Modular Reasoning
A software quality skill

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About Me

- Coding since 1999
- BS Computer Science 2013
- MS Computer Science 2014
- C#, XAML, Python, C, C++, more
- 10 years in radiotherapy software - patient positioning
- 8 days at Radformation

Contents

Intro

- Fact: Humans can keep about 7 things in working memory
- Fact: Programs contain more than 7 things
  - usually by orders of magnitude

Q: How do we write programs that humans can reason about?

Goals

- Help you write understandable code
- Teach design-level thinking
- Improve code quality

Motivating Quiz

Q: As part of a large application, you are reading an input and need to escape all single quotes.

Which of these two options is better and why? Assume both assign the same value to x.

```
x = sanitize(readInput())
```

```
x = readInput().replaceAll("'", "\\'")
```

- A: Option 1 because it's shorter
- B: Option 1 because option 2 is incorrect, even though it always works
- C: Option 2 because it's more clear what it does
- D: Option 2 because it's more efficient, avoiding the function call overhead

3...

2...

1...

Answer: B

Q: How could something that always works be incorrect?

A: Errors in modular reasoning.

Source: https://mirdin.com/quizzes/software-design-quiz/

Motivating Quiz

Q: Which is correct?

```
write(1, "foo", len)
```

```
write(stdout, "foo", len)
```

A: The second

Q: Why?

A: The first is incorrect because

- It is not possible to know that it works without making assumptions about the rest of the system.
- The number `1` is a secret to another module.
  - Namely, the system's implementation of the POSIX standard
- Even though it works now, this secret could change without notice.
- The idea of the number `1` and the idea of the stream `stdout` are distinct, even though they are the same in implementation right now.

-> The implementation/interface distinction states that the specification of what code must do is distinct from what the code actually does.

Motivating Quiz

```
x = sanitize(readInput())
```

```
x = readInput().replaceAll("'", "\\'")
```

The general idea of a sanitized string and the specific idea of a string with all single quotes escaped by a backslash are different.

The exact sanitization rules should be considered a secret to its module which could change without notice.

What is a Module?

- From PL (Programming Language) Theory
- A unit of organization that can keep a secret
- The secret is shared internally
- The secret is concealed externally

There are many ways to express modularity in progamming languages.

- Language Modules: ALGOL, OCaml, ML, Rust, Haskell
- Function/Method
- Class
- Namespace
- Assembly
- Process (e.g. web APIs, pipes, other IPC)

- local constants, calculations

```python
def sanitize(input_string):
  # the sanitization rules are a secret to this function
  return input_string.replace("'", "\\'")
```

- private, protected members

```csharp
public class UsTaxCode : ITaxCode
{
  // A secret to the class
  private const int _retirementAge = 65;

  public bool IsRetirementAge(int age) => age > _retirementAge;
}
```

```csharp
public class AsciiTools
{
  // another secret
  private const int _minChar = 65;

  public bool IsAlphanumeric(int c) => c > _minChar;
}
```

Q: These secrets are identical.
Should they be merged?

A: No, because they have different
specifications, i.e. reasons to
change.

- Assemblies
- e.g. .dll, .so files
- internal members

```csharp
namespace MyProject;

// Cannot be referenced outside MyProject.dll
internal class ThisAssemblyOnly
{
  ...
}
```

What is Modular Reasoning?

The ability to make decisions about a module while looking only at its implementation and the specification (i.e. interface or contract) of other modules.

Modular reasoning lets an engineer reason about the correctness of a module without reading the rest of the program.

Q: How big should a module be?

A: From cognitive science [1][2], humans can hold about 7 pieces of information in short-term memory. Modules should hold up to that amount.

