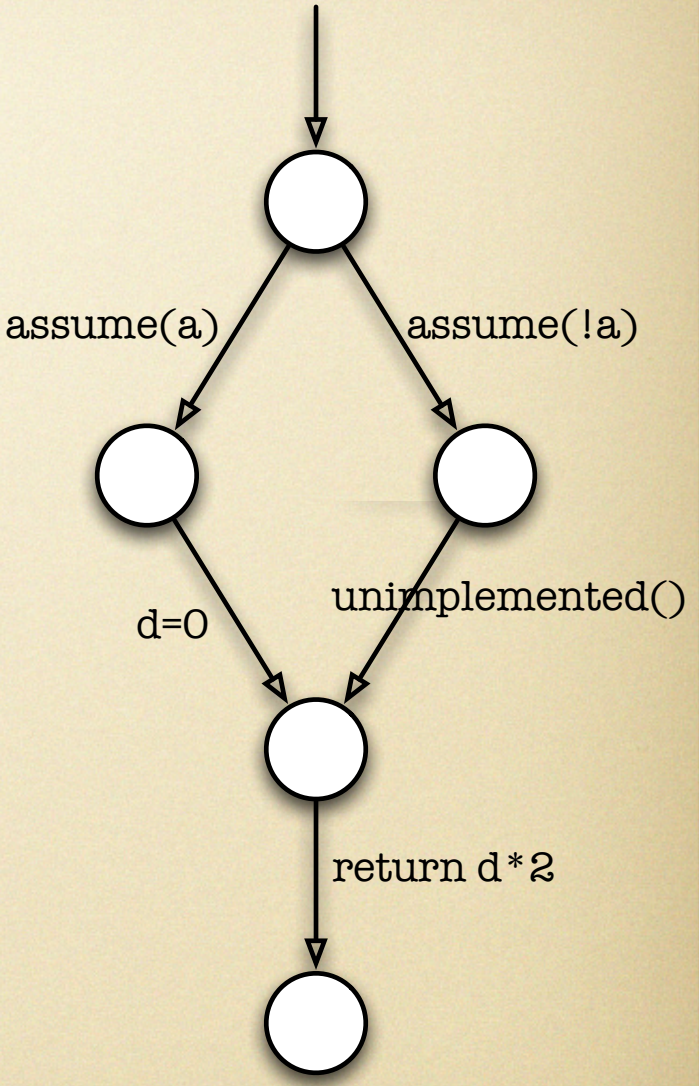

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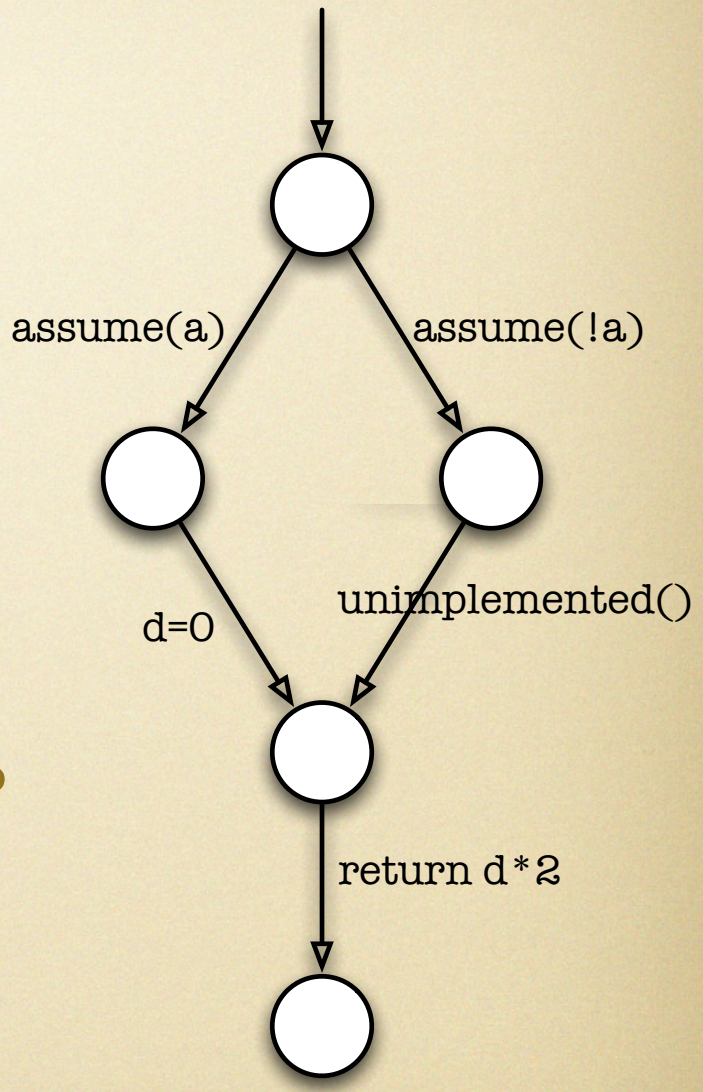

- Earlier: *"For this example* ***`@basicblockentry`*** *is tantamount to* ***`@4+@6+@7`***`"`
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Coverage Patterns

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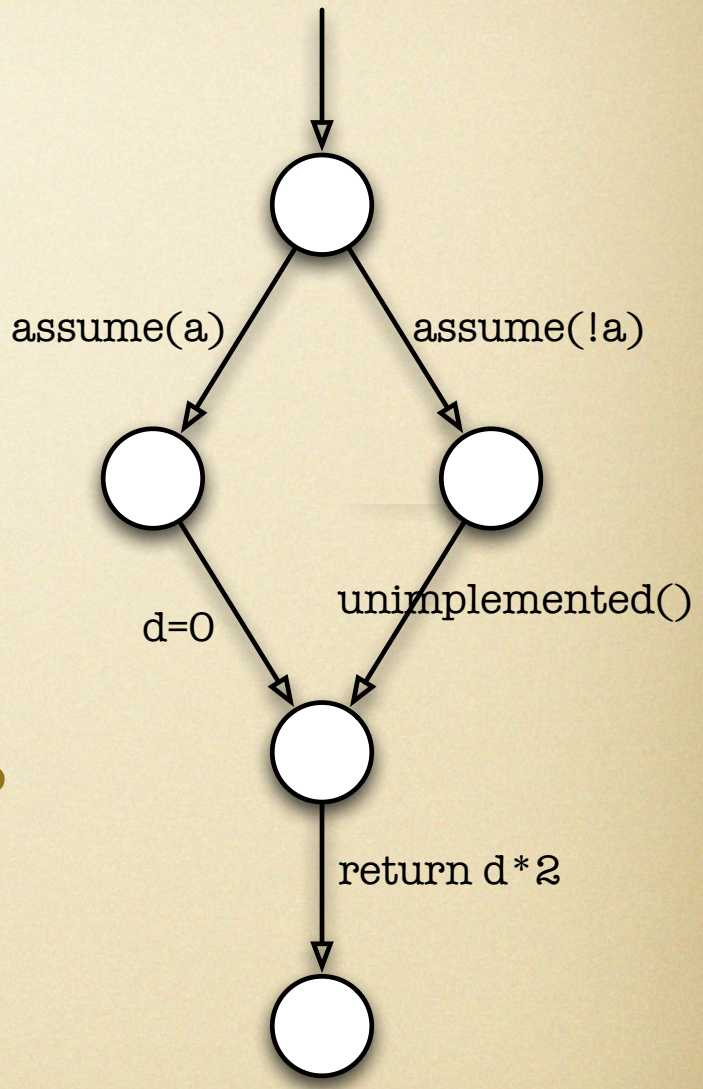

- Earlier: *"For this example* **`@basicblockentry`** *is tantamount to* **`@4+@6+@7`**`"`
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- **`cover "ID*".@basicblockentry."ID*".@basicblockentry."ID*"`**
- **`@basicblockentry`** and **`@4+@6+@7`** describe *the same language of CFA edges*

