Which program is better? Why?

A

```
(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))
```

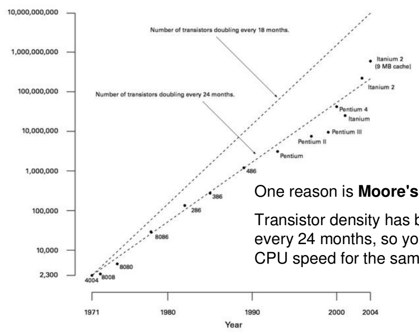
B

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


What do we mean by “better”?

1. Correctness
   - Does the program compute correct results?
   - Programming is about communicating to the computer what you want it to do
2. Clarity
   - Can it be easily read and understood?
   - Programming is just as much about communicating to other people (and yourself!)
     - An unreadable program is (in the long run) a useless program
3. Maintainability
   - Can it be easily changed?
4. Performance
   - Algorithm choice: order of growth in time & space
   - Optimization: tweaking the constant factors

Why is optimization last on the list?



One reason is **Moore's Law**

Transistor density has been doubling every 24 months, so you get twice the CPU speed for the same money.

Today's lecture: how to make your programs better

- Clarity
  - Readable code
  - Documentation
  - Types
- Correctness
  - Debugging
  - Error checking
  - Testing
- Maintainability
  - Creating and respecting abstractions

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 put extra demands on the caller (like setting the initial values of an iterative procedure): wrap them up inside an abstraction

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

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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))
```

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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 common patterns that can be easily named, or that may be useful elsewhere, and pull them out as abstractions

```
(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))
```

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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 in time or space)

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

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Performance?

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

- Is `square` faster than `sqrt`? (Maybe, but does it matter?)

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

- What if we **inline** `square` and `divides?` (Probably not worth it. Only do this if it improves the readability of the code.)

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

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Summary: 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
  - This makes each procedure shorter, which makes it easier to understand.
  - Reading good code should be like "drinking through a straw"
- Choose good, descriptive names for procedures and variables
- **Clarity first**, then performance
  - If performance really matters, than focus on algorithm improvements (better order of growth) rather than small optimizations (constant factors)

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Finding prime numbers in a range

- Let's use our prime-testing procedure to find all primes in a range [min,max]

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

- Simplify the code by naming the result of the common expression

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


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) (adjoin min other-primes))
          (else other-primes))))
```

- **Let's test it for a small range:**

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

…………… d'oh! never prints a result

Debugging tools

- The **ubiquitous** print/display expression

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

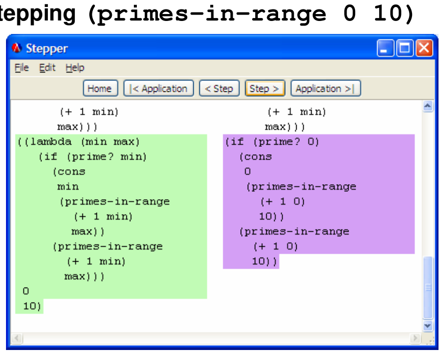
- Virtually every programming system has something like `display`, so you can always fall back on it

Debugging tools

- The ubiquitous print/display expression
- **Stepping** shows the state of computation at each stage of substitution model
  - In DrScheme:
    - Change language level to "Intermediate Student with Lambda"
    - Put test expression at the end of definitions `(primes-in-range 0 10)`
    - Press 

  - Or, without changing the language level:
    - Press Debug
    - (the user interface looks different, however)

Stepping `(primes-in-range 0 10)`



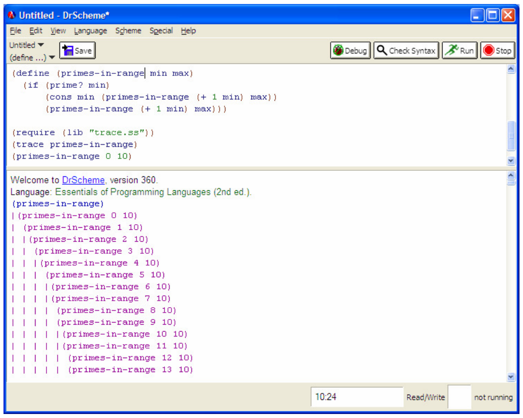
Debugging tools

- The ubiquitous print/display expression
- Stepping
- **Tracing** tracks when procedures are entered or exited
  - Every time a traced procedure is entered, Scheme prints its name and arguments
  - Every time it exits, Scheme prints its return value
  - In DrScheme:
    - Put test expression at the end of your definitions `(primes-in-range 0 10)`
    - Add this code just before your test expression:

```
(require (lib "trace.ss"))
(trace primes-in-range prime? find-divisor)
```

