Bugs, crawling all over

6.037 - Structure and Interpretation of Computer Programs

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Lecture 5

Which program is better? Why?

```
(define (prime? n)
 (= n (smallest-divisor n)))

(define (smallest-divisor n)
 (find-divisor n 2))

(define (find-divisor n d)
 (cond ((> (square d) n) n)
       ((divides? d n) d)
       (else (find-divisor n (+ d 1)))))

(define (divides? a b)
  (= (remainder b a) 0))
```

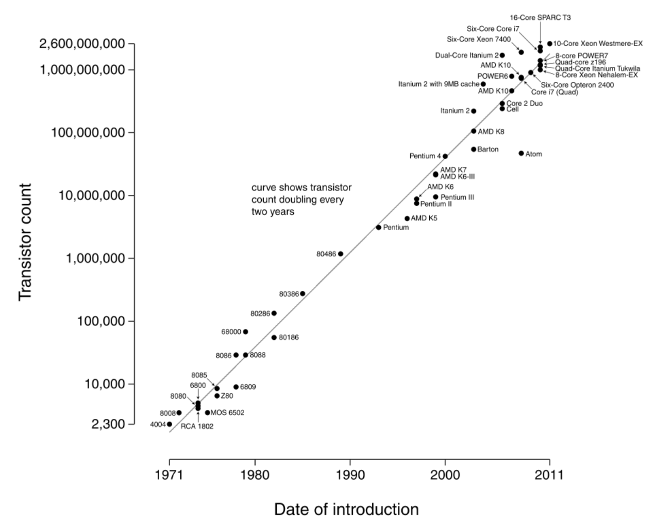
```
(define (prime? temp1 temp2)
     (cond ((>= temp2 temp1) #t) ((= (remainder
  temp1 temp2) 0) #f) (else (prime? temp1 (+
            temp2 1)))))
```


What do we mean by “better”?

- Correctness
  - Does the program compute correct results?
  - Programming is about communicating the algorithm to the computer
  - Is it clear what the correct result should be?
- Clarity
  - Can it be easily read and understood?
  - Programming is also about communicating the algorithm to people!
  - An unreadable program is a useless program
  - Does not benefit from abstraction
- Maintainability
  - Can it be easily changed?
- Performance
  - Algorithm choice: order of growth in time & space
  - Optimization: tweaking of constant factors

Why is optimization last?

Microprocessor Transistor Counts 1971-2011 & Moore’s Law



http://en.wikipedia.org/wiki/File:Transistor_Count_and_Moore%27s_Law_-_2011.svg

Making code more readable

```
(define (prime? temp1 temp2)
     (cond ((>= temp2 temp1) #t) ((= (remainder
  temp1 temp2) 0) #f) (else (prime? temp1 (+
            temp2 1)))))
```

Use indentation to show structure:

```
(define (prime? temp1 temp2)
 (cond ((>= temp2 temp1) #t)
       ((= (remainder temp1 temp2) 0) #f)
       (else (prime? temp1 (+ temp2 1)))))
```


Making code more readable

```
(define (prime? temp1 temp2)
 (cond ((>= temp2 temp1) #t)
       ((= (remainder temp1 temp2) 0) #f)
       (else (prime? temp1 (+ temp2 1)))))
```

Don't ask the caller to supply extra arguments for iterative calls:

```
(define (prime? temp1)
 (do-it temp1 2))
(define (do-it temp1 temp2)
 (cond ((>= temp2 temp1) #t)
       ((= (remainder temp1 temp2) 0) #f)
       (else (do-it (+ temp2 1)))))
```


Making code more readable

```
(define (prime? temp1)
 (do-it temp1 2))
(define (do-it temp1 temp2)
 (cond ((>= temp2 temp1) #t)
       ((= (remainder temp1 temp2) 0) #f)
       (else (do-it (+ temp2 1)))))
```

Use block structure to hide your helper procedures:

```
(define (prime? temp1)
 (define (do-it temp2)
  (cond ((>= temp2 temp1) #t)
        ((= (remainder temp1 temp2) 0) #f)
        (else (do-it (+ temp2 1)))))
 (do-it 2))
```


Making code more readable

```
(define (prime? temp1)
 (define (do-it temp2)
  (cond ((>= temp2 temp1) #t)
        ((= (remainder temp1 temp2) 0) #f)
        (else (do-it (+ temp2 1)))))
 (do-it 2))
```

