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# CSE 331

# Software Design & Implementation

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Lecture 2 – Reasoning About Straight-Line Code

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# Motivation for Reasoning

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- Need a way to determine, sans computer, whether code is correct
- Most important part of the correctness techniques
  - tools, **inspection**, testing
- You need a way to do this in interviews
  - this is why interviews are done without computers
- This is not easy (see HW0)

# Our Approach

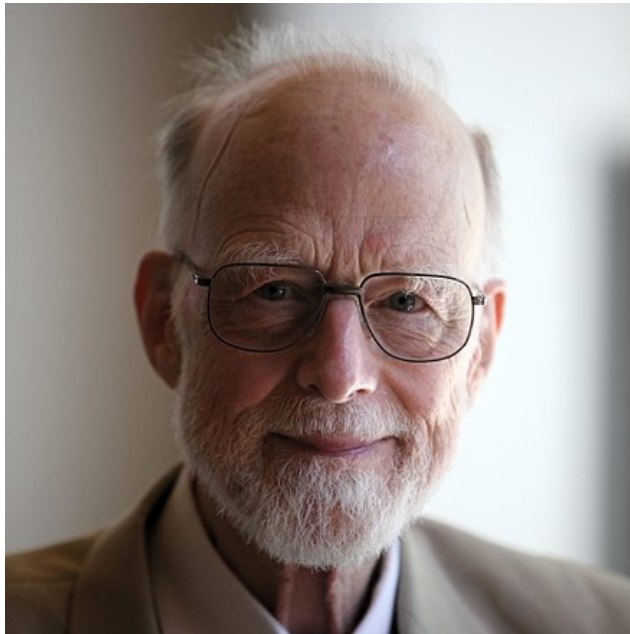
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- We will learn a set of **formal tools** for proving correctness
  - (later, this will also allow us to generate the code)
- Most professionals can do reasoning like this in their head
  - the interviewer is doing so while you write on the whiteboard
  - *eventually*, it will be the same for you
- Learning the formal version is useful
  - a “turn the crank” approach (no intuition required)
  - necessary for hard problems
    - we turn to formal tools when problems get too hard

# Hoare Logic

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- Classic approach to logical reasoning about code
  - named after its inventor, Sir Anthony Hoare



# Terminology of Hoare Logic

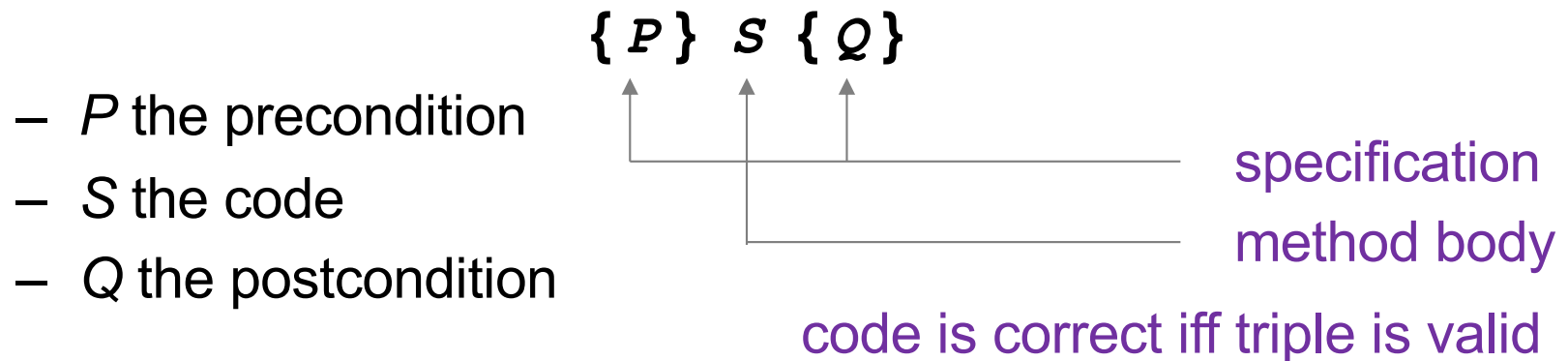
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- The *program state* is the values of all the (relevant) variables
- An *assertion* is a true / false claim (proposition) about the state at a given point during execution (e.g., on line 39)
- An assertion *holds* for a program state if the claim is true when the variables have those values
  