    - Press Run

procedures you want to trace



Oops -- primes-in-range never checks min > max

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

- We need to compute other-primes **after** checking whether min > max

```
(define (primes-in-range min max)
 (if (> min max)
   '()
   (let ((other-primes (primes-in-range (+ 1 min) max)))
      (if (prime? min)
          (adjoin min other-primes)
          other-primes))))
```


Finding prime numbers in a range

```
(define (primes-in-range min max)
 (if (> min max)
   '()
   (let ((other-primes (primes-in-range (+ 1 min) max)))
      (if (prime? min)
          (adjoin min other-primes)
          other-primes))))
```

- **OK, now let's test it again:**

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

hmm... let's look at 0 and 1 first

We lost track of our 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))
```

- `prime?` only works on a restricted domain (n ≥ 2)
  - So we shouldn't have even called it on 0 or 1. (What about -1?)
  - We probably knew this when we were writing `prime?`, but by now we've forgotten
- All programs have hidden assumptions. Don't assume you'll remember them, or that another programmer will be able to guess them!
- At the very least, we should have written this assumption down in a comment:

```
(define (prime? n)
 ; n must be >= 2
 ...)
```


Documenting your code

- Documentation improves your code's **readability**, allows for **maintenance** (changing it later), and supports **reuse**
  - Can you read your code **a year** after writing it and still understand:
    - ... what inputs to give it?
    - ... what output it gives back?
    - ... what it's supposed to do?
    - ... why you made particular design decisions?
- How to document a procedure
  - Describe its inputs and output
  - Write down any assumptions about the inputs
  - Write down expected state of computation at key points in code
  - Write down reasons for tricky decisions

Documenting procedures

```
(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

- Useless comments just clutter the code

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

- Better: comment that says **why**, rather than just what

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

- Even better: readable code that makes the comment unnecessary

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


Wouldn't it be better to make no assumptions?

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

- One approach: check the assumptions and signal an error if they're violated (**assertion**)

```
(define (prime? n)
  ; Tests if n is prime (divisible only by 1 and itself)
  ; n must be >= 2
  ...
  (if (< n 2)
      (error "prime? requires n >= 2, given: " n)
      (find-divisor 2))
```


Wouldn't it be better to make no assumptions?

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

- Another approach: write a procedure whose value is correct for all inputs (a **total** function, rather than a partial function)

```
(define (prime? n)
  ; Tests if n is prime (divisible only by 1 and itself)
  ; By convention, 1 and 0 and negative integers are
  ; not prime.
  ...
  (if (< n 2)
      #f
      (find-divisor 2))
```

- In general, procedures that make fewer assumptions (and check them) are safer and easier to use