Choose good names for procedures and variables:

```
(define (prime? n)
 (define (find-divisor d)
  (cond ((>= d n) #t)
        ((= (remainder n d) 0) #f)
        (else (find-divisor (+ d 1)))))
 (find-divisor 2))
```

Making code more readable

```
(define (prime? n)
 (define (find-divisor d)
  (cond ((>= d n) #t)
        ((= (remainder n d) 0) #f)
        (else (find-divisor (+ d 1)))))
 (find-divisor 2))
```

Find useful common patterns:

```
(define (prime? n)
 (define (find-divisor d)
  (cond ((>= d n) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
 (find-divisor 2))

(define (divides? d n)
 (= (remainder n d) 0))
```


Performance?

```
(define (prime? n)
 (define (find-divisor d)
  (cond ((>= d n) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
 (find-divisor 2))

(define (divides? d n)
 (= (remainder n d) 0))
```

Focus on algorithm improvements (order of growth)

Performance?

```
  (cond ((>= d (sqrt n)) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
```

Is `square` faster than `sqrt`?

```
  (cond ((>= (square d) n) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
```

What if we inline `square` and `divides`?

```
  (cond ((>= (* d d) n) #t)
        ((= (remainder n d) 0) #f)
        (else (find-divisor (+ d 1)))))
```

Micro-optimizations are generally useless

Making code more readable

- Indent code for readability
- Find common, **easily-named** patterns in your code, and pull them out as procedures and data abstractions
  - Makes procedures shorter, able to fit more in your head
- Choose good, descriptive names for procedures and variables
- **Clarity first**, then performance
  - If performance matters, focus on the algorithm first
  - Small optimizations are just constant factors

Finding prime numbers in a range

```
(define (primes-in-range min max)
 (cond ((> min max) '())
       ((prime? min)
        (cons min
              (primes-in-range (+ 1 min)
                               max)))
       (else (primes-in-range (+ 1 min) max))))
```


Finding prime numbers in a range

```
(define (primes-in-range min max)
 (let ((other-primes (primes-in-range (+ 1 min) max)))
  (cond ((> min max) '())
        ((prime? min) (cons min other-primes))
        (else other-primes))))

(primes-in-range 0 10)   ; expect (2 3 5 7)
.......
```


Dealing with bugs in your code

- We all write perfect code
- Clearly never any bugs in it
- But *other people's code* has bugs in it

Dealing with bugs in other people's code

- What do you do when you find a bug in a program?
- **Write a bug report**
- Anyone can do this
- A lot of people do it *badly*

Bad bug reports

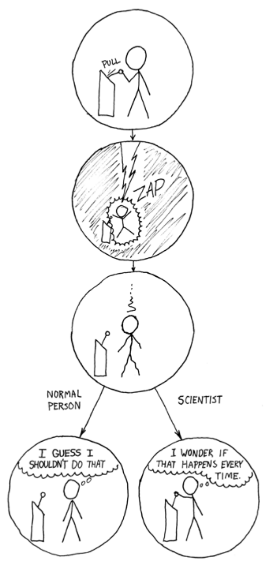
```
To: Alyssa P. Hacker
From: Ben Bitdiddle

Your prime-finding program doesn't work.

Please advise.

 - Ben
```


Questions to ask

- What did you do to cause the bug?
- Is it repeatable?
- What did you expect it to do?
- What did it actually do?

What did you do?

- Precise instructions are important
- *Simple* precise instructions are even better
- *Repeatability* is key



What were you expecting?