- An assertion before the code is a *precondition*
  - these represent assumptions about when that code is used
- An assertion after the code is a *postcondition*
  - these represent what we want the code to accomplish

# Hoare Logic

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- A **Hoare triple** is two assertions and one piece of code:



- A Hoare triple  $\{ P \} \ S \ \{ Q \}$  is called **valid** if:
  - in any state where  $P$  holds, executing  $S$  produces a state where  $Q$  holds
  - i.e., if  $P$  is true before  $S$ , then  $Q$  must be true after it
  - otherwise the triple is called **invalid**

# Notation

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- Hoare logic writes assertions in  $\{..\}$ 
  - since Java code also has  $\{..\}$ , I will use  $\{\{...\}\}$
  - e.g.,  $\{\{ w \geq 1 \}\} \mathbf{x} = 2 * \mathbf{w}; \{\{ x \geq 2 \}\}$
- Assertions are math / logic not Java
  - you can use the usual math notation
    - (e.g.,  $=$  instead of  $==$  for equals)
  - purpose is communication with other humans (not computers)
  - we will need **and**, **or**, **not** as well
    - can also write use  $\wedge$  (and)  $\vee$  (or) etc.
- The Java language also has assertions (**assert** statements)
  - throws an exception if the condition does not evaluate true
  - we will discuss these more later in the course

# Example 1

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Is the following Hoare triple valid or invalid?

- assume all variables are integers and there is no overflow

$\{\{ x \neq 0 \}\} y = x * x; \{\{ y > 0 \}\}$



# Example 1

---

Is the following Hoare triple valid or invalid?

- assume all variables are integers and there is no overflow

$\{\{ \mathbf{x} \neq 0 \}\} \mathbf{y} = \mathbf{x} * \mathbf{x}; \{\{ \mathbf{y} > 0 \}\}$

Valid

- $\mathbf{y}$  could only be zero if  $\mathbf{x}$  were zero (which it isn't)

# Example 2

---

Is the following Hoare triple valid or invalid?

- assume all variables are integers and there is no overflow

$\{\{ z \neq 1 \}\} y = z * z; \{\{ y \neq z \}\}$

# Example 2

---

Is the following Hoare triple valid or invalid?

- assume all variables are integers and there is no overflow

$$\{\{ z \neq 1 \}\} y = z * z; \{\{ y \neq z \}\}$$

Invalid

- counterexample:  $z = 0$

# Checking Validity

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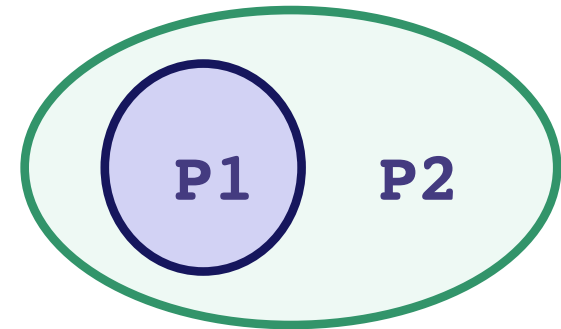
- So far: decided if a Hoare triple is valid by ... **hard** thinking
- Soon: “turn the crank” methods for reasoning about
  - assignment statements
  - conditionals
  - [next lecture] loops
  - (all code can be understood in terms of those 3 elements)
- Can use those to check correctness in a “turn the crank” manner
- Next: a way to compare different assertions
  - useful, e.g., to compare possible preconditions

# Weaker vs. Stronger Assertions

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If P1 implies P2 (written  $P1 \Rightarrow P2$ ), then:

- P1 is **stronger** than P2
- P2 is **weaker** than P1



Whenever P1 holds, P2 also holds

- So it is more (or at least as) “difficult” to satisfy P1
  - the program states where P1 holds are a subset of the program states where P2 holds
- So P1 puts more constraints on program states
- So it is a stronger set of requirements on the program state
  - P1 gives you more information about the state than P2

# Examples

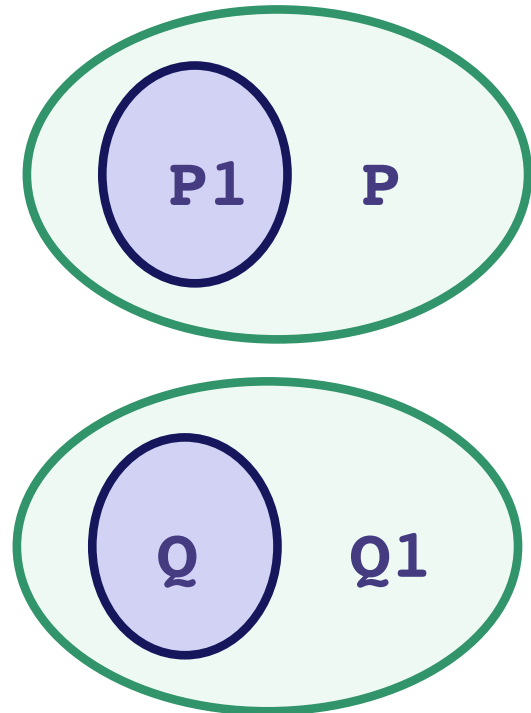
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- $x = 17$  is stronger than  $x > 0$
- $x$  is prime is neither stronger nor weaker than  $x$  is odd
- $x$  is prime and  $x > 2$  is stronger than  $x$  is odd

# Hoare Logic Facts

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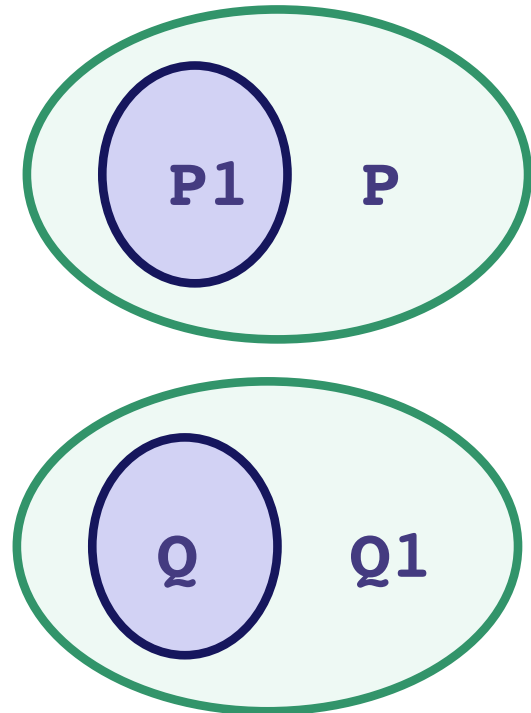
- Suppose  $\{P\} S \{Q\}$  is valid.
- If  $P1$  is stronger than  $P$ , then  $\{P1\} S \{Q\}$  is valid.
- If  $Q1$  is weaker than  $Q$ , then  $\{P\} S \{Q1\}$  is valid.
- Example:
  - Suppose  $P$  is  $x \geq 0$  and  $P1$  is  $x > 0$
  - Suppose  $Q$  is  $y > 0$  and  $Q1$  is  $y \geq 0$
  - Since  $\{x \geq 0\} y = x+1 \{y > 0\}$  is valid,  $\{x > 0\} y = x+1 \{y \geq 0\}$  is also valid



# Hoare Logic Facts

---

- Suppose  $\{P\} S \{Q\}$  is valid.
- If  $P1$  is stronger than  $P$ , then  $\{P1\} S \{Q\}$  is valid.
- If  $Q1$  is weaker than  $Q$ , then  $\{P\} S \{Q1\}$  is valid.
- **Key points:**
  - always okay to **strengthen** a precondition
  - always okay to **weaken** a postcondition





