Program Representations
Program Representation

- Before we can reason about programs, we must have a vocabulary and a *model* to analyze
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- Difficult models:
  - Compiled binaries

  1001101
  0101011
  1101011
  0001110
  frob.exe
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    - Often used in reverse engineering or security tasks
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Why might binaries be good for security tasks?
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  – *Source code*
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  – \textbf{Source code}
    • Very language specific
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- **Difficult models:**
  - Compiled binaries
  - **Source code**
    - Very language specific
    - Relationships can be hard to extract

- Foo.c
- Bar.c
- Baz.c
Program Representation

- Before we can reason about programs, we must have a vocabulary and a model to analyze.

- Difficult models:
  - Compiled binaries
  - Source code
    - Very language specific
    - Relationships can be hard to extract
    - Often used when relating to comments or specs
Program Representation

- Before we can reason about programs, we must have a vocabulary and a *model* to analyze.

- Difficult models:
  - Compiled binaries
  - Source code

- A *good* representation should make explicit the relationships you want to analyze.
Program Representation

Core graph representations for analysis:
1) Abstract Syntax Trees
2) Control Flow Graphs
3) Program Dependence Graphs
4) Call Graphs
5) Points-to Graphs
1) Abstract Syntax Trees

- Lifts the source into a canonical tree form

```python
for i in range(5, 10):
a[i] = i * 5
```
1) Abstract Syntax Trees

- Lifts the source into a canonical tree form
  - **Internal** nodes are operators, statements, etc.

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for i in range(5,10):
    a[i] = i * 5
```

Diagram:
- `for`
- `range`
- `[]`
- `*`

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**14**
1) Abstract Syntax Trees

- Lifts the source into a canonical tree form
  - **Internal** nodes are operators, statements, etc.
  - **Leaves** are values, variables, operands

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for i in range(5,10):
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1) Abstract Syntax Trees

- Lifts the source into a canonical tree form
- Used for syntax analysis & transformation:

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- Lifts the source into a canonical tree form
- Used for syntax analysis & transformation:
  - Simple bug patterns
  - Style checking
  - Refactoring
  - Training prediction/completion models

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1) Abstract Syntax Trees

- Lifts the source into a canonical tree form
- Used for syntax analysis & transformation:
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But the same program may still be spelled many ways.
2) Control Flow Graphs

- Express the possible decisions and possible paths through a program

```python
cond = input()
if cond:
    a = foo()
else:
    a = bar()
print(a)
```
2) Control Flow Graphs

- Express the possible decisions and possible paths through a program

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cond = input()
if cond:
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```

Diagram:
- `cond = ...`
- `if cond:
  - a = foo()
  - a = bar()
- `print(a)`
2) Control Flow Graphs

- Express the possible decisions and possible paths through a program
  - **Basic Blocks** (Nodes) are straight line code

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  - *Basic Blocks* (Nodes) are straight line code
  - *Edges* show how decisions can lead to different basic blocks

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2) Control Flow Graphs

- Express the possible decisions and possible paths through a program
  - **Basic Blocks** (Nodes) are straight line code
  - **Edges** show how decisions can lead to different basic blocks
  - **Paths** through the graph are potential paths through the program

```python
cond = input()
if cond:
    a = foo()
else:
    a = bar()
print(a)
```
2) Control Flow Graphs (CFGs)

- Language specific features are often abstracted away

```python
sum = 0
i = 1
while i < N:
    i = i + 1
    sum = sum + i
print(sum)
```
2) Control Flow Graphs (CFGs)

- Language specific features are often abstracted away

```python
sum = 0
i = 1
while i < N:
    i = i + 1
    sum = sum + i
print(sum)
```

The 'while' is gone

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Why is the 'if' in a separate block?