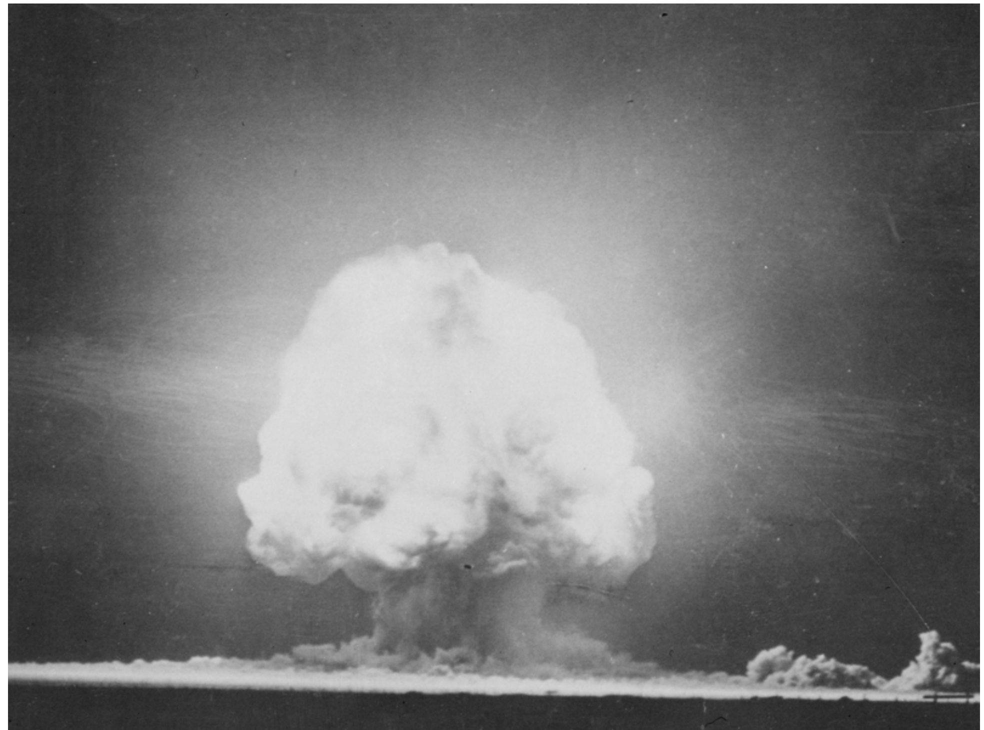
- State and re-check your assumptions
- Your belief of the right answer may differ from the specification of the author's

```
; Dividing by zero is always an error
(/ 5 0)  ; error
(/ 5 0.) ; +inf.0
```

- Sometimes the bug is in the user
- Read the documentation
- Leave open the possibility of PEBKAC

What happened?

“It didn’t work”



The many flavors of failure

- **“Nothing happens”**
- ... or is it just very slow?
- ... does it pinwheel?
- ... does it consume all of your CPU?
- ... does it consume all of your memory?
- **“The answer is not what I expect”**
- ... what is the significant way in which it differs from your expectations?
- **“It gives an error message”**
- ... and what does that message say?
- ... and is there anything in the error log?

Better bug reports

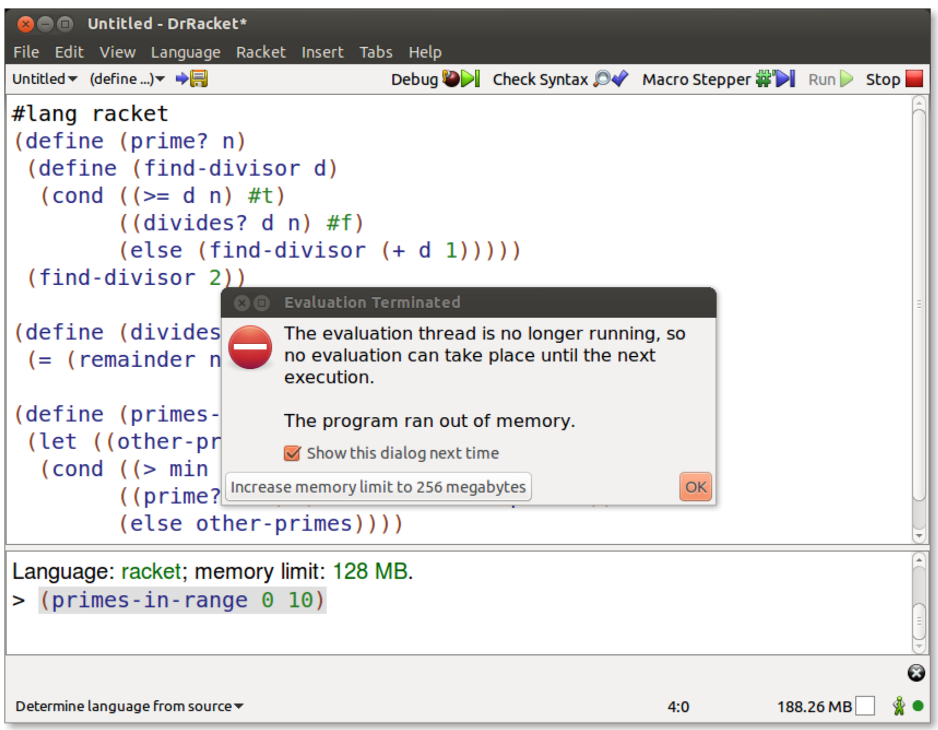
```
To: Alyssa P. Hacker
From: Ben Bitdiddle

primes-in-range appears to never halt.  I ran:

  (primes-in-range 0 10)

...and it just kept going, never outputting anything;
I’d expect it to return (1 2 3 5 7).  I waited for 10
minutes, but it appeared to just make my laptop hot.

 - Ben
```

Check expectations

- As the author, do we agree that `(primes-in-range 0 10)` should halt?