# Forward & Backward Reasoning

# Example of Forward Reasoning

---

Work forward from the precondition

`{{ w > 0 }}`

`x = 17;`

`{{ _____ }}`

`y = 42;`

`{{ _____ }}`

`z = w + x + y;`

`{{ _____ }}`

# Example of Forward Reasoning

---

Work forward from the precondition

$\{\{ w > 0 \}\}$

$\mathbf{x = 17;}$

$\{\{ w > 0 \text{ and } x = 17 \}\}$

$\mathbf{y = 42;}$

$\{\{ \text{_____} \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ \text{_____} \}\}$

# Example of Forward Reasoning

---

Work forward from the precondition

$\{\{ w > 0 \}\}$

$\mathbf{x = 17;}$

$\{\{ w > 0 \text{ and } x = 17 \}\}$

$\mathbf{y = 42;}$

$\{\{ w > 0 \text{ and } x = 17 \text{ and } y = 42 \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ \text{_____} \}\}$

# Example of Forward Reasoning

---

Work forward from the precondition

$\{\{ w > 0 \}\}$

$\mathbf{x = 17;}$

$\{\{ w > 0 \text{ and } x = 17 \}\}$

$\mathbf{y = 42;}$

$\{\{ w > 0 \text{ and } x = 17 \text{ and } y = 42 \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ w > 0 \text{ and } x = 17 \text{ and } y = 42 \text{ and } z = w + x + y \}\}$

# Example of Forward Reasoning

---

Work forward from the precondition

$\{\{ w > 0 \}\}$

$\mathbf{x = 17;}$

$\{\{ w > 0 \text{ and } x = 17 \}\}$

$\mathbf{y = 42;}$

$\{\{ w > 0 \text{ and } x = 17 \text{ and } y = 42 \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ w > 0 \text{ and } x = 17 \text{ and } y = 42 \text{ and } z = w + 59 \}\}$

# Forward Reasoning

---

- Start with the **given** precondition
- Fill in the **strongest** postcondition
- For an assignment,  $\mathbf{x} = \mathbf{y}$ ...
  - add the fact “ $x = y$ ” to what is known
  - important subtleties here... (more on those later)
- Later: if statements and loops...

# Example of Backward Reasoning

---

Work backward from the desired postcondition

`{{ _____ }}`

`x = 17;`

`{{ _____ }}`

`y = 42;`

`{{ _____ }}`

`z = w + x + y;`

`{{ z < 0 }}`



# Example of Backward Reasoning

---

Work backward from the desired postcondition

$\{ \underline{\hspace{10em}} \}$

$\mathbf{x = 17;}$

$\{ \underline{\hspace{10em}} \}$

$\mathbf{y = 42;}$

$\{ \mathbf{w + x + y < 0} \}$

$\mathbf{z = w + x + y;}$

$\{ \mathbf{z < 0} \}$

# Example of Backward Reasoning

---

Work backward from the desired postcondition

$\{ \underline{\hspace{10em}} \}$

$\mathbf{x = 17;}$

$\{ \{ w + x + 42 < 0 \} \}$

$\mathbf{y = 42;}$

$\{ \{ w + x + y < 0 \} \}$

$\mathbf{z = w + x + y;}$

$\{ \{ z < 0 \} \}$

# Example of Backward Reasoning

---

Work backward from the desired postcondition

$\{\{ w + 17 + 42 < 0 \}\}$

$\mathbf{x = 17;}$

$\{\{ w + x + 42 < 0 \}\}$

$\mathbf{y = 42;}$

$\{\{ w + x + y < 0 \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ z < 0 \}\}$

# Backward Reasoning

---

- Start with the **required** postcondition
- Fill in the **weakest** precondition
- For an assignment,  $\mathbf{x} = \mathbf{y}$ :
  - just replace “x” with “y” in the postcondition
  - if the condition using “y” holds beforehand, then the condition with “x” will afterward since  $x = y$  then
- Later: if statements and loops...