```
sum = 0
i = 1
while i < N:
    i = i + 1
    sum = sum + i
print(sum)
```

```
sum = 0
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if i < N:
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print(sum)
```
2) Control Flow Graphs (CFGs)

- Language specific features are often abstracted away

What would the CFG of the equivalent 'for' look like?
3) Program Dependence Graph (PDG)

- A *Program Dependence Graph* captures how instructions can influence each other.
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- Instruction X *depends* on Y if Y *can influence* X
3) Program Dependence Graph (PDG)

- A *Program Dependence Graph* captures how instructions can influence each other.
- Instruction $X$ depends on $Y$ if $Y$ can influence $X$.
  - Nodes are instructions.
  - An edge $Y \rightarrow X$ shows that $Y$ influences $X$. 
3) Program Dependence Graph (PDG)

- A *Program Dependence Graph* captures how instructions can influence each other
- Instruction X depends on Y if Y *can influence* X
- 2 main types of influence:
  - Data dependence
  - Control dependence
Data Dependence

X data depends on Y if

- There exists a path from Y to X in the CFG
Data Dependence

X data depends on Y if
- There exists a path from Y to X in the CFG
- A variable/value definition at Y is used at X
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1)\(a = \ldots\)
2)\(b = \ldots\)
3)\(a = \ldots\)
4)\(c = a\)

\[\ldots = b + a\]
Data Dependence

X data depends on Y if

- There exists a path from Y to X in the CFG
- A variable/value definition at Y is used at X

\[ \begin{align*}
1) & \quad a = \ldots \\
2) & \quad b = \ldots \\
3) & \quad a = \ldots \\
4) & \quad c = a \\
\ldots & \quad = b + a \\
\end{align*} \]
Control Dependence

Preliminary: X dominates Y if
- every path from the entry node to Y passes X
  - strict, normal, & immediate dominance
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1) sum = 0
2) i = 1
3) while i < N:
   4) i = i + 1
   5) sum = sum + i
6) print(sum)

DOM(6) = ?
IDOM(6) = ?
Control Dependence

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1) sum = 0
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DOM(6)={1,2,3,6}  IDOM(6)=3
Control Dependence

Preliminary: X dominates Y if
- every path from the entry node to Y passes X
  - strict, normal, & immediate dominance

What does this mean intuitively?

DOM(6)={1,2,3,6}  IDOM(6)=3
Control Dependence

Preliminary: X \textit{post} dominates Y if
- every path from the Y \textit{to exit} passes X
  - strict, normal, & immediate dominance
Control Dependence

Preliminary: X post dominates Y if
- every path from the Y to exit passes X
  - strict, normal, & immediate dominance

1) sum = 0
2) i = 1
3) while i < N:
4) i = i + 1
5) sum = sum + i
6) print(sum)

PDOM(5) = ?
IPDOM(5) = ?
Control Dependence

Preliminary: X \textit{post} dominates Y if
- every path from the \textit{Y to exit} passes X
  - strict, normal, \& immediate dominance

1) sum = 0
2) i = 1
3) while i < N:
   4) i = i + 1
   5) sum = sum + i
6) print(sum)

PDOM(5) = \{3,5,6\}  IPDOM(5) = 3
Control Dependence

Preliminary: X post dominates Y if
  • every path from the Y to exit passes X
    – strict, normal, & immediate dominance

What does this mean intuitively?

```
1) sum = 0
2) i = 1
3) while i < N:
   4) i = i + 1
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6) print(sum)
```

```
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PDOM(5)={3,5,6}  IPDOM(5)=3
Control Dependence (Finally)

Y is control dependent on X iff
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- Definition 1:

X directly decides whether Y executes
Control Dependence (Finally)

Y is control dependent on X iff

- **Definition 1:**
  - X directly decides whether Y executes

- **Definition 2:**
  - There exists a path from X to Y s.t. Y post dominates every node between X and Y.
  - Y does not strictly post dominate X
Y is control dependent on X iff

- Definition 1:
  X directly decides whether Y executes

- Definition 2:
  - There exists a path from X to Y s.t. Y post dominates every node between X and Y.
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Control Dependence

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Control Dependence

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```
1) sum = 0
2) i = 1
3) while i < N:
    4) i = i + 1
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6) print(sum)
```

What is CD(5)? CD(3)
Control Dependence

- There exists a path from X to Y s.t. Y post dominates every node between X and Y.
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What is CD(7)?

1) sum = 0
2) i = 1
3) while i < N:
   4) i = i + 1
   5) if 0 == i%2:
      6) continue
   7) sum = sum + i
8) print(sum)

1) sum = 0
2) i = 1
3) if i < N
4) i = i + 1
5) if 0 ...
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Control Dependence

- There exists a path from X to Y s.t. Y post dominates every node between X and Y.
- Y does not strictly post dominate X

1) if X or Y:
    2) print(X)
    3) print(Y)

What is CD(2)?
Control Dependence

- There exists a path from X to Y s.t. Y post dominates every node between X and Y.
- Y does not strictly post dominate X

1) if X or Y:
  2) print(X)
  3) print(Y)

What is CD(2)?

1A) if X:
  1B) if Y:
    2) print(X)
    3) print(Y)

2) print(X)

3) print(Y)
3) Program Dependence Graph (PDG)

The PDG is the combination of

- The control dependence graph
- The data dependence graph
3) Program Dependence Graph (PDG)

The **PDG** is the combination of

- The control dependence graph
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Recall: Edges identify *potential influence*
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Recall: Edges identify *potential influence*

- **Debugging:** What may have caused a bug?
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Recall: Edges identify *potential influence*

- **Debugging:** What may have caused a bug?
- **Security:** Can sensitive information leak?
3) Program Dependence Graph (PDG)

The PDG is the combination of

- The control dependence graph
- The data dependence graph

Recall: Edges identify *potential influence*

- **Debugging**: What may have caused a bug?
- **Security**: Can sensitive information leak?
- **Testing**: How can I reach a statement?
- ...


4) Call Graph (Multigraph)

- Captures the **composition** of a program
  - Nodes are functions
  - Edges show possible calls
4) Call Graph (Multigraph)

- Captures the **composition** of a program
  - Nodes are functions
  - Edges show possible calls