Replicate the error

- Can we replicate the error?



Replicate the error

- Can we replicate the error?
- We get a different outcome!
- Either this is a <u>different</u> cause, or the <u>same</u> cause with a different symptom
- Always re-check you actually fixed the relevant bug at the end

Is this the simplest error case?

```
;; Out of memory; test from user
(primes-in-range 0 10)

;; Ditto; so 0 not at fault
(primes-in-range 9 10)

;; Simpler upper bound
(primes-in-range 0 1)
```


Use abstraction barriers to your advantage

- There appears to be nothing special about `0` or `10`
- All calls to `primes-in-range` run out of memory
- **Divide and conquer** – verify that lower abstractions work
- Abstractions (procedural and structural) are good points to check

Check the lower abstractions

```
(define (primes-in-range min max)
 (let ((other-primes (primes-in-range (+ 1 min) max)))
  (cond ((> min max) '())
        ((prime? min) (cons min other-primes))
        (else other-primes))))

;; Check that our prime? code works!
(prime? 2)   ; -> #t
```



```
(define (primes-in-range min max)
 (let ((other-primes (primes-in-range (+ 1 min) max)))
  (cond ((> min max) '())
        ((prime? min) (cons min other-primes))
        (else other-primes))))

(primes-in-range 0 10)  ;; expect (2 3 5 7)
; => (0 1 2 3 4 5 7 9)
```

Assumptions

```
(define (prime? n)
 (define (find-divisor d)
  (cond ((>= d (sqrt n)) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
 (find-divisor 2))
```

- Only works on $n \geq 2$
- Everything has hidden assumptions
- Document them!

Documenting code

- Documentation improves **readability**, allows for **maintenance**, and supports **reuse**.
- Describe input and output
- Any assumptions about inputs or internal state
- Interesting decisions or algorithms

Documenting code

```
(define (prime? n)
 ; Tests if n is prime (divisible only by 1 and
 ; itself)
 ; n must be >= 2

 ; Test each divisor from 2 to sqrt(n),
 ; since if a divisor > sqrt(n) exists,
 ; there must be another divisor < sqrt(n)
 (define (find-divisor d)
  (cond ((>= d (sqrt n)) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
 (find-divisor 2))

(define (divides? d n)
 ; Tests if d is a factor of n (i.e. n/d is an integer)
 ; d cannot be 0
 (= (remainder n d) 0))
```


Not all comments are good

Horrid comment:

```
(define k 2)  ;; set k to 2
```

Better comment:

```
(define k 2)  ;; 2 is the smallest prime
```

Better yet, obviate the need for the comment:

```
(define smallest-prime 2)
```

The how and why of comments

- Comments should explain "how" or "why"
- "What" is almost never useful

Make no assumptions?

Use assertions to check assumptions and provide good errors:

```
(define (prime? n)
 ; Tests if n is prime (divisible only by 1 and
 ; itself)
 ; n must be >= 2

 (find-divisor 2))
```


Make no assumptions?

Or, better, cover all of your bases:

```
(define (prime? n)
 ; Tests if n is prime (divisible only by 1 and
 ; itself)
 ; n must be >= 2

 (find-divisor 2))
```


Make no assumptions?

All of your bases?

```
(prime? "5")
(if (<= "5" 1) #f (find-divisor 2))
(<= "5" 1)
<=: expected argument of type <real number>;
    given "5"
```

Include input/output types in a comment

All better!

```
(primes-in-range 0 10)  ; (expect 2 3 5 7)
(2 3 4 5 7 9)

(prime? 9) ; => #t
```


How do you know what works?. . .