# Correctness by Forward Reasoning

---

Use forward reasoning to determine if this code is correct:

`{{ w > 0 }}`

`x = 17;`

`y = 42;`

`z = w + x + y;`

`{{ z > 50 }}`

# Example of Forward Reasoning

---

$\{\{ w > 0 \}\}$

$\mathbf{x = 17;}$

$\{\{ w > 0 \text{ and } x=17 \}\}$

$\mathbf{y = 42;}$

$\{\{ w > 0 \text{ and } x=17 \text{ and } y=42 \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ w > 0 \text{ and } x=17 \text{ and } y=42 \text{ and } z = w + 59 \}\}$

$\{\{ z > 50 \}\}$

Do the facts that are always true imply the facts we need?

I.e., is the bottom statement **weaker** than the top one?

(Recall that weakening the postcondition is always okay.)

# Correctness by Backward Reasoning

---

Use backward reasoning to determine if this code is correct:

```
{{ w < -60 }}
```

```
  x = 17;
```

```
  y = 42;
```

```
  z = w + x + y;
```

```
{{ z < 0 }}
```

# Correctness by Backward Reasoning

---

Use backward reasoning to determine if this code is correct:

$\{\{ w < -60 \}\}$

$\{\{ w + 17 + 42 < 0 \}\} \iff \{\{ w < -59 \}\}$

$\mathbf{x = 17;}$

$\{\{ w + x + 42 < 0 \}\}$

$\mathbf{y = 42;}$

$\{\{ w + x + y < 0 \}\}$

$\mathbf{z = w + x + y;}$

$\{\{ z < 0 \}\}$

Do the facts that are always true imply the facts we need?

I.e., is the top statement **stronger** than the bottom one?

(Recall that strengthening the precondition is always okay.)



# Combining Forward & Backward

---

It is okay to use both types of reasoning

- Reason forward from precondition
- Reason backward from postcondition

Will meet in the middle:

**{{ P }}**

**S1**

**S2**

**{{ Q }}**

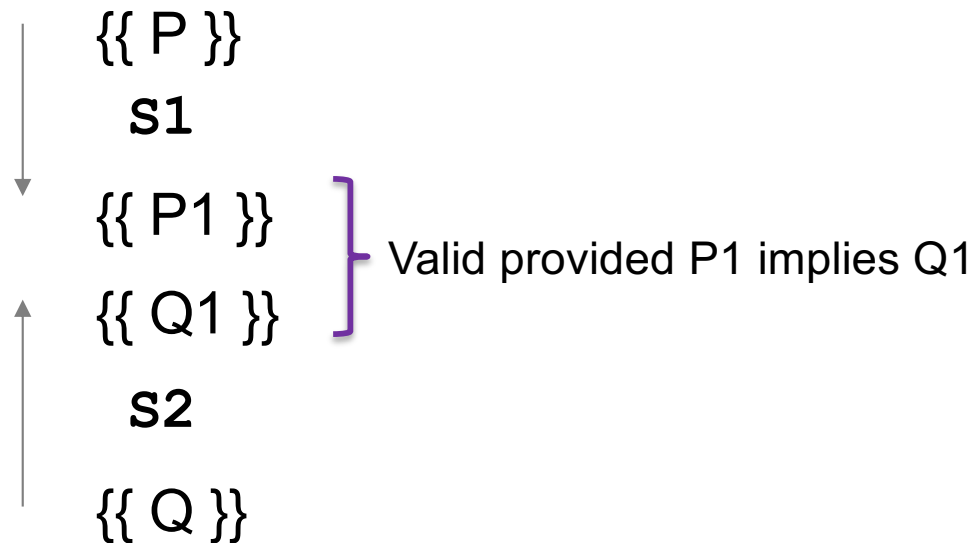
# Combining Forward & Backward

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It is okay to use both types of reasoning

- Reason forward from precondition
- Reason backward from postcondition

Will meet in the middle:



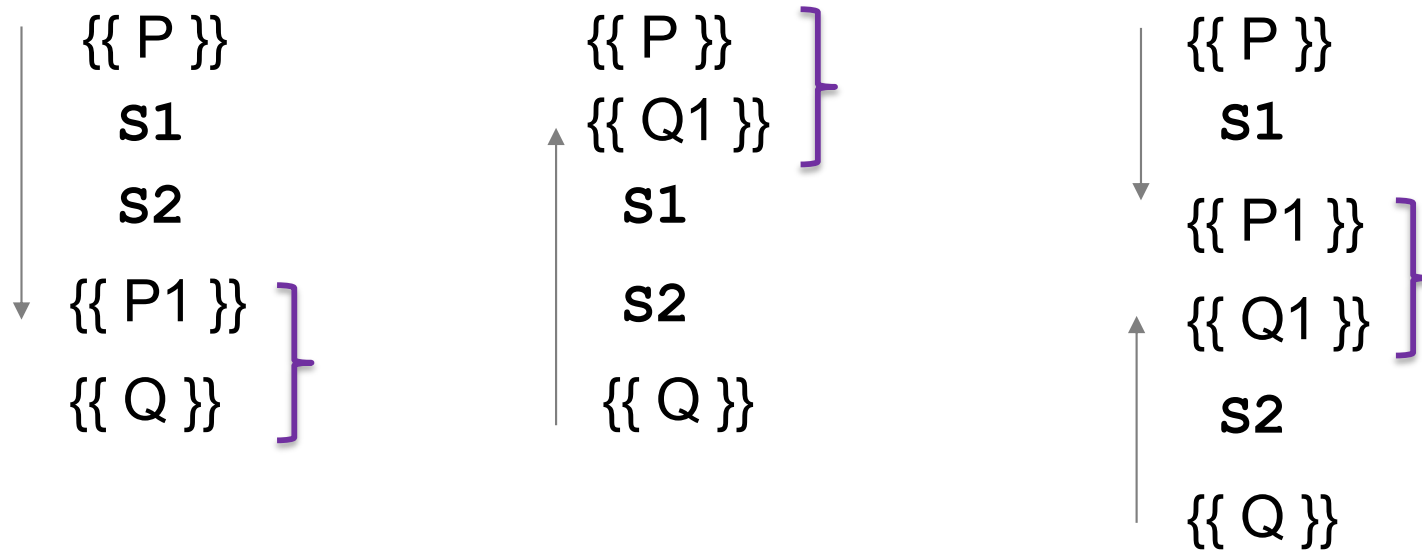
# Combining Forward & Backward

---

Reasoning in either direction gives valid assertions

Just need to check adjacent assertions:

- top assertion must imply bottom one



# Subtleties in Forward Reasoning...

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- Forward reasoning can **fail** if applied blindly...

$\{\{\}\}$

$w = x + y;$

$\{\{w = x + y\}\}$

$x = 4;$

$\{\{w = x + y \text{ and } x = 4\}\}$

$y = 3;$

$\{\{w = x + y \text{ and } x = 4 \text{ and } y = 3\}\}$

This implies that  $w = 7$ , but that is not true!

- $w$  equals whatever  $x + y$  was **before** they were changed

# Fix 1

---

- Use **subscripts** to refer to old values of the variables
- Un-subscripted variables should always mean **current** value

`{{ }}`

`w = x + y;`

`{{ w = x + y }}`

`x = 4;`

`{{ w = x1 + y and x = 4 }}`

`y = 3;`

`{{ w = x1 + y1 and x = 4 and y = 3 }}`

# Fix 2 (better)

---

- Express prior values in terms of the current value

$\{\{\}\}$

$w = x + y;$

$\{\{w = x + y\}\}$

$x = x + 4;$

$\{\{w = x_1 + y \text{ and } x = x_1 + 4\}\}$  Now,  $x_1 = x - 4$

$\Rightarrow \{\{w = x - 4 + y\}\}$

So  $w = x_1 + y \Leftrightarrow w = x - 4 + y$

Note for updating variables, e.g.,  $x = x + 4$ :