Edges and Beyond

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
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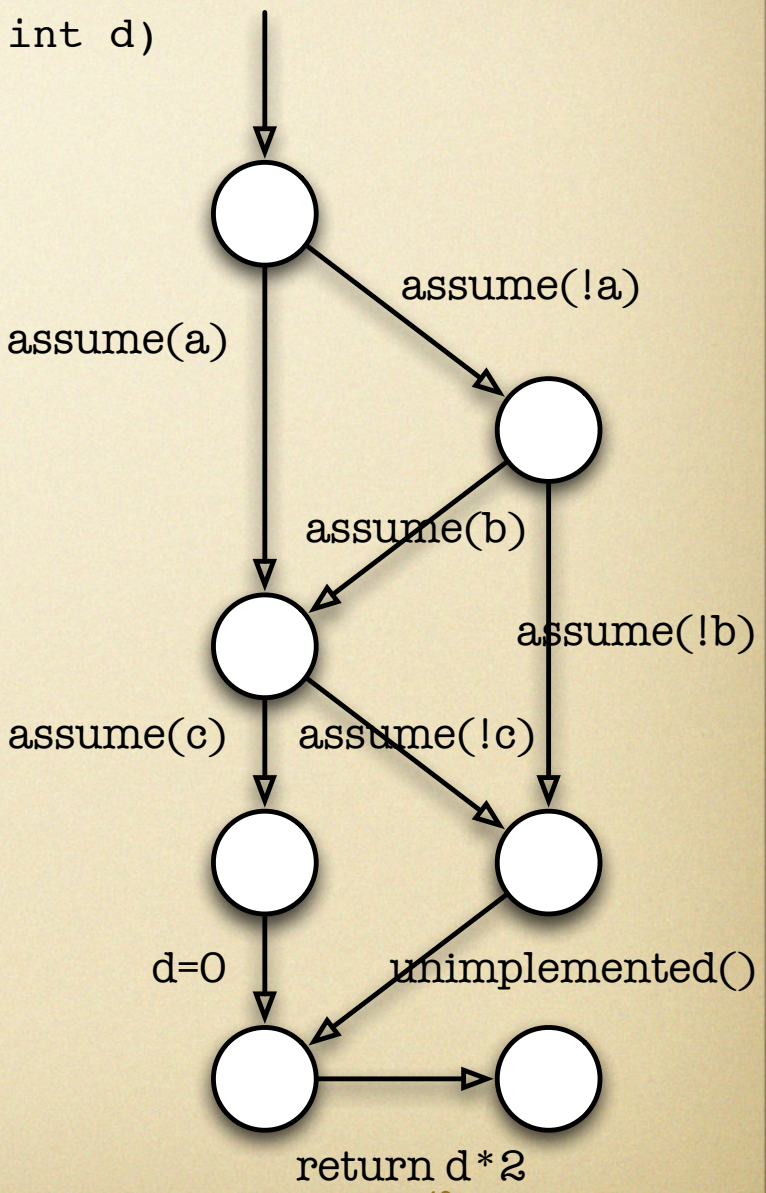
7    return d*2;
8  }
```



Edges and Beyond

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1  int example(int a, int b, int c, int d)
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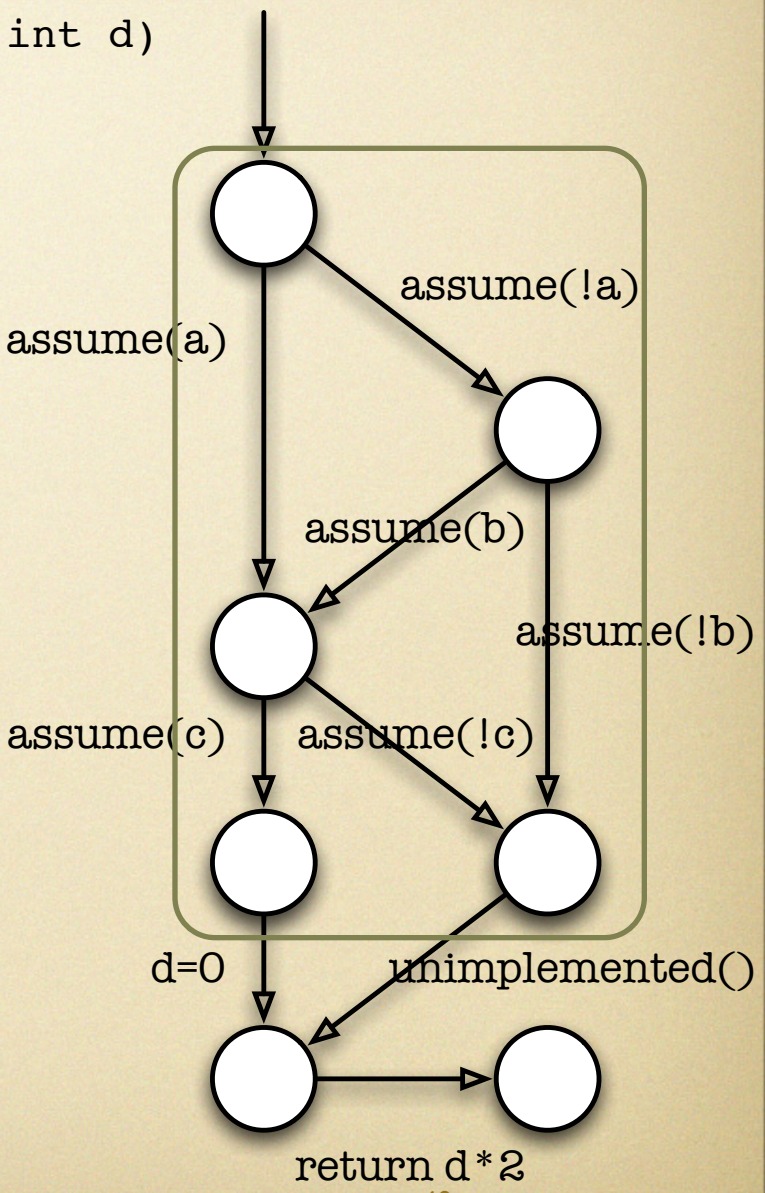
- `cover @conditiongraph`



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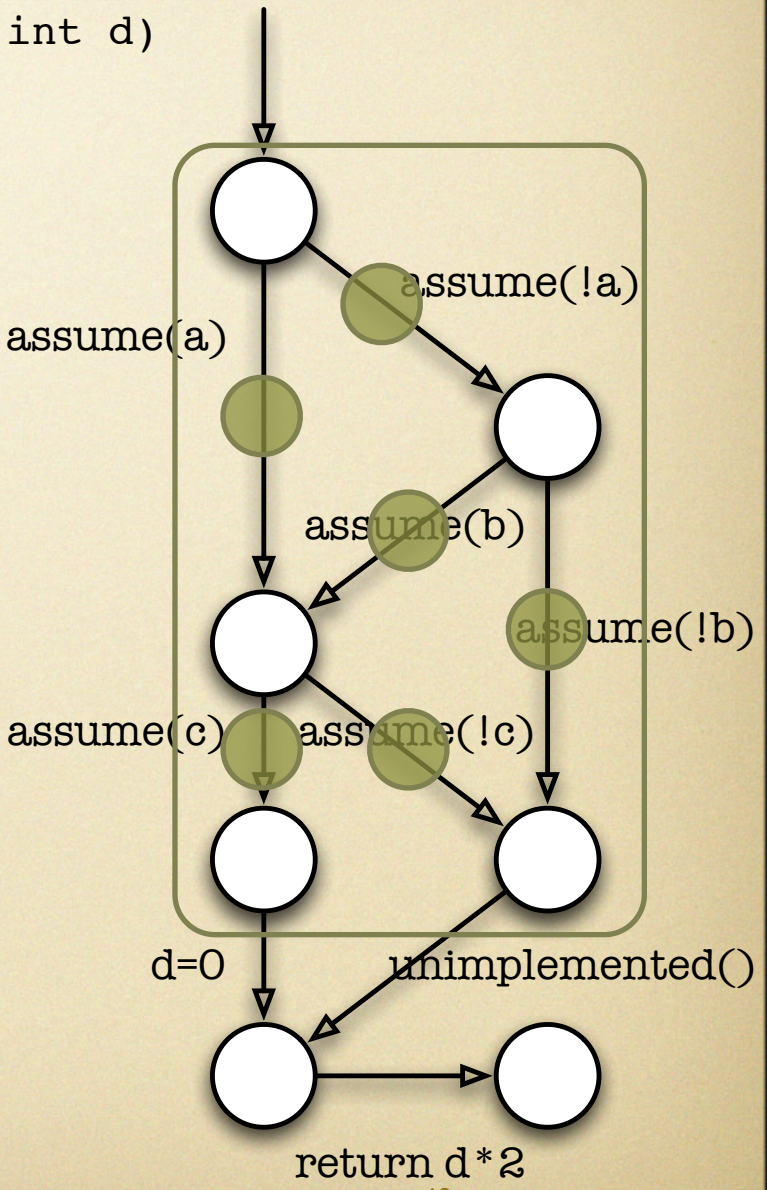
- **cover @conditiongraph**
- **cover EDGES(@conditiongraph)**



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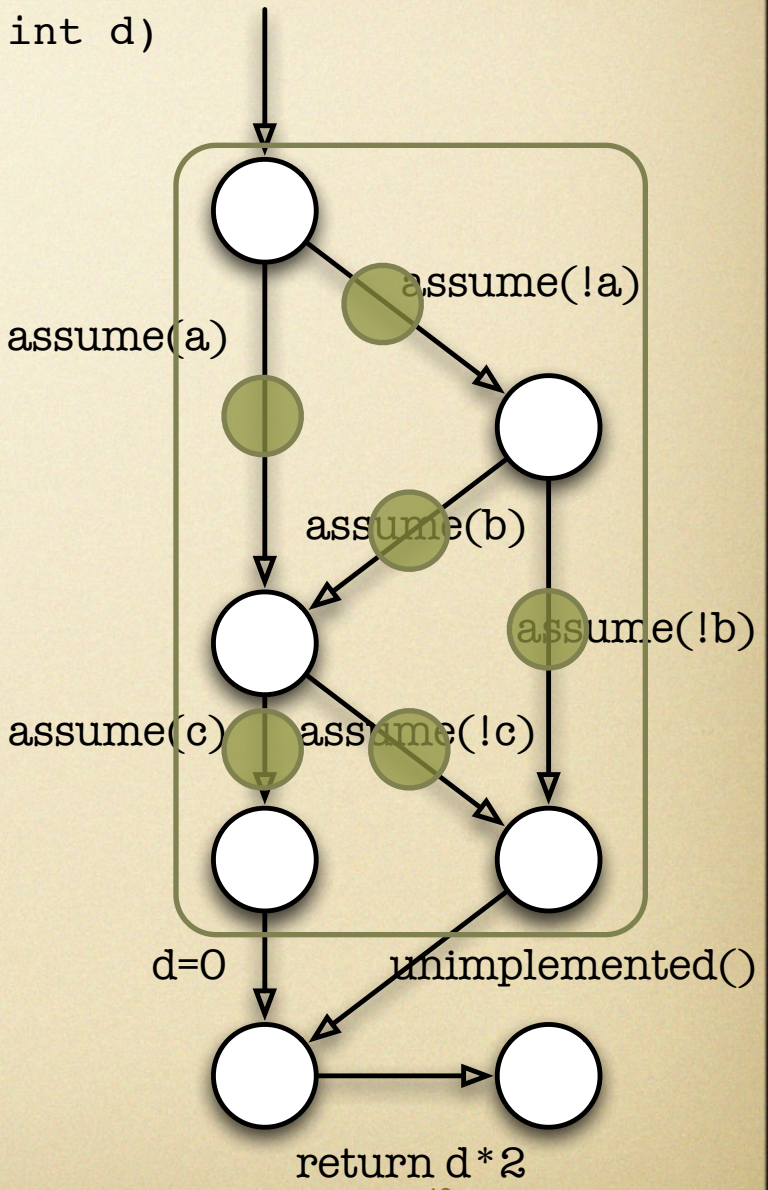
- **cover @conditiongraph**
- **cover EDGES(@conditiongraph)**
- 6 test goals, 3 test cases suffice:



