CSE 331

Software Design & Implementation

Topic: Introduction

Discussion: What are you excited for this summer?

Reminders

- Read the welcome email
- Check your access to Ed, Gradescope, and Canvas
- Should see email about Gitlab repositories soon

Upcoming Deadlines

- Syllabus Quiz due Thursday (6/22)
- HW1 due Thursday (6/22)

Last Time…

- Welcome email
- Syllabus Overview

Today's Agenda

- Upcoming Assignments
- Motivation
- Reasoning

Upcoming Assignments

Syllabus Quiz

- Due on Thursday night
  - read the syllabus in depth
  - answer a few multiple choice/select questions
  - infinite attempts before deadline
- Why?
  - had a lot of confusion in past quarters
  - make student requests manageable for course staff

HW1

- Due on Thursday night
  - practice interview question
  - **write** an algorithm to rearrange array elements as described
  - **argue** in concise, convincing English that it is correct
    - don't just explain *what the code does!*
  - **do not run** your code! (pretend it's on a whiteboard)
    - know that is correct *without* running it (a necessary skill)

- This is expected to be difficult (esp. the "argue" part)
  - graded on effort, not correctness
  - do not spend more than 90 minutes on it
  - want you to see that it is tricky… *without the tools coming next*

Motivation

What are the goals of CSE 331?

Learn the skills to be able to contribute to a modern software project

- move from CSE 143 problems toward what you'll see in industry and in upper-level courses

Specifically, how to write code of

- higher **quality**
- increased **complexity**

We will discuss *tools* and *techniques* to help with this and the *concepts* and *ideas* behind them

- there are *timeless principles* to both
- widely used across the industry

What is high quality?

Code is high quality when it is

1. **Correct**
   Everything else is of secondary importance

2. Easy to **change**
   Most work is making changes to existing systems

3. Easy to **understand**
   Needed for 1 & 2 above

How do we ensure correctness…

… when **people** are involved?

People have been known to

- walk into windows
- drive away with a coffee cup on the roof
- drive away still tied to gas pump
- lecture wearing one brown shoe and one black shoe

Key Insight

1. Can't stop people from making mistakes

How do we ensure correctness?

Best practice: use three techniques (we'll study each)

1. **Tools**
   - type checkers, test runners, etc.
2. **Inspection**
   - think through your code carefully
   - have another person review your code
3. **Testing**
   - usually >50% of the work in building software

technical interviews focus on this
(a.k.a. "reasoning")

Together can catch >97% of bugs.

Scale makes everything harder

Many studies showing scale makes quality harder to achieve

- Time to write N-line program grows faster than linear
  - Good estimate is $O(N^{1.05})$ [Boehm, '81]
- Bugs grow like $\Theta(N \log N)$ [Jones, '12]
  - 10% of errors are between modules [Seaman, '08]
- Communication costs dominate schedules [Brooks, '75]
- Small probability cases become high probability cases
  - Corner cases are more important with more users

Corollary: quality must be even higher, per line, in order to achieve overall quality in a *large* program

How do we cope with scale?

We tackle increased software scale with **modularity**

- Split code into pieces that can be built independently
- Each must be documented so others can use it
- Also helps understandability and changeability

What are the goals of CSE 331?

In summary, we want our to support code of:

Higher Quality:

- Correct
- Easy to change
- Easy to understand

Increased Complexity:

- Modular

Reasoning

Our Approach

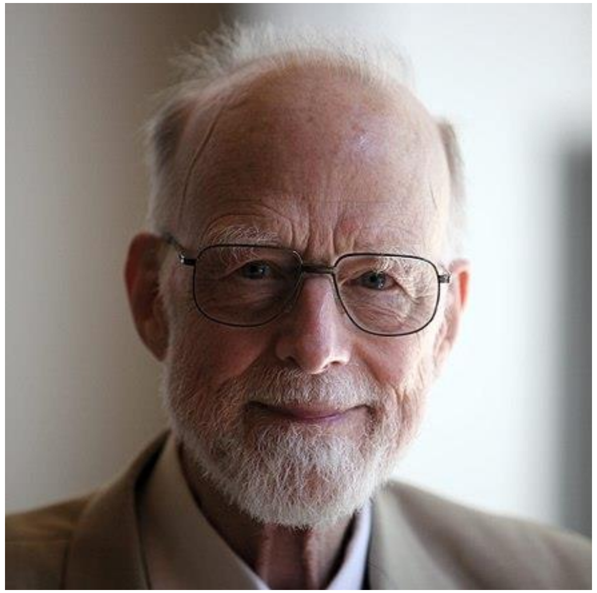
- We will learn a set of **formal tools** for proving correctness
  - math can seem daunting – it will connect back!
  - later, this will also allow us to generate the code
- Most professionals can do reasoning like this in their head
  - most do an *informal* version of what we will see
  - with practice, it will be the same for you
- Formal version has key advantages
  - teachable
  - mechanical (no intuition or creativity required)
  - necessary for hard problems
    - we turn to formal tools when problems get too hard

Formal Reasoning

- Invented by Robert Floyd and Sir Anthony Hoare
  - Floyd won the Turing award in 1978
  - Hoare won the Turing award in 1980

Robert Floyd

picture from Wikipedia



Tony Hoare

Terminology of Floyd Logic

- 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 Triples

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

  {*P*} *S* {*Q*}

  - *P* the precondition
  - *S* the code
  - *Q* the postcondition

specification

method body

code is correct iff triple is valid

- 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

- Floyd logic writes assertions in {..}
  - since Java code also has {..}, we will use {{…}}
  - e.g., {{ `w >= 1` }} `x = 2 * w;` {{ `x >= 2` }}
- Assertions are math, not Java
  - you should use the usual math notation
    - (e.g., **=** instead of **==** for equals)
  - purpose is communication with humans (not computers)
  - we will need **and**, **or**, **not** as well
    - can also write use ∧ (and) ∨ (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

Is the following Hoare triple valid or invalid?

- assume all variables are integers and there is no overflow

```
{{ x != 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

```
{{ x != 0 }} y = x*x; {{ y > 0 }}
```

Valid

- **y** could only be zero if **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 != 1 }} y = z*z; {{ y != z }}
```

Example 2

Is the following Hoare triple valid or invalid?

- assume all variables are integers and there is no overflow

```
{{ z != 1 }} y = z*z; {{ y != z }}
```

Invalid

- counterexample: `z = 0`

Checking Validity

- So far:
  - code is correct iff Hoare triple valid
  - decided if a Hoare triple is valid by ... **hard** thinking

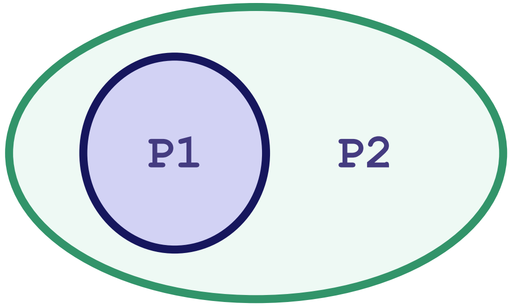
- Soon: mechanical process for reasoning about
  - assignment statements
  - [next section] conditionals
  - [next lecture] loops
  - (all code can be understood in terms of those 3 elements)

- Next: terminology for comparing different assertions
  - useful, e.g., to compare possible preconditions

Weaker vs. Stronger Assertions

If P1 implies P2 (written P1 ⇒ 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