- Backward reasoning just substitutes new value (no change)
- Forward reasoning requires you to invert the “+” operation

# Forward vs. Backward

---

- Forward reasoning:
  - Find strongest postcondition
  - Intuitive: “simulate” the code in your head
    - BUT you need to change facts to refer to *prior values*
  - Inefficient: Introduces many irrelevant facts
    - usually need to weaken as you go to keep things sane
- Backward reasoning
  - Find weakest precondition
  - Formally simpler
  - Efficient
  - (Initially) unintuitive

# If Statements



# If Statements

---

Forward reasoning

```
{{ P }}  
if (cond)  
  S1  
else  
  S2  
{{ ? }}
```

# If Statements

---

Forward reasoning

```
  {{ P }}  
  if (cond)  
  → {{ P and cond }}  
    S1  
  else  
  → {{ P and not cond }}  
    S2  
  {{ ? }}
```



# If Statements

---

## Forward reasoning

$\{ P \}$

if (cond)

$\{ P \text{ and } \text{cond} \}$

S1

$\{ P1 \}$


else

$\{ P \text{ and not } \text{cond} \}$

S2

$\{ P2 \}$

$\{ P1 \text{ or } P2 \}$



# If Statements

---

Backward reasoning

```
{ { ? } }  
if (cond)  
  S1  
else  
  S2  
{ { Q } }
```

# If Statements

---

Backward reasoning

```
  {{ ? }}  
  if (cond)  
    S1  
  → {{ Q }}  
  else  
    S2  
  → {{ Q }}  
  {{ Q }}
```

# If Statements

---

## Backward reasoning

```

{{ ? }}
if (cond)
  ↑ {{ Q1 }}
  S1
  {{ Q }}
else
  ↑ {{ Q2 }}
  S2
  {{ Q }}
{{ Q }}
```

# If Statements

---

Backward reasoning

`{{ cond and Q1 or`

`not cond and Q2 }}`

`if (cond)`

`{{ Q1 }}`

`S1`

`{{ Q }}`

`else`

`{{ Q2 }}`

`S2`

`{{ Q }}`

`{{ Q }}`



# If-Statement Example

---

Forward reasoning

```
{ }  
if (x >= 0)  
    y = x;  
else  
    y = -x;  
{ ? }
```

# If-Statement Example

---

Forward reasoning

```
  {{ }}  
  if (x >= 0)  
    → {{ x >= 0 }}  
      y = x;  
  else  
    → {{ x < 0 }}  
      y = -x;  
  {{ ? }}
```

# If-Statement Example

---

Forward reasoning

```
{}  
if (x >= 0)  
  {{ x >= 0 }}  
  y = x;  
  ↓  
  {{ x >= 0 and y = x }}  
else  
  {{ x < 0 }}  
  y = -x;  
  ↓  
  {{ x < 0 and y = -x }}  
{{ ? }}
```

# If-Statement Example

---

Forward reasoning

$\{\{\}\}$

if (x  $\geq$  0)

$\{\{x \geq 0\}\}$

y = x;

$\{\{x \geq 0 \text{ and } y = x\}\}$

else

$\{\{x < 0\}\}$

y = -x;

$\{\{x < 0 \text{ and } y = -x\}\}$

$\{\{(x \geq 0 \text{ and } y = x) \text{ or}$

(x < 0 and y = -x)\}\}

# If-Statement Example

---

Forward reasoning

```
{{ }}
if (x >= 0)
  {{ x >= 0 }}
  y = x;
  {{ x >= 0 and y = x }}
else
  {{ x < 0 }}
  y = -x;
  {{ x < 0 and y = -x }}
{{ y = |x| }}
```

# If-Statement Example

---

Forward reasoning

```
{}  
if (x >= 0)  
  {{ x >= 0 }}  
  y = x;  
  {{ x >= 0 and y = x }}  
else  
  {{ x < 0 }}  
  y = -x;  
  {{ x < 0 and y = -x }}  
{{ y = |x| }}
```