```
foo()  
  foo calls bar & baz
  ▲
  ▼
bar()  baz()  
  ▲
  ▼
bam()  quux()
```
4) Call Graph (Multigraph)

- Captures the **composition** of a program
  - Nodes are functions
  - Edges show possible calls

```
foo()  baz()  quux()
```

```
foo calls bar & baz
```

```
bar()  baz()  quux()
```

```
bar calls bam
```

```
bam()  baz()  quux()
```
4) Call Graph (Multigraph)

- Captures the **composition** of a program
  - Nodes are functions
  - Edges show possible calls

What does this capture?
4) Call Graph (Multigraph)

• Captures the **composition** of a program
  - Nodes are functions
  - Edges show possible calls

How should we handle function pointers?
5) Points-to Graphs

Pointers / indirection create two difficult problems:
5) Points-to Graphs

Pointers / indirection create two difficult problems:

- **Aliasing**
  
  - Multiple variables may denote the same memory location
5) Points-to Graphs

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- **Ambiguity**
  - One variable may potentially denote several different targets in memory.
5) Points-to Graphs

Pointers / indirection create two difficult problems:

- **Aliasing**
  - Multiple variables may denote the same memory location

- **Ambiguity**
  - One variable may potentially denote several different targets in memory.

```c
x.lock();
...
y.unlock();
```

```c
x = password;
...
broadcast(y);
```
5) Points-to Graphs

Points-to graphs capture this points-to relation

- The relation \((p,x)\) where \(p\) MAY/MUST point to \(x\)
  - Both MAY and MUST information can be useful
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1) \(r = C()\)
2) \(p.f = r\)
3) \(t = C()\)
4) if ...:
5) \(q = p\)
6) \(r.f = t\)
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2) p.f = r
3) t = C()
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\begin{align*}
1) & \quad r = C() \\
2) & \quad p.f = r \\
3) & \quad t = C() \\
4) & \quad \text{if ...} \\
5) & \quad q = p \\
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\end{align*}
\]
5) Points-to Graphs

Points-to graphs capture this points-to relation

• The relation (p,x) where p MAY/MUST point to x
  – Both MAY and MUST information can be useful

1) r = C()
2) p.f = r
3) t = C()
4) if ...:
5) q = p
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p.f.f MUST ALIAS t
q MAY ALIAS p
Execution Representations

- *Program* representations are *static*
  - All possible program behaviors at once
  - Usually projected onto the CFG
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- **Program** representations are *static*
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- **Execution** representations are *dynamic*
  - Only the behavior of a single real execution
Execution Representations

• **Program** representations are *static*
  – All possible program behaviors at once
  – Usually projected onto the CFG

• **Execution** representations are *dynamic*
  – Only the behavior of a single real execution
  – Multiple instances of an instruction occur multiple times
Control Flow Trace

1) sum = 0
2) i = 1
3) if i < N
   4) i = i + 1
   5) sum = sum + i
   6) print(sum)

1) sum = 0
2) i = 1
3) if i < N
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   5) sum = sum + i
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All Equivalent
1) \text{sum} = 0 \\
2) i = 1 \\
3) \text{if } i < N \\
4) i = i + 1 \\
5) \text{sum} = \text{sum} + i \\
6) \text{print}(\text{sum})
Dynamic Dependence Graph

1) \( \text{sum} = 0 \)
2) \( i = 1 \)
3) if \( i < N \)
4) \( i = i + 1 \)
5) \( \text{sum} = \text{sum} + i \)
6) \( \text{print(sum)} \)
Dynamic Dependence Graph

1) \( \text{sum} = 0 \)
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   - 4) \( i = i + 1 \)
   - 5) \( \text{sum} = \text{sum} + i \)
6) print(\text{sum})
Dynamic Dependence Graph

Notably a bit difficult for a human to wade through.
Dynamic Dependence Graph

1) `sum = 0`
2) `i = 1`
3) `if i < N`
4) `i = i + 1`
5) `sum = sum + i`
6) `print(sum)`

Notably a *bit* difficult for a human to wade through.

If only we could focus on the parts that interest us...
Program Representations

Given these models, we can start to discuss interesting transformations and analyses on real programs.

Such as... slicing