- **`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`**

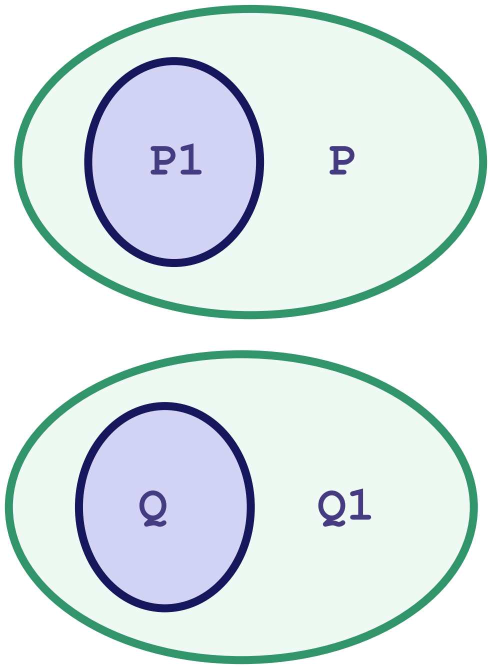
Floyd Logic Facts

- Suppose **`{P} S {Q}`** is valid.

- If **`P1`** is stronger than **`P`**,
  then **`{P1} S {Q}`** is valid.

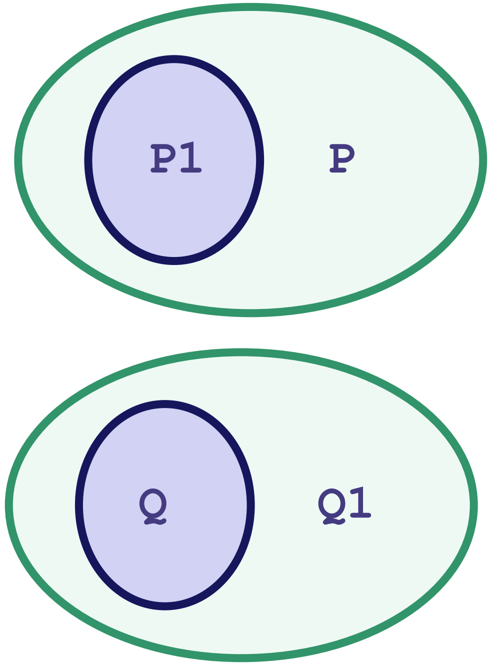
- If **`Q1`** is weaker than **`Q`**,
  then **`{P} S {Q1}`** is valid.

- Example:
  - Suppose **`P`** is x >= 0 and **`P1`** is x > 0
  - Suppose **`Q`** is y > 0 and **`Q1`** is y >= 0
  - Since {{ x >= 0 }} **`y = x+1`** {{ y > 0 }} is valid,
    {{ x > 0 }} **`y = x+1`** {{ y >= 0 }} is also valid



Floyd Logic Facts

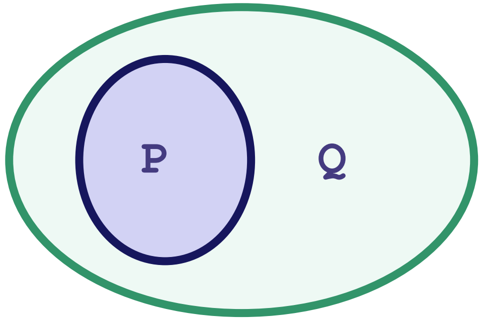
- Suppose **`{P} S {Q}`** is valid.
- If **`P1`** is stronger than **`P`**,
  then **`{P1} S {Q}`** is valid.
- If **`Q1`** is weaker than **`Q`**,
  then **`{P} S {Q1}`** is valid.
- **Key points**:
  - always okay to **strengthen** a **precondition**
  - always okay to **weaken** a **postcondition**



Floyd Logic Facts

- When is **`{P} ; {Q}`** is valid?
  - with no code in between

- Valid if any state satisfying P also satisfies Q
- I.e., if P is **stronger** than Q



Forward & Backward Reasoning

Forward Reasoning

- Start with the **given** precondition
- Fill in the **strongest** postcondition

- For an assignment, **`x = y`**...
  - add the fact “x = y” to what is known
  - important <u>subtleties</u> here... (more on those later)

- Later: if statements and loops...