**Warning:** many write `{{ y >= 0 }}` here

That is true but it is *strictly* weaker.  
(It includes cases where  $y \neq x$ )

# If-Statement Example

---

Forward reasoning

```
{}  
if (x >= 0)  
  {x >= 0}  
  y = x;  
  {x >= 0 and y = x}  
else  
  {x < 0}  
  y = -x;  
  {x < 0 and y = -x}  
{y = |x|}
```

Backward reasoning

```
{?}  
if (x >= 0)  
  y = x;  
else  
  y = -x;  
{y = |x|}
```

# If-Statement Example

---

Forward reasoning

```
{}  
if (x >= 0)  
  {x >= 0}  
  y = x;  
  {x >= 0 and y = x}  
else  
  {x < 0}  
  y = -x;  
  {x < 0 and y = -x}  
{y = |x|}
```

Backward reasoning

```
{?}  
if (x >= 0)  
  y = x;  
  → {y = |x|}  
else  
  y = -x;  
  → {y = |x|}  
{y = |x|}
```



# If-Statement Example

---

Forward reasoning

```
{ { }  
if (x >= 0)  
  { { x >= 0 } }  
  y = x;  
  { { x >= 0 and y = x } }  
else  
  { { x < 0 } }  
  y = -x;  
  { { x < 0 and y = -x } }  
{ { y = |x| } }
```

Backward reasoning

```
{ { ? } }  
if (x >= 0)  
  { { x = |x| } }  
  y = x;  
  { { y = |x| } }  
else  
  { { -x = |x| } }  
  y = -x;  
  { { y = |x| } }  
{ { y = |x| } }
```

# If-Statement Example

---

Forward reasoning

```
{{ }}  
if (x >= 0)  
  {{ x >= 0 }}  
  y = x;  
  {{ x >= 0 and y = x }}  
else  
  {{ x < 0 }}  
  y = -x;  
  {{ x < 0 and y = -x }}  
{{ y = |x| }}
```

Backward reasoning

```
{{ ? }}  
if (x >= 0)  
  {{ x >= 0 }}  
  y = x;  
  {{ y = |x| }}  
else  
  {{ x <= 0 }}  
  y = -x;  
  {{ y = |x| }}  
{{ y = |x| }}
```

# If-Statement Example

---

Forward reasoning

```
{}  
if (x >= 0)  
  {} x >= 0 {}  
  y = x;  
  {} x >= 0 and y = x {}  
else  
  {} x < 0 {}  
  y = -x;  
  {} x < 0 and y = -x {}  
{} y = |x| {}
```

Backward reasoning

```
{} (x >= 0 and x >= 0) or  
  (x < 0 and x <= 0) {}  
if (x >= 0)  
  {} x >= 0 {}  
  y = x;  
  {} y = |x| {}  
else  
  {} x <= 0 {}  
  y = -x;  
  {} y = |x| {}  
{} y = |x| {}
```

# If-Statement Example

---

Forward reasoning

```
{}  
if (x >= 0)  
  {} x >= 0 {}  
  y = x;  
  {} x >= 0 and y = x {}  
else  
  {} x < 0 {}  
  y = -x;  
  {} x < 0 and y = -x {}  
{} y = |x| {}
```

Backward reasoning

```
{x >= 0 or x < 0}  
if (x >= 0)  
  {} x >= 0 {}  
  y = x;  
  {} y = |x| {}  
else  
  {} x <= 0 {}  
  y = -x;  
  {} y = |x| {}  
{} y = |x| {}
```

# If-Statement Example

---

Forward reasoning

```
{  
}  
if (x >= 0)  
  {  
    x >= 0  
    y = x;  
    x >= 0 and y = x  
  }  
else  
  {  
    x < 0  
    y = -x;  
    x < 0 and y = -x  
  }  
y = |x|
```

Backward reasoning

```
{  
}  
if (x >= 0)  
  {  
    x >= 0  
    y = x;  
    y = |x|  
  }  
else  
  {  
    x <= 0  
    y = -x;  
    y = |x|  
  }  
y = |x|
```

Next time: Loops...