- [1] https://www.oreilly.com/library/view/code-that-fits/9780137464302/
- [2] https://www.manning.com/books/the-programmers-brain

Design-Level Thinking

- Key idea: Design is apart from the code.
- Software design is a narrative over physical code
  - There can be many code implementations that satisfy a design

> There can be many code implementations that satisfy a design

Here's a specification.

```
public interface ICalculator
{
  // Returns the integer quotient
  public int Divide(int x, int y);
}
```

What's the difference between these two implementations?

```
public class X : ICalculator
{
    public int Divide(int x, int y) => x / y;
}
```

```
public class Y : ICalculator
{
    public int Divide(int x, int y) => y switch
    {
        0 => int.MaxValue,
        _ => x / y
    };
}
```

> There can be many code implementations that satisfy a design

Here's a specification.

```
public interface ICalculator
{
  // Returns the integer quotient
  public int Divide(int x, int y);
}
```

What's the difference between these two implementations?

```
public class RawCalculator : ICalculator
{
    public int Divide(int x, int y) => x / y;
}
```

```
public class SafeCalculator : ICalculator
{
    public int Divide(int x, int y) => y switch
    {
        0 => int.MaxValue,
        _ => x / y
    };
}
```

One prevents division by zero

Evidence for the level of design: Reverse-engineering

Reverse-engineering is only possible because design is separate from implementation.

Imagine you need to rewrite a large program.

All you have is the source code:

- no docs
- original authors were hit by a bus

How would you do it?

- Whether you know it or not, you'd first extract a design, i.e. intentions and specifications.
- You'd then write your new program according to that design.
- You might to this iteratively.

There's a catch: going from code to design is lossy.

In pseudocode:

```
let code1 = ...
let design2 = reverse(code1)
let code2 = implement(design2)
assert(equivalent(code1, code2)) // Fails
```

The Three Levels of Program Correctness

Q: How do we know a program is correct?

A: There are three approaches.

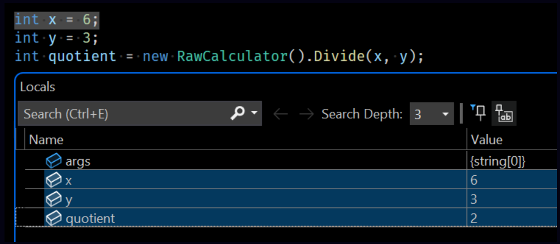
- Runtime
- Code
- Logic

Level 1: Runtime

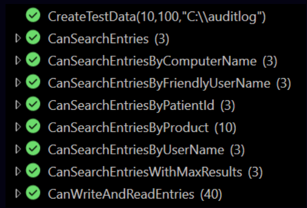
- Considers only a specific execution of a program

```
int quotient = new RawCalculator().Divide(6, 3);
// { quotient == 2 }
```

- What you see at a breakpoint in a debugger



- All unit tests work at this level



Level 1 says:

> A program is incorrect if it runs and produces a wrong result.

Level 2: Concrete implementation / Code

- Considers all possible executions of a program
- What the current implementation could do given arbitrary inputs and an arbitrary environment.

```
public class RawCalculator : ICalculator
{
    public int Divide(int x, int y) => x / y;
}

int impossible = new RawCalculator(1, 0); // throws
```

- Static analyzers work at this level

Level 2 says:

> A program is incorrect if there exists some environment or input under which it produces a wrong result

Level 3: Logic

- Considers how the code is derived
- At this level, we consider only the abstract specification (i.e. interface, contract) of each module.
- We don't look at any particular implementation.
- We assume a module may be replaced at any time with a different implementation.
- We can then determine the module's correctness by only looking at its code and the contracts of its dependencies.

```
ICalculator calc = ...;
int quotient = calc.Divide(6, 0);
```

- Junior dev: "Let's ship it. It's ok because I know calc is a `SafeCalculator`."
- Senior dev: "That is not a stable guarantee. What if tomorrow we are given a `RawCalculator`?"
- Junior dev: "Ok. We need to either not pass `0` or handle `DivideByZeroException`."

Level 3 says:

> A program is incorrect if the reasoning for why it should be correct is flawed.

Stable Guarantees

- If we program only to guarantees made by other modules' spec, then we are programming at the logic/design level.