Edges and Beyond

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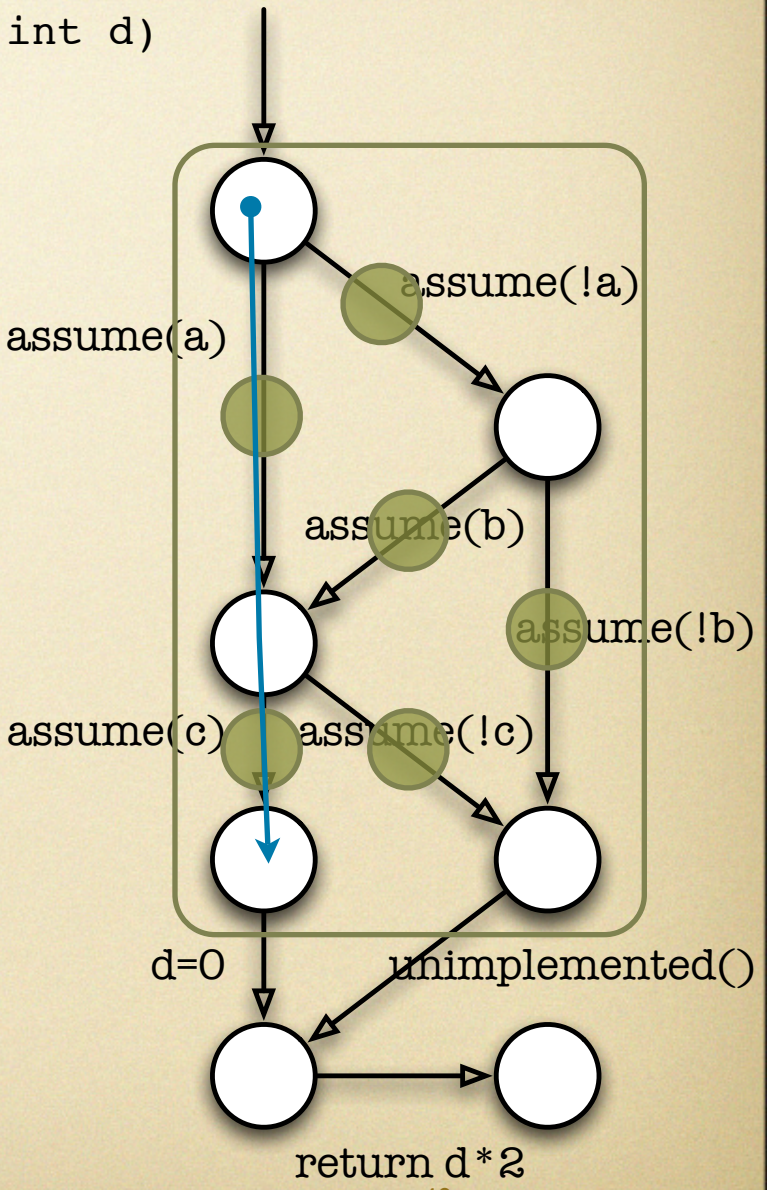
- **cover @conditiongraph**
- **cover EDGES(@conditiongraph)**
- 6 test goals, 3 test cases suffice:
  - a = 1, c = 1



Edges and Beyond

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- **cover @conditiongraph**
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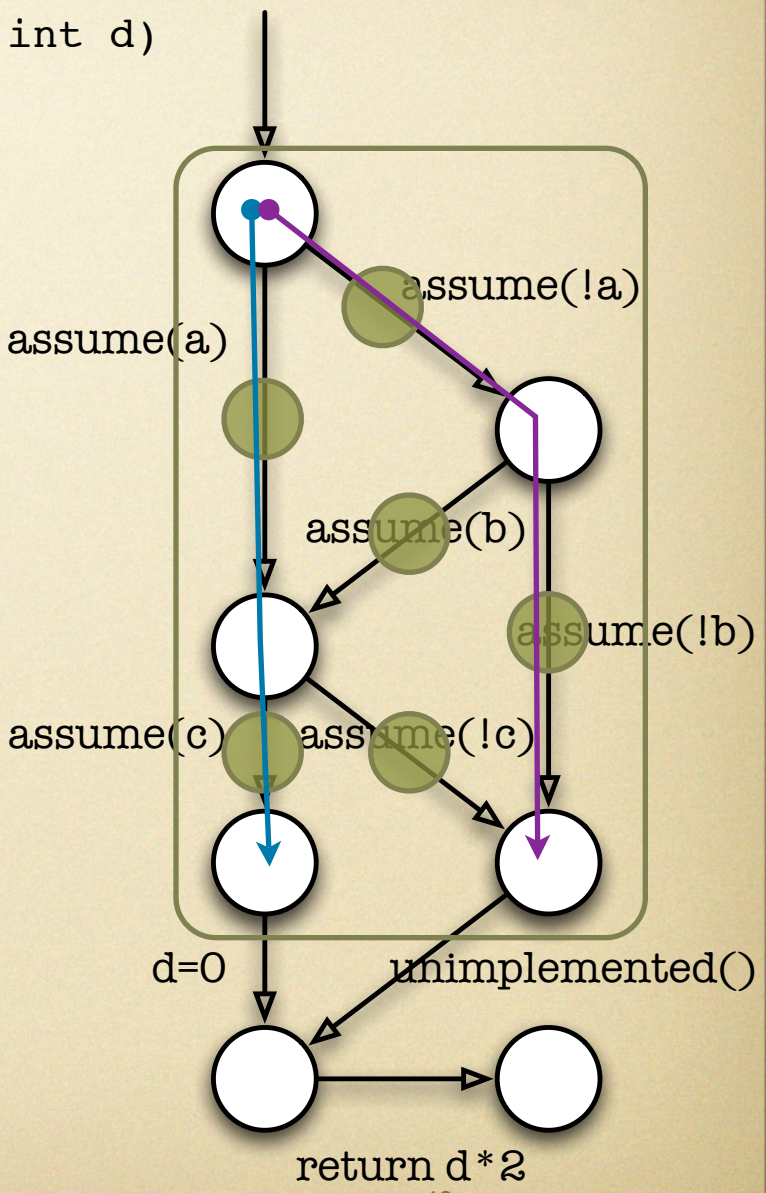
- 6 test goals, 3 test cases suffice:
  - a = 1, c = 1
  - a = 0, b = 0



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- **cover @conditiongraph**
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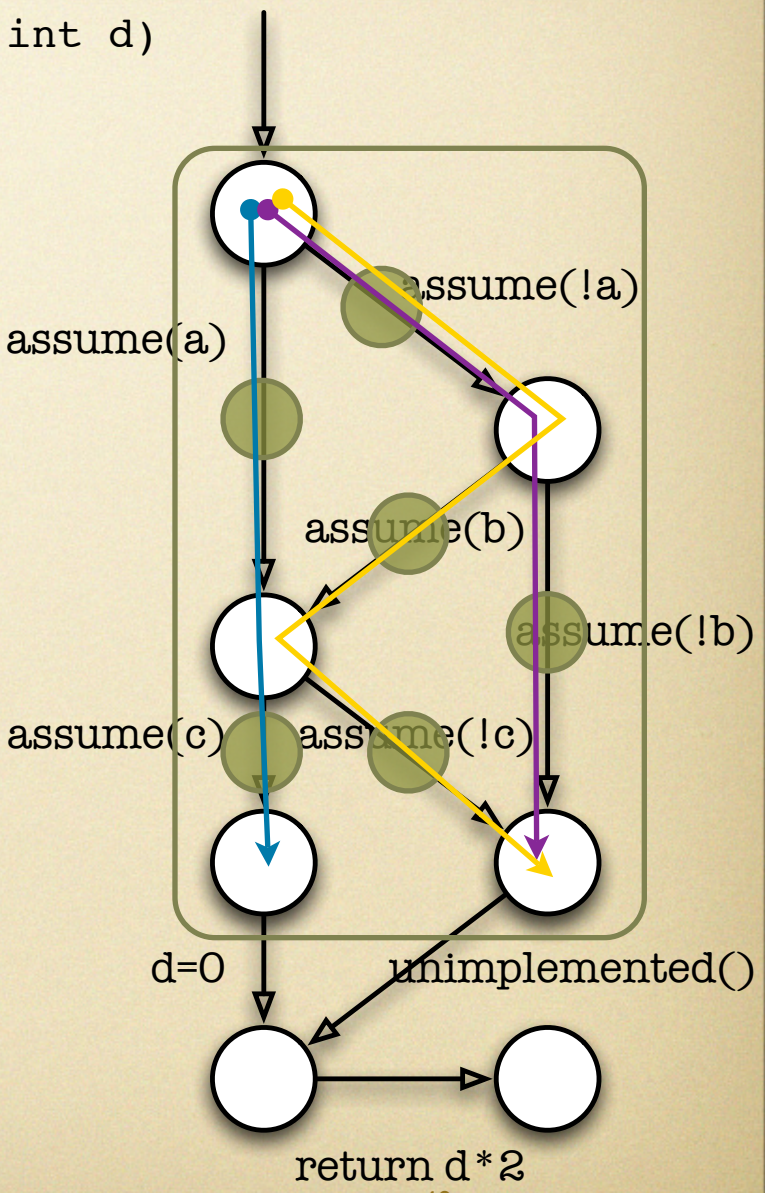
  - a = 1, c = 1
  - a = 0, b = 0
  - a = 0, b = 1, c = 0