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

{{ $w > 0$ }}

```
x = 17;
```

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

```
y = 42;
```

{{ ______________________________ }}

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

{{ ______________________________ }}

Example of Forward Reasoning

Work forward from the precondition

{{ w > 0 }}

```
x = 17;
```

{{ w > 0 and x = 17 }}

```
y = 42;
```

{{ w > 0 and x = 17 and y = 42 }}

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

{{ ________________________________ }}

Example of Forward Reasoning

Work forward from the precondition

{{ w > 0 }}

```
x = 17;
```

{{ w > 0 and x = 17 }}

```
y = 42;
```

{{ w > 0 and x = 17 and y = 42 }}

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

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

Example of Forward Reasoning

Work forward from the precondition

{{ w > 0 }}

```
x = 17;
```

{{ w > 0 and x = 17 }}

```
y = 42;
```

{{ w > 0 and x = 17 and y = 42 }}

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

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

Forward Reasoning

- Start with the **given** precondition
- Fill in the **strongest** postcondition

- For an assignment, **`x = y`**...
  - add the fact “x = y” to what is known
  - important <u>subtleties</u> here… (more on those later)

- Later: if statements and loops…

Backward Reasoning

- Start with the **required** postcondition
- Fill in the **weakest** precondition

- For an assignment, `x = 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…

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

{{ ______________________________ }}

`x = 17;`

{{ ______________________________ }}

`y = 42;`

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

`z = w + x + y;`

{{ $z < 0$ }}

Example of Backward Reasoning

Work backward from the desired postcondition

{{ ________________________ }}

```
x = 17;
```

{{ w + x + 42 < 0 }}

```
y = 42;
```

{{ w + x + y < 0 }}

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

{{ z < 0 }}

Example of Backward Reasoning

Work backward from the desired postcondition

{{ w + 17 + 42 < 0 }}

```
x = 17;
```

{{ w + x + 42 < 0 }}

```
y = 42;
```

{{ w + x + y < 0 }}

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

{{ z < 0 }}

Backward Reasoning

- Start with the **required** postcondition
- Fill in the **weakest** precondition

- For an assignment, `x = 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 }}
 x = 17;
{{ w > 0 and x = 17 }}
 y = 42;
{{ w > 0 and x = 17 and y = 42 }}
 z = w + x + y;
{{ w > 0 and x = 17 and y = 42 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 }}    ⟺ {{ w < -59 }}
 x = 17;
{{ w + x + 42 < 0 }}
 y = 42;
{{ w + x + y < 0 }}
 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

It is okay to use both types of reasoning

- Reason forward from precondition
- Reason backward from postcondition

Will meet in the middle:

{{ P }}
```
S1
```
{{ P1 }}

{{ Q1 }}
```
S2
```
{{ Q }}

Valid provided P1 implies Q1

Combining Forward & Backward

Reasoning in either direction gives valid assertions

Just need to check adjacent assertions:

- top assertion must imply bottom one

{{ P }}
S1
S2
{{ P1 }}
{{ Q }}

{{ P }}
{{ Q1 }}
S1
S2
{{ Q }}

{{ P }}
S1
{{ P1 }}
{{ Q1 }}
S2
{{ Q }}

Subtleties in Forward Reasoning…

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

{{ }}
```
w = x + y;
```
{{ w = x + y }}
```
x = 4;
```
{{ w = x + y and x = 4 }}
```
y = 3;
```
{{ w = x + y and x = 4 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;
```

{{ $w = x_1 + y$ and $x = 4$ }}

```
 y = 3;
```

{{ $w = x_1 + y_1$ and $x = 4$ and $y = 3$ }}

Fix 2 (better, when possible)

- Express prior values in terms of the current value

{{ }}
`w = x + y;`
{{ $w = x + y$ }}
`x = x + 4;`
{{ $w = x_1 + y$ and $x = x_1 + 4$ }}

Now, $x_1 = x - 4$

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

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

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, but (initially) unintuitive
  - Efficient

Before next class…

1. Familiarize yourself with website:

   http://courses.cs.washington.edu/courses/cse331/23su/

   – read the welcome email
   – read the syllabus

2. Try to do HW1 and syllabus quiz before section tomorrow!
   – submit a PDF on Gradescope
   – limit this to at most 60 min
   – do not use formal reasoning