Spec: Preconditions

- the facts a function assumes to be true before it runs

Spec: Invariants

- the facts a function assumes to remain true while it runs
- for pure functions, invariants == preconditions

Spec: Postconditions

- the facts a function guarantees to be true after it has run

Stable Guarantees

```csharp
public class RawCalculator : ICalculator
{
    // Strong assumption: y is not 0
    // Weak guarantees: could throw
    public int Divide(int x, int y) => x / y;
}
```

```csharp
public class SafeCalculator : ICalculator
{
    // Weaker assumption: y can be 0
    // Stronger guarantees: will not throw
    public int Divide(int x, int y) => y switch
    {
        0 => int.MaxValue,
        _ => x / y
    };
}
```

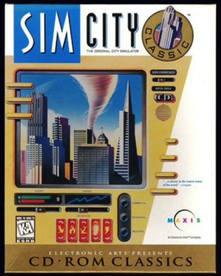
"You have heard it said, but I tell you..."

- Heard of "Defensive Coding"?
  - More precise: Program to stable guarantees
    - Think about preconditions, invariants and postconditions.
- Heard of "Encapsulation"?
  - More precise: think about modules and secrets.
  - When using a module (function, class, etc)
    - Always meet or exceed its assumptions.
    - Only rely on its guarantees.

Errors in Modular Reasoning

1. Depending on a stricter output (stronger postconditions) than the specification guarantees.
2. Depending on being able to use looser input (weaker preconditions) than the specification guarantees.

Errors in Modular Reasoning: Example



"the original Sim City had a use-after-free error. At the concrete implementation/code level, this was totally fine, since freed memory in DOS was valid until the next malloc, and so the program worked."

"At the logical level, this was a defect, because the spec for `free` says you need to act as if ... any future `free` implementation may actually [reallocate the memory]... once Windows 3.1 rolled around with a new memory manager, SimCity would start crashing.

"Microsoft had to add a special case to check if SimCity was running and switch to a legacy memory manager if so."

Sources

https://www.pathsensitive.com/2018/01/the-three-levels-of-software-why-code.html

https://www.joelonsoftware.com/2004/06/13/how-microsoft-lost-the-api-war/

```csharp
[assembly: InternalsVisibleTo("Tests")]

public class UsTaxCode : ITaxCode
{
  // A secret to the class
  /*private*/ internal const int _retirementAge = 65;

  public bool IsRetirementAge(int age) => age > _retirementAge;
}
```

```csharp
// In Tests.dll
[Fact]
public void RetirementAge_Is65()
{
  // Don't do this!
  new UsTaxCode()._retirementAge.Should().Be(65);
}
```

Q: Why is this an error in modular reasoning?

A: It isn't a stable guarantee.

But this is:

```csharp
// In Tests.dll
[Theory]
[InlineData(64, false)]
[InlineData(65, false)]
[InlineData(66, true)]
public void IsRetirementAge_IsCorrect(int age, bool expected)
{
  // OK, uses only public API
  new UsTaxCode().IsRetirementAge(age).Should().Be(expected);
}
```

Review Quiz

- Q: How can a program that never goes wrong still be wrong?
    - A: Errors in modular reasoning
- Q: What kind of bug does an error in modular reasoning produce?
    - A: A bug where a program works now but it might break in the future.
- Q: Modular reasoning lets an engineer...
    - A. Make smaller classes, functions, and files.
    - B. Feel smarter
    - C. Reason about code correctness without reading the rest of the program.
- A: C

Summary

- Our goal is not to just deliver correct software today.
- It's to continue to deliver correct software far into the future.
- We can do that by remembering Level 3, the layer of design and logic.
- With Modular Reasoning, we can confidently change large programs.

Resources

- https://mirdin.com
- https://mirdin.com/quizzes/software-design-quiz/
- https://www.pathsensitive.com/2018/01/the-three-levels-of-software-why-code.html
- https://www.pathsensitive.com/2018/01/the-design-of-software-is-thing-apart.html
- https://note89.github.io/pipe-dream/
- https://www.slater.dev/a-design-is-a-mold-for-code/

Discussion