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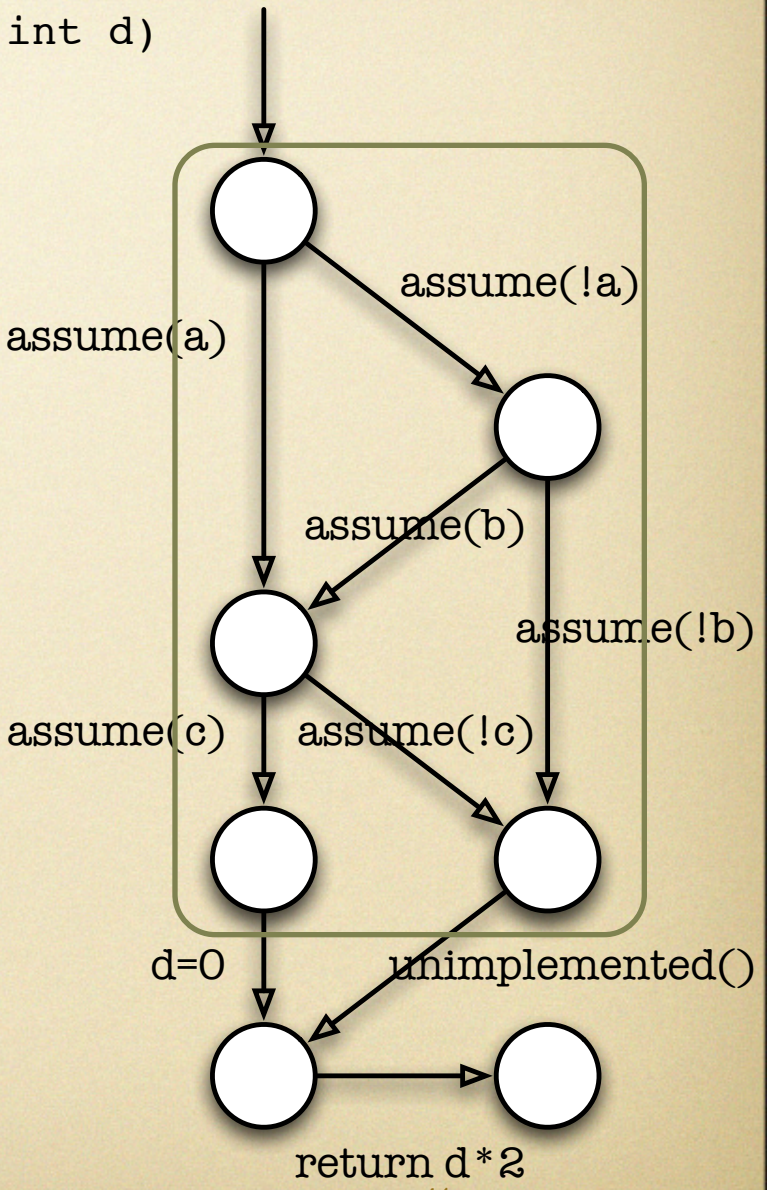

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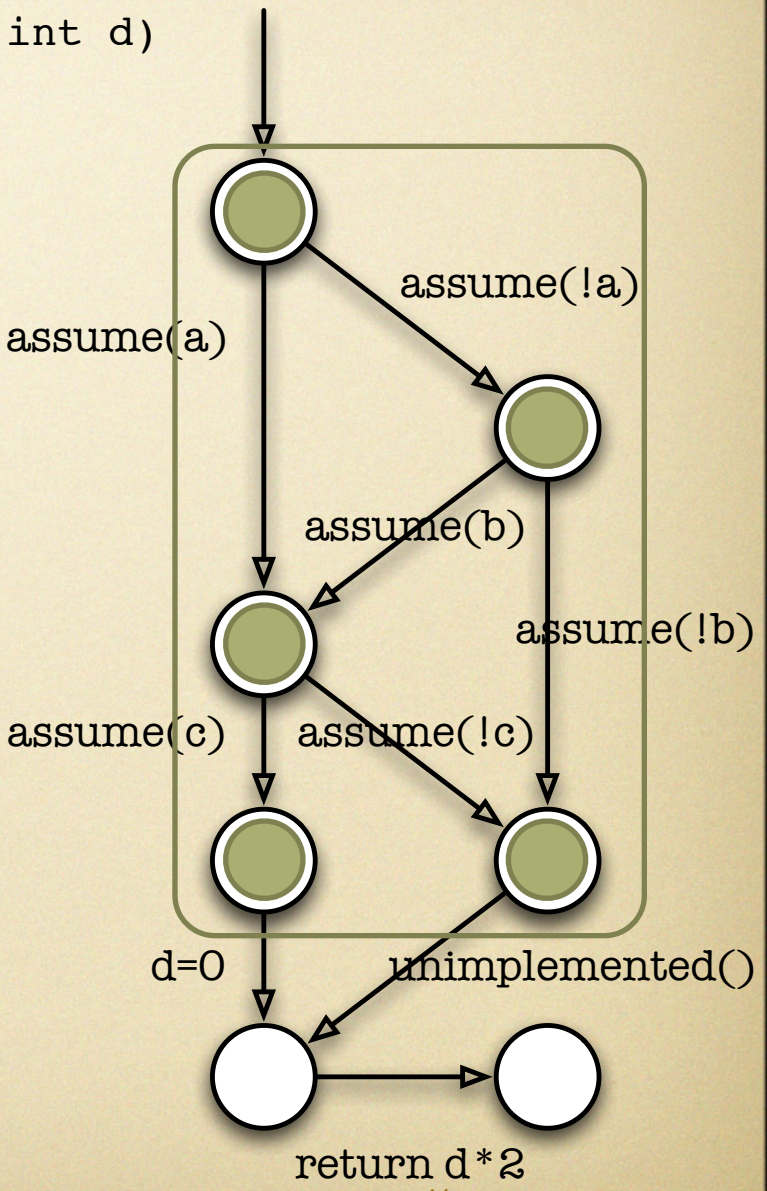
- `cover NODES(@conditiongraph)`



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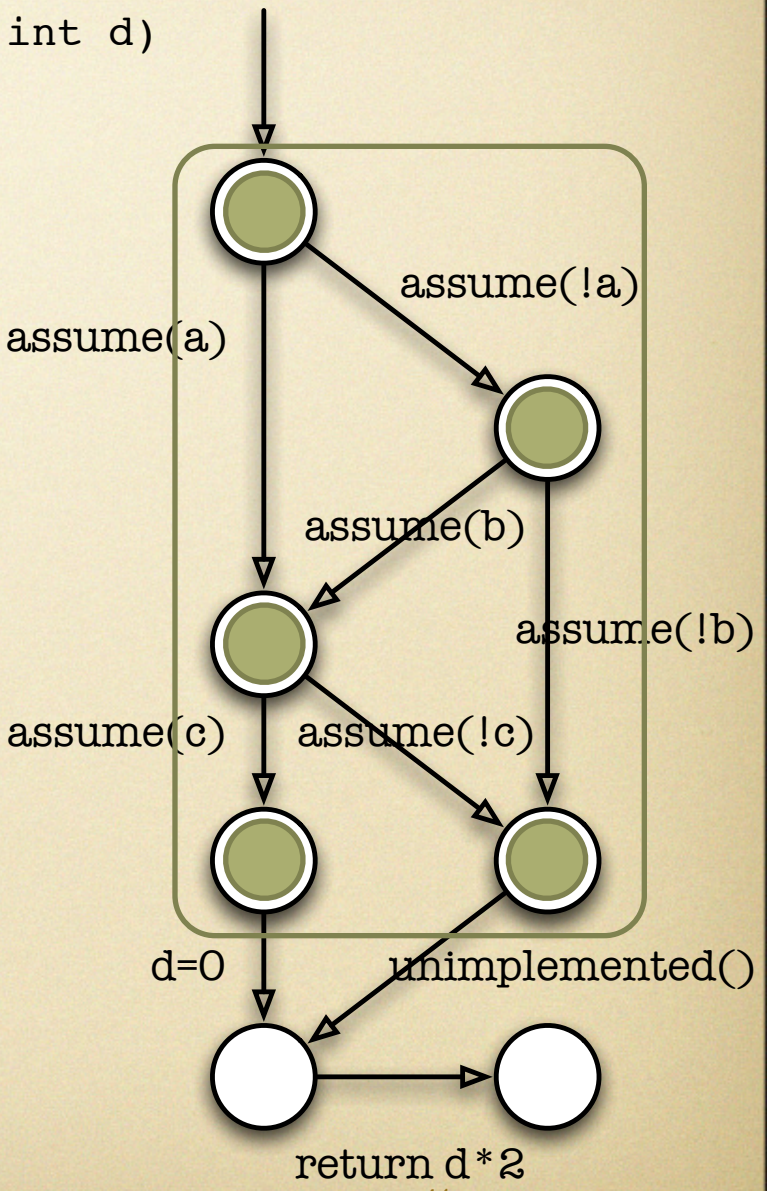
- 5 test goals, 2 test cases suffice:



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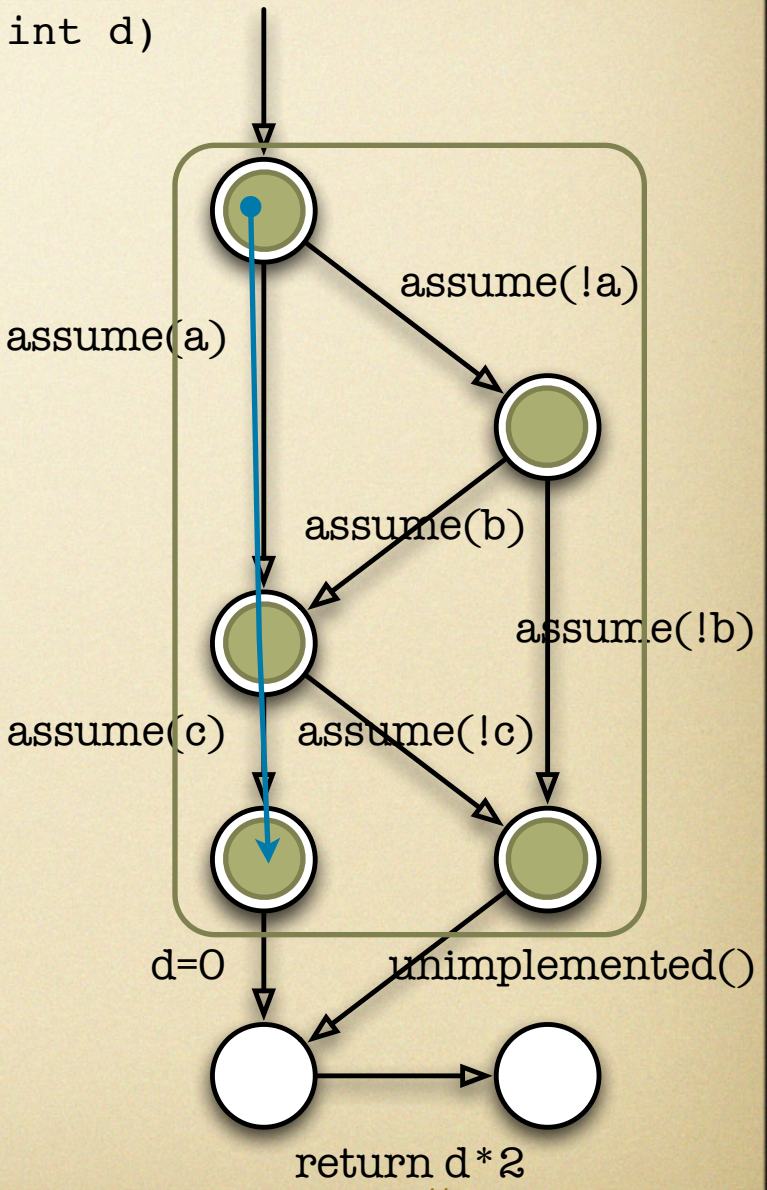

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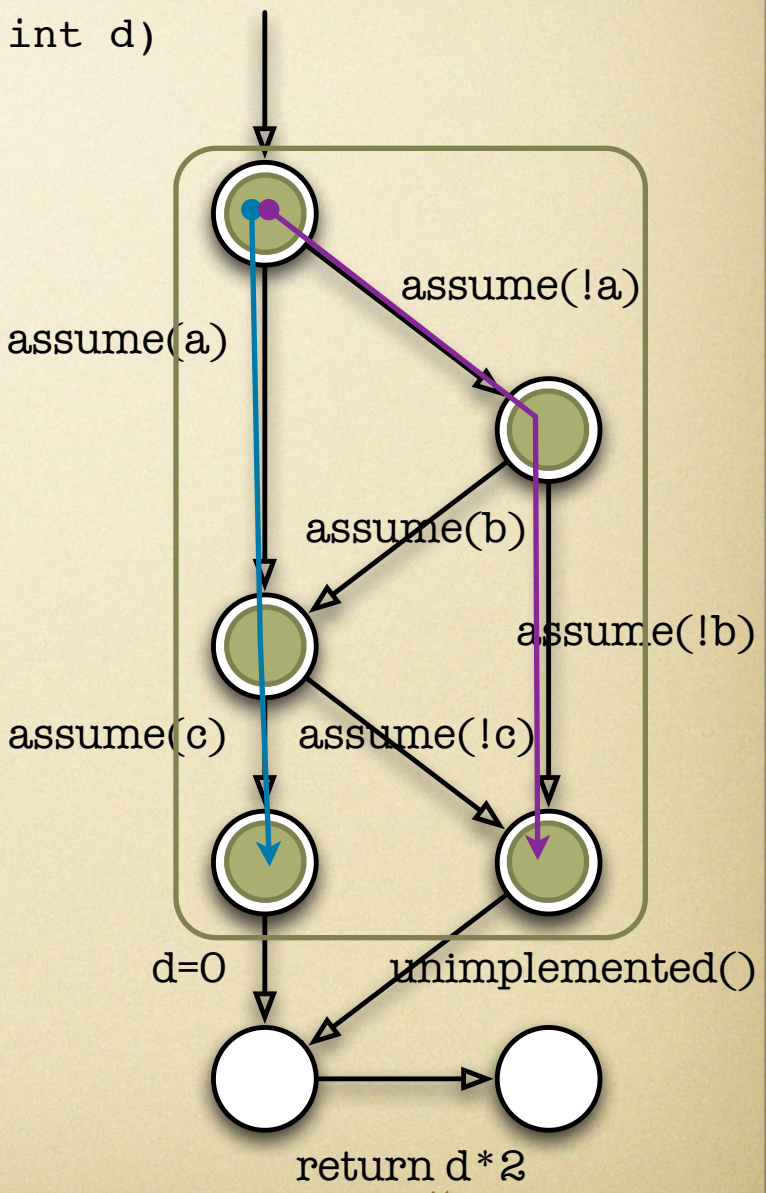

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  - a = 0, b = 0

Edges and Beyond

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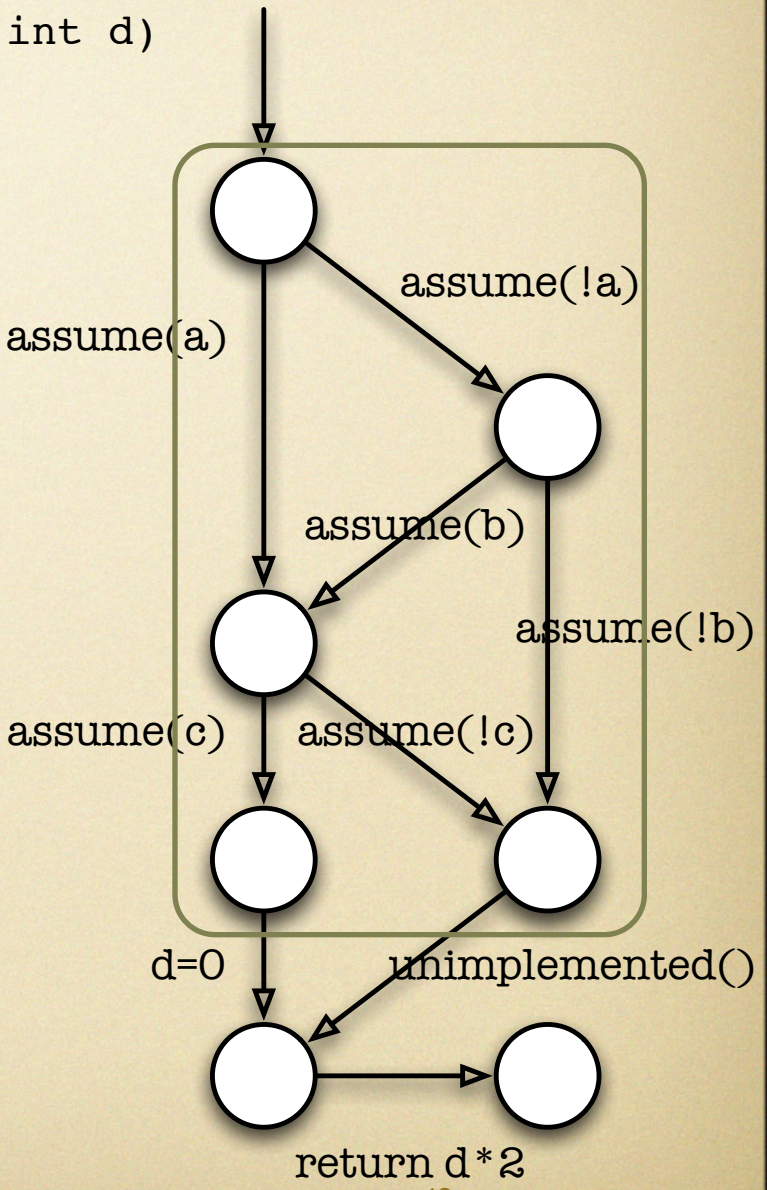

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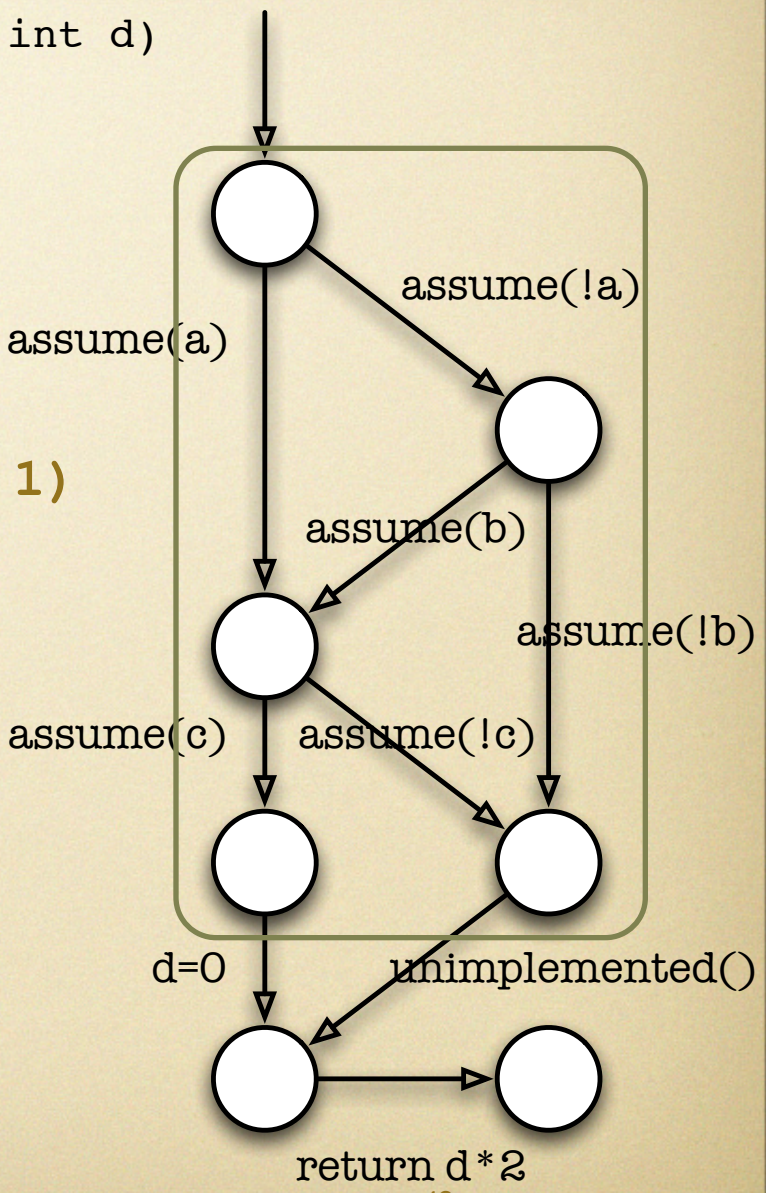
```