- Assume you get a *good* bug report
- With simple, precise instructions that allow you to repeat it
- Would be good if we never had this bug again. . .
- Hey, computers are good at executing simple, precise instructions
- **Write a test case** for the bug

When to write tests

- When should you write tests?
- **ALL OF THE TIME**.
- Mostly after a bug is found
- You can also write tests *before* a feature is added – "test-first methodology"
- But at least a tests-sometime methodology is key
- Test each moving part before you use it elsewhere

Choosing good test cases

- How do you choose what to test?
- Start with simple cases
- Test the boundaries of your data and recursive cases
- Check a variety of kinds of input (empty list, single element, many)

Choosing good test cases

```
(prime? 0)  ;; Test the lower limits
(prime? 1)
(prime? 2)
(prime? 3)
(prime? 7)  ;; Simple should-be-true test
(prime? 10) ;; Simple should-be-false test
(prime? 9)  ;; Square numbers should be false
```


Boundary cases

```
(define (prime? n)
 ; Tests if n is prime (divisible only by 1 and
 ; itself)

 ; Test each divisor from 2 to sqrt(n),
 ; since if a divisor > sqrt(n) exists,
 ; there must be another divisor < sqrt(n)
 (define (find-divisor d)
  (cond ((>= d (sqrt n)) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
 (if (< n 2)
     #f
     (find-divisor 2)))
```


Boundary cases

```
(define (prime? n)
 ; Tests if n is prime (divisible only by 1 and
 ; itself)

 ; Test each divisor from 2 to sqrt(n),
 ; since if a divisor > sqrt(n) exists,
 ; there must be another divisor < sqrt(n)
 (define (find-divisor d)
  (cond ((>= d (sqrt n)) #t)
        ((divides? d n) #f)
        (else (find-divisor (+ d 1)))))
 (if (< n 2)
     #f
     (find-divisor 2)))
```


"What will this change break?"

- "Did I actually fix the bug?"
- Having tests means not needing to know all of the code
- Small changes can have far-reaching impacts
- You can keep maybe about 50k LOC in your head at once
- Tests keep the proper functionality on disk, not in your head

“When did I break this functionality?”

- Tests written now are like debugging in the past
- Run your test against old versions of your code
- If it ever worked, you’ll find what change broke it
- *Bisection* in time is awesome
- (but only as awesome as your ability to use your version control)

“Why did I do it that way?”

- Store your code in “version control”
- Git, Subversion, Mercurial, ~~Bazaar, DARCS, CVS, RCS, SCCS,...~~
- Version control lets you group a set of changes into a chunk
- And then write a message about the how and why of the change
- Commit messages are like comments – the intended audience is you in the future

How to write tests

- Languages have test frameworks
- JUnit (Java), PyUnit (Python), Test::Unit (Ruby), Test::More (Perl)
- Racket has `RackUnit`


```
(require rackunit)

(check-false (prime? 0) "0 is composite")
(check-false (prime? 1) "1 is composite")
(check-true  (prime? 2) "2 is the smallest prime")
(check-true  (prime? 3) "3 is also prime")
(check-true  (prime? 7) "Larger prime")
(check-false (prime? 10) "Divisible by 2 is composite")
(check-false (prime? 9) "Square means composite")
```