- **`cover PATHS(@conditiongraph, 1)`**
- Includes repetition bound (finiteness)



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- **`cover PATHS(@conditiongraph, 1)`**
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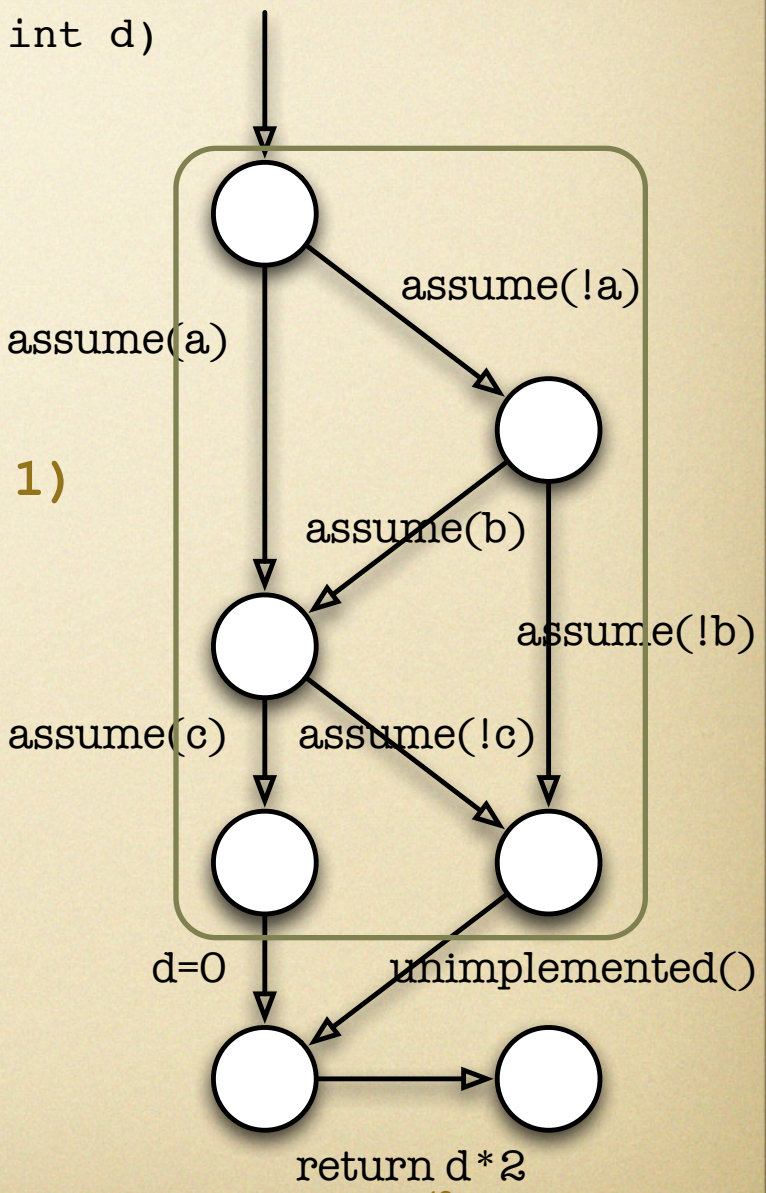
- 5 test goals, 5 test cases required:



Edges and Beyond

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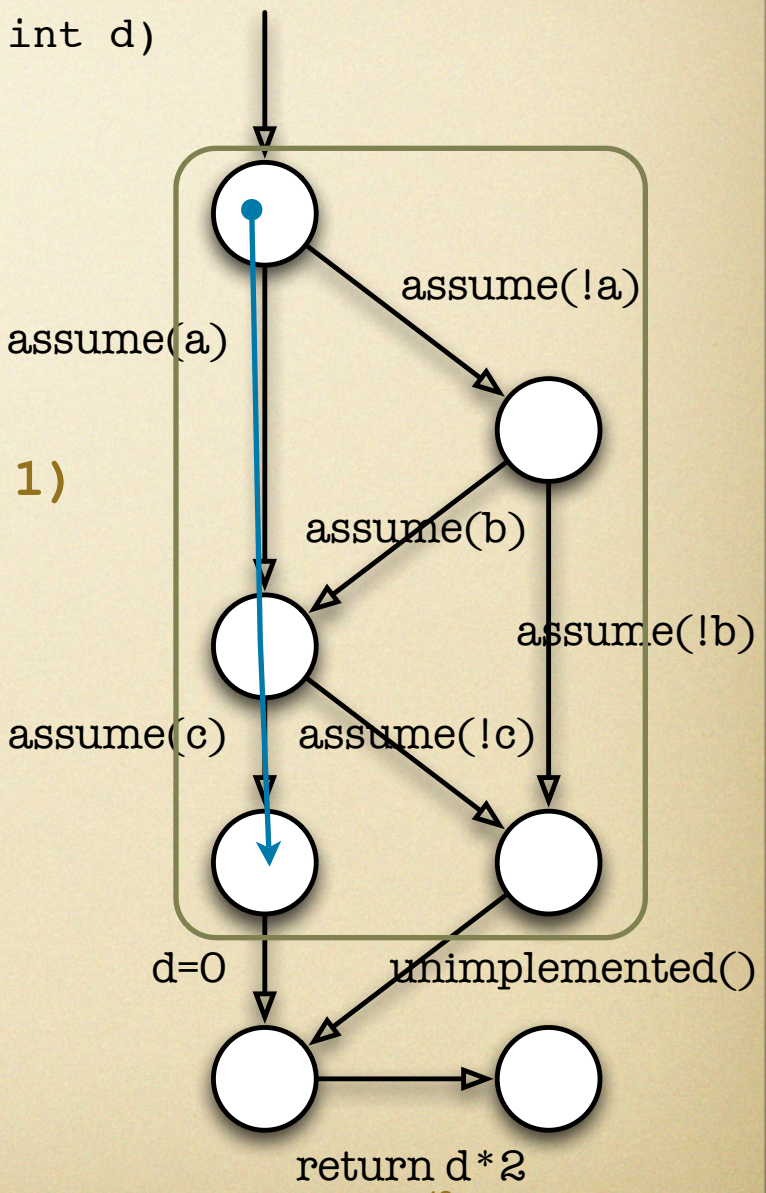

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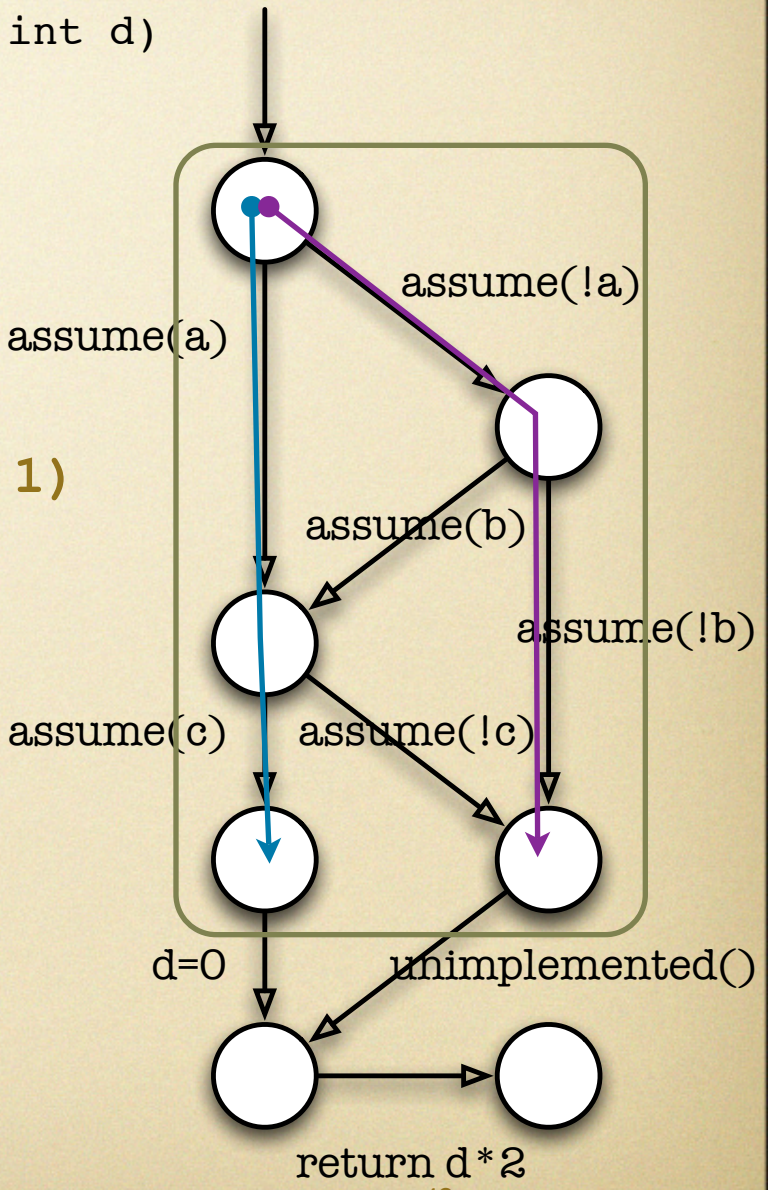
- 5 test goals, 5 test cases required:
  - a = 1, c = 1
  - a = 0, b = 0



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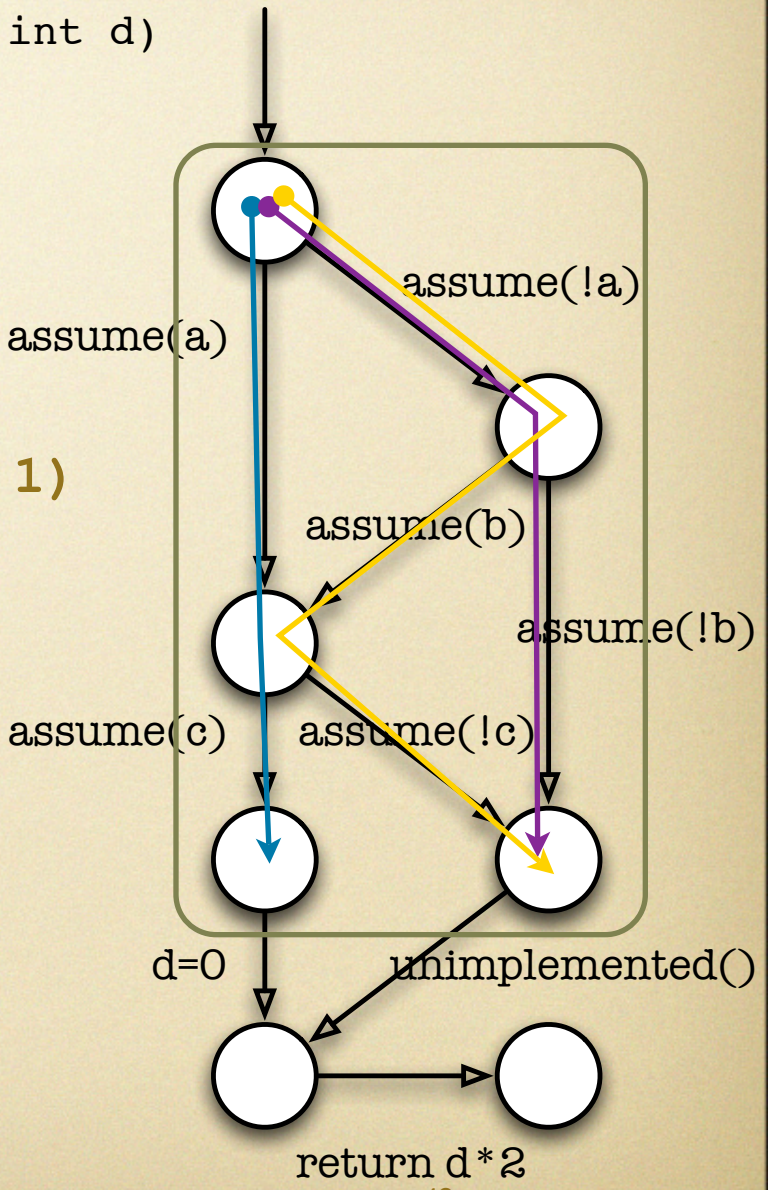
- Includes repetition bound (finiteness)
- 5 test goals, 5 test cases required:
  - a = 1, c = 1
  - a = 0, b = 0
  - a = 0, b = 1, c = 0



Edges and Beyond

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

- `cover PATHS(@conditiongraph, 1)`
- Includes repetition bound (finiteness)
- 5 test goals, 5 test cases required:
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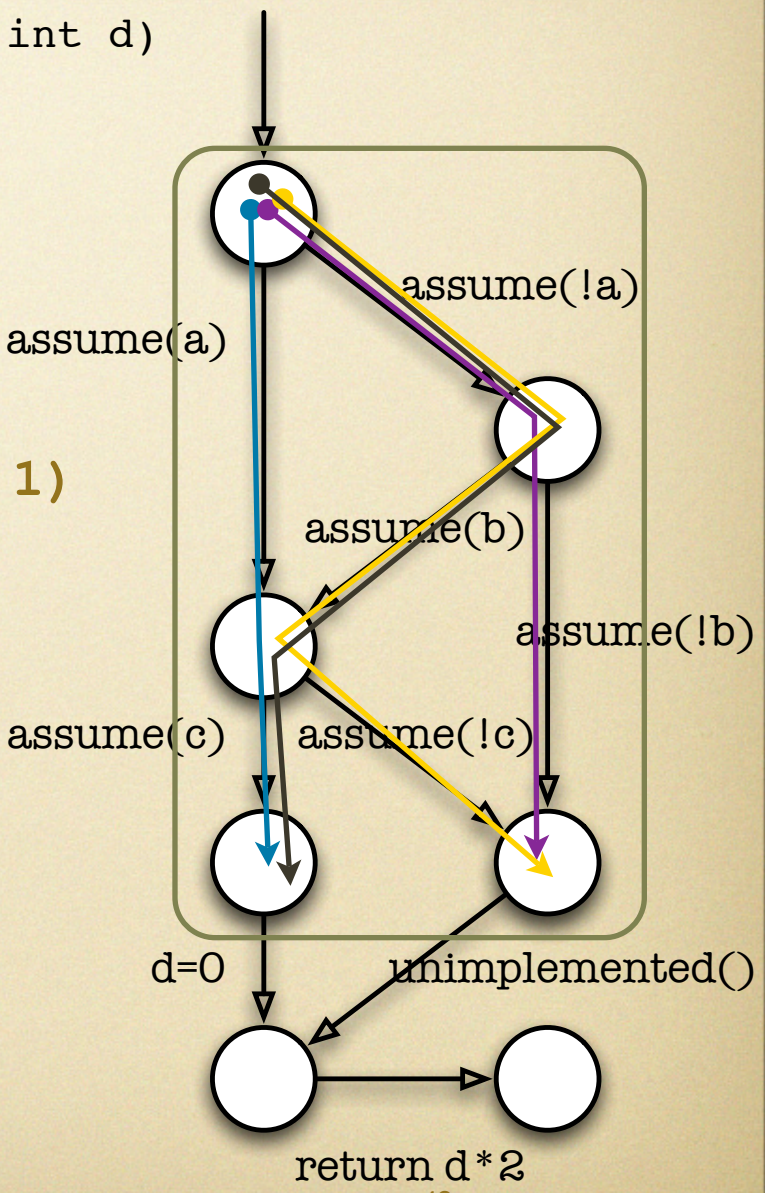
  - a = 0, b = 0
  - a = 0, b = 1, c = 0
  - a = 0, b = 1, c = 1



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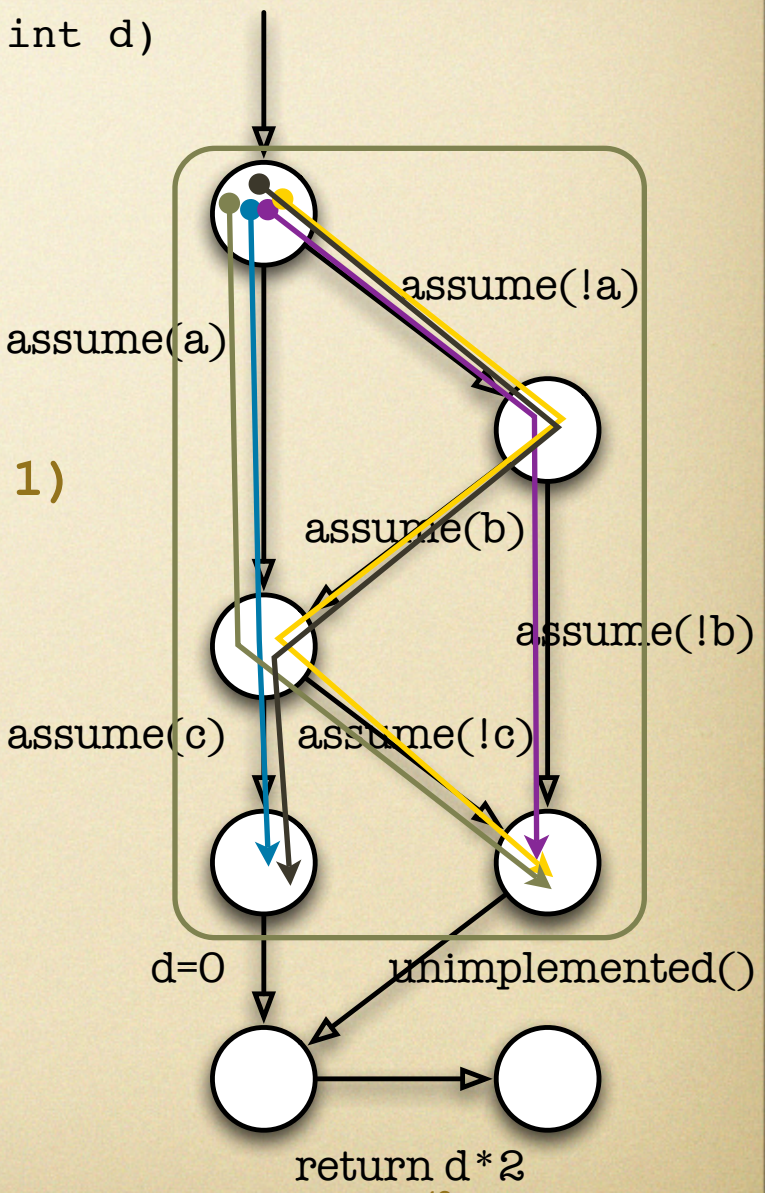

FQL Queries

FQL Queries

in *scope* **cover** *goals* **passing** *constraints*

FQL Queries

```
in scope cover goals passing constraints
```

- *scope:* CFA transformer/filter function

FQL Queries

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in scope cover goals passing constraints
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- *scope:* CFA transformer/filter function
- *goals:* coverage pattern

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"For each test goal inside scope, provide a test case which satisfies the passing constraints."

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in scope cover goals passing constraints
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Condition coverage in function *partition* with test cases that reach *line 7* at least once.

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```
in scope cover goals passing constraints
```

- *scope:* CFA transformer/filter function
- *goals:* coverage pattern
- *constraints:* path pattern

"For each test goal inside scope, provide a test case which satisfies the passing constraints."

```
in @func(partition) cover @conditionedge passing @7
```

Condition coverage in function *partition* with test cases that reach *line 7* at least once.

Standard Coverage Criteria

```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

```
cover @basicblockentry
```

Basic Block Coverage

Requires a test suite such that each basic block is executed at least once

Standard Coverage Criteria

```
 1 int partition(int a[], int left, int right) {
 2   int v = a[right], i = left - 1, j = right, t;
 3   for (;;) {
 4     while (a[++i] < v) ;
 5     while (j > left && a[--j] > v) ;
 6     if (i >= j) break;
 7     t = a[i]; a[i] = a[j]; a[j] = t;
 8   }
 9   t = a[i]; a[i] = a[right]; a[right] = t;
10   return i;
11 }
```

```
cover @basicblockentry
```

Basic Block Coverage

Requires a test suite such that each basic block is executed at least once

Standard Coverage Criteria

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

```
cover @decisionedge
```

Decision Coverage

Conditional statements evaluate to true/false

Standard Coverage Criteria

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

```
cover @conditionedge
```

Condition Coverage

Atomic conditions evaluate to true/false

Standard Coverage Criteria

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

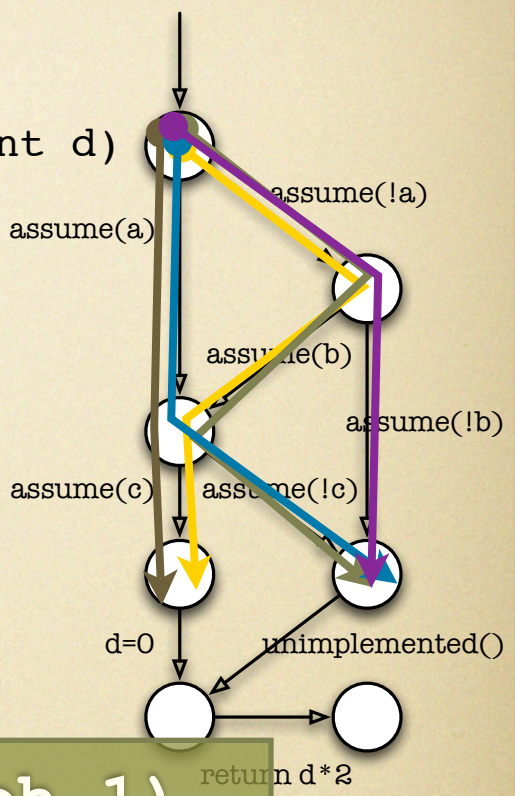
```
cover @conditionedge+@decisionedge
```