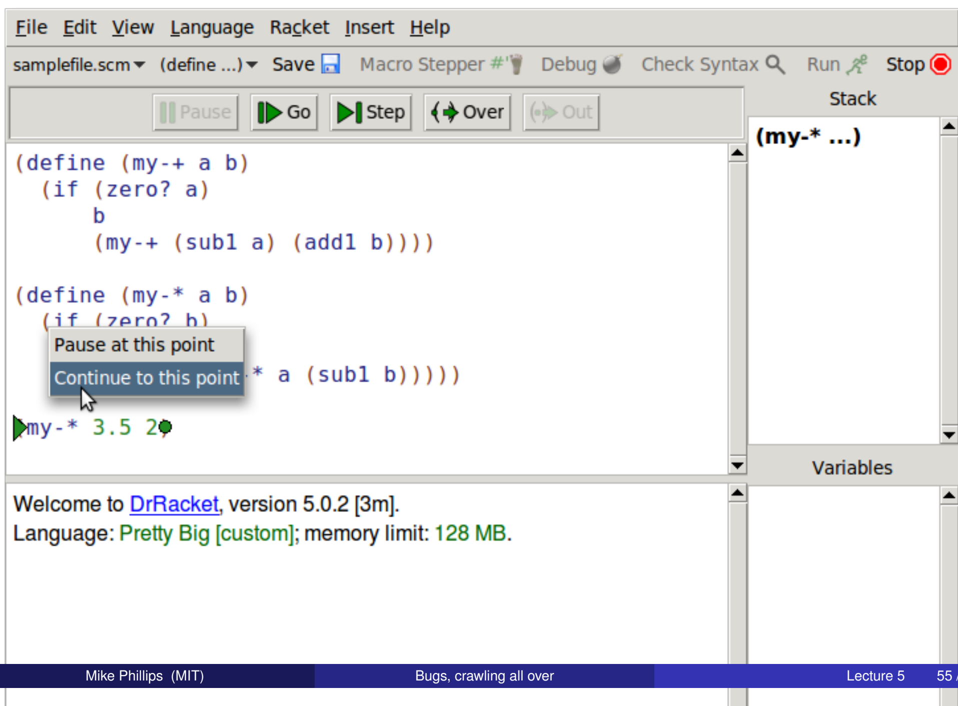
Debugging 101

```
(display ...)
```

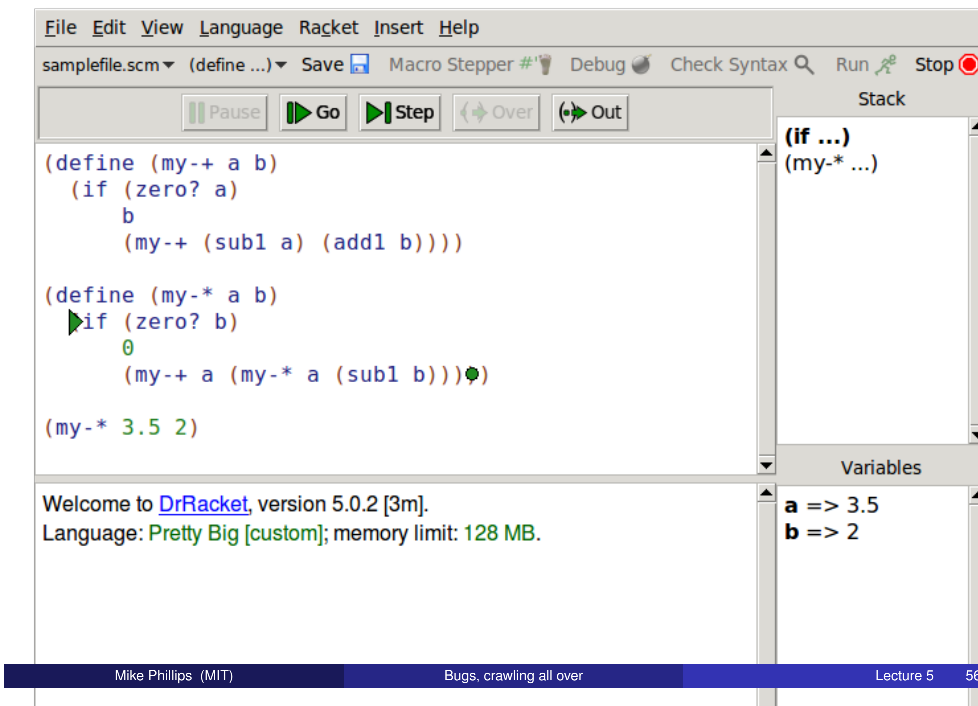

Reasons why display is awesome

- Learn the name of one function, and you can debug in a new language
- Faster to implement than learning a new debugger
- Provides written log of code decisions
- Find out which branch the code took?
  `(display "No fallback value found!")`
- Find out the return value of a function?
  `(display retval)`
- Find if a function is called?
  `(display "IaIaCthuluFtagn() called!")`

Interactive debuggers



Interactive debuggers



Interactive debugger glossary

Go – Continue until you hit a breakpoint
Breakpoint – Function or line to stop at
Watch – Value or expression to continuously display
Step – Proceed to next expression
Step over – Run until we have the value of the current expression, or hit a breakpoint
Out – Run until we have the value of the surrounding expression, or hit a breakpoint
Call stack – Nested list of function calls that we are in; also, “backtrace.”

Heisenbugs

- Some bugs go away when you examine them
- Debugging statements can have side effects

```
(define foo 0)
(define (new-foo) (set! foo (add1 foo)) foo)

(define sum 0)
(display
 (let loop ()
   (if (< foo 10)
       (begin
         (display (new-foo))(newline)
         (set! sum (+ sum (new-foo)))
         (loop))
       sum)))
```


Common failure paradigms

- Some error messages tell you immediately what you should be looking for
- `application: not a procedure; expected a procedure that can be applied to arguments, given: 6; arguments were: 7 8`
- `cdr: expects argument of type <pair>; given ()`
- `cannot reference an identifier before its definition: paramter`
- Learn them for your given language (ConcurrentModificationException, null pointer dereference, etc)