Condition/Decision Coverage

Union of condition and decision coverage

Standard Coverage Criteria

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```




```
cover paths(@conditiongraph,1)
```

Multiple Condition Coverage

All Boolean combinations of atomic conditions in complex conditions

Standard Coverage Criteria

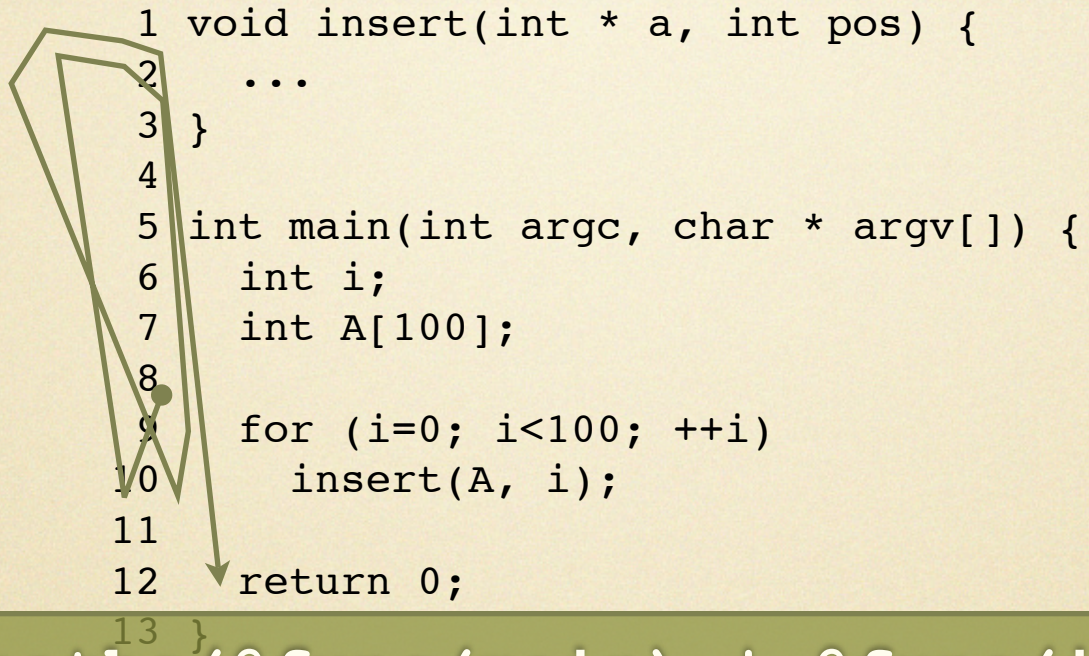
```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

```
cover @def(d).”not(@def(d))*”.@use(d)
```

Def-Use Coverage

Cover all definition/use pairs of a variable *d*

Beyond Standard Criteria



```
1  void insert(int * a, int pos) {
2    ...
3  }
4
5  int main(int argc, char * argv[]) {
6    int i;
7    int A[100];
8
9    for (i=0; i<100; ++i)
10     insert(A, i);
11
12   return 0;
13 }
```

```
cover paths(@func(main) | @func(insert),2)
```

Loop-Bounded Path Coverage

- All paths through *main* and *insert*
- Pass each statement two times

Beyond Standard Criteria

```
 1 int partition(int a[], int left, int right) {
 2   int v = a[right], i = left - 1, j = right, t;
 3   for (;;) {
 4     while (a[++i] < v) ;
 5     while (j > left && a[--j] > v) ;
 6     if (i >= j) break;
 7     t = a[i]; a[i] = a[j]; a[j] = t;
 8   }
 9   t = a[i]; a[i] = a[right]; a[right] = t;
10   return i;
11 }
```

```
cover @basicblockentry->@basicblockentry+
@basicblockentry->@basicblockentry->
@basicblockentry
```

Cartesian Block Coverage

All pairs and triples of basic blocks in function *partition*

Specs for Working Programmers

```
1  int example(int a, int b, int c, int d)
2  {
3    if ((a || b) && c)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

```
cover @4+@6
```

Cover Specific Lines of Code

Lines 4 and 6

Specs for Working Programmers

```
 1 void eval(int * a, int first, int last) {
 2   if (first > last) return;
 3   printf("a[%d]=%d\n", first, a[first]);
 4   eval(a+1, first+1, last);
 5   return;
 6 }
 7
 8 int main(int argc, char * argv[]) {
 9   int i;
10   int A[100];
11
12   for (i=0; i<100; ++i)
13     insert(A, i);
14
15   eval(A, 0, 100);
16   return 0;
17 }
```

```
cover @basicblockentry & @func(eval)
```

Restricted Scope of Analysis

Basic block coverage in function *eval* only

Specs for Working Programmers

```
 1 void sort(int * a, int len) {
 2   int i, t;
 3   for (i=1; i<len; ++i) {
 4     if (compare(a[i-1], a[i])) continue;
 5     t=a[i]; a[i]=a[i-1]; a[i-1]=t;
 6   }
 7 }
 8
 9 void eval(int * a, int len) {
10   int i;
11   for (i=0; i < 3; ++i)
12     printf("a[%d]=%d\n", i, a[i]);
13 }
14
15 int main(int argc, char * argv[]) {
16   int i; int A[100];
17   for (i=0; i < 100; ++i) sort(A, 100);
18   eval(A, 100);
19   return 0;
20 }
```

```
cover (@conditionedge & @func(sort)) ->
  (@basicblockentry & @func(eval))
```

Interaction Coverage

Cover all pairs of conditions in *sort* and basic blocks in *eval*

Specs for Working Programmers

```
 1 void sort(int * a, int len) {
 2   int i, t;
 3   for (i=1; i<len; ++i) {
 4     if (compare(a[i-1], a[i])) continue;
 5     t=a[i];
 6     a[i]=a[i-1];
 7     a[i-1]=t;
 8   }
 9   return;
10 }
```

```
cover {len>=2} . {len<=15} .
@basicblockentry & @func(sort)
```

Constrained Inputs

- Basic block coverage in *sort*
- Each test case shall use list of 2 to 15 elements

Specs for Working Programmers

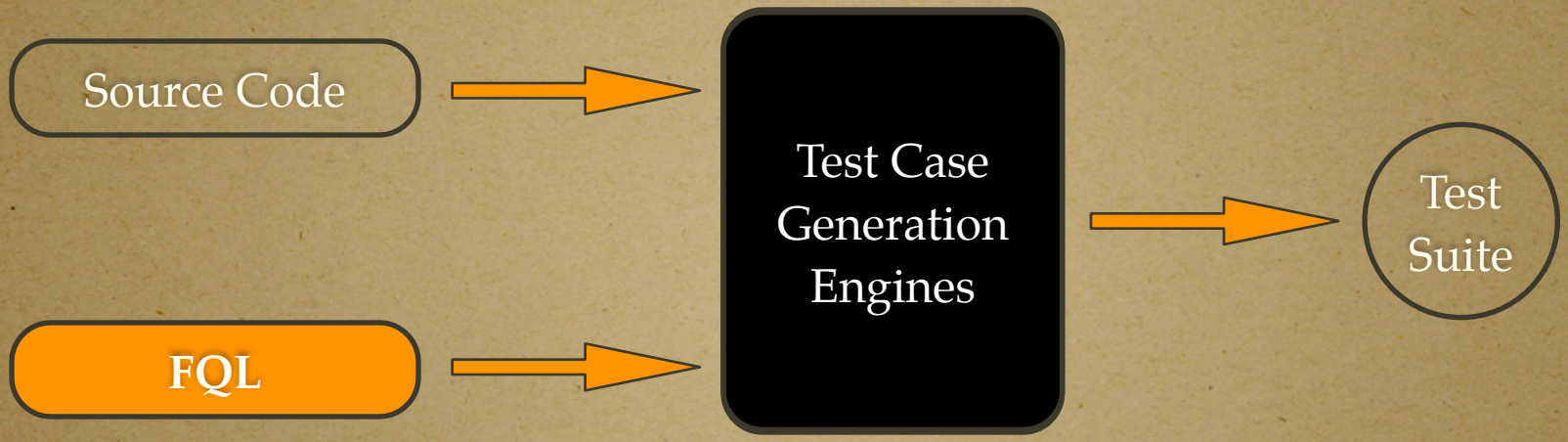
```
1  int example(int a, int d)
2  {
3    if (a)
4      d = 0;
5    else
6      unimplemented();
7    return d*2;
8  }
```

```
cover @basicblockentry & @func(example)
  passing ^not(@call(unimplemented))*$
```

Avoid Unfinished Code

- Basic block coverage in *example*
- Never call *unimplemented*

Conclusions and Current Work



- Specification language based on quoted regular expressions to precisely specify where to go
- Two test input generation engines
- Currently evaluating with partners from automotive and avionics industry
- Extending our work to model-based testing

http://code.forsyte.de/fshell

http://code.forsyte.de/fshell

Experimental Results

Source	SLOC	BB (**Q1**) #goals	#tc	CC (**Q2**) #goals	#tc	BB^2 (**Q18**) #goals	#tc	#inf
coreutils/cat.c	27	16	4	10	4	224	6	39
coreutils/echo.c	161	27	8	20	11	675	93	198
coreutils/nohup.c	33	17	6	12	5	255	13	133
coreutils/seq.c	37	28	7	20	7	728	23	394
coreutils/tee.c	73	21	9	16	8	399	30	127
kbfiltr.c	3507	250	2	196	2	62000	2	61911
pseudo-vfs.c	553	10	3	6	3	80	3	44
matlab.c	3444	30	6	22	6	840	10	441
memman.c	245	53	8	40	8	2756	29	1749
PicoSAT	6592	191	43	153	39	36099	417	26352