Did we really eliminate all the assumptions?

```
(define (prime? n)
   ...
   (if (< n 2)
       #f
       (find-divisor 2))

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

- Comparison is not defined for string & number: they are different **types**

Review: Types

- Remember (from last lecture) our taxonomy of expression types:
  - Simple data
    - Number
      - Integer
      - Real
      - Rational
    - String
    - Boolean
  - Compound data
    - Pair<A,B>
    - List<A>
  - Procedures
    - A,B,C,... → Z
- We use this only for notational purposes, to **document** and **reason about** our code. Scheme checks argument types for built-in procedures, but *not for user-defined procedures.*

Review: Types for compound data

- Pair<A,B>
  - A compound data structure formed by a cons pair, in which the first element is of type A, and the second of type B

    `(cons 1 2)` has type Pair<number, number>
- List<A> = Pair<A, List<A> or nil>
  - A compound data structure that is recursively defined as a pair, whose first element is of type A, and whose second element is either a list of type A or the empty list.

    `(list 1 2 3)` has type List<number>

    `(list 1 "2" 3)` has type List<number or string>

Review: Types for procedures

- We denote a procedure's type by indicating the types of each of its arguments, and the type of the returned value, plus the symbol → to indicate that the arguments are mapped to the return value
  - e.g. **number → number** specifies a procedure that takes a number as input, and returns a number as value

Examples

100	
#t	
(expt 2 5)	
expt	
(cons 2 5)	
cons	
(list "a" "b" "c")	
(cons "a" (cons "b" '()))	
(lambda (x) (* x x))	
(lambda (x) (if x 1 0))	

Types, precisely

- A type describes a **set** of Scheme **values**
  - `number → number` describes the set: all procedures, whose result is a number, that also require one argument that must be a number
- The type of a Scheme **expression** is the set of values that it might have
  - If the expression might have multiple types, you can either use a superset type, or simply **"or"** the types together

```
(if p 5 2.3)       ; number
(if p 5 "hello")   ; integer or string
```

- Scheme expressions that do not have a value (like **`define`**) **have no type**

Types as contracts

```
(+ 5 10) => 15
(+ "5" 10)
```

+: expects type <number> as 1st argument, given: "5"

- The type of + is $\underbrace{\texttt{number, number}}_{\text{two arguments, both numbers}} \rightarrow \underbrace{\texttt{number}}_{\text{result value of + is a number}}$
- The type of a procedure is a **contract**:
  - If the operands have the specified types, the procedure will result in a value of the specified type
  - Otherwise, its behavior is **undefined**
    - Maybe an error, maybe random behavior

Using types in your program

- Include types in procedure comments
- (Possibly) check types of arguments and return values to ensure that they match the type in the comment

```
(define (prime? n)
  ; Tests if n is prime (divisible only by 1 and itself)
  ; Type: integer → boolean
  ; n must be >= 2
  ...
  (if (and (integer? n) (>= n 2))
      (find-divisor 2)
      (error "prime? requires integer >= 2, given " n))
```


Summary: how to document procedures

- Write down the type of the procedure (which includes the types of the inputs and outputs)
- Describe the purpose of its inputs and outputs
- Write down any assumptions about the inputs as well
- Write down expected state of computation at key points in code
- Write down reasons for tricky decisions

Finding prime numbers in a range

```
(define (primes-in-range min max)
 (if (> min max)
   '()
   (let ((other-primes (primes-in-range (+ 1 min) max)))
      (if (prime? min)
          (adjoin min other-primes)
          other-primes))))

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

so what happened here?

we understand this now

Testing

- Write the test cases *first*
  - Helps you anticipate the tricky parts
  - Encourages you to write a general solution
- Test each part of your program individually before trying to build on it (**unit testing**)
  - We neglected to do this with **`prime?`**
  - We built **`primes-in-range`** on top of it without testing **`prime?`** carefully

Choosing Good Test Cases

- Pick a few obvious values
  - `(prime? 47) => #t`
  - `(prime? 20) => #f`
- Pick values at limits of legal range
  - `(prime? 2) => #t`
  - `(prime? 1) => #f`
  - `(prime? 0) => #f`

Choosing Good Test Cases

- Pick values that trigger base cases and recursive cases of recursive procedure
  - **`(fib 0)`** ; base case
  - **`(fib 1)`** ; base case
  - **`(fib 2)`** ; first recursive case
  - **`(fib 6)`** ; deep recursive case
- Pick values that span legal range
- Pick values that reflect different kinds of input
  - Odd versus even integers
  - Empty list, single element list, many element list

Choosing Good Test Cases

- Pick values that lie at boundaries **within** your code

```
(define (prime? n)
 ; tests if n is prime ...
 (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)))
```

- n=1 and n=2 are at the boundary of the `(< n 2)` test
- n=d^2 is at the boundary of the `(>= d (sqrt n))` test
  - `(prime? 4) => #t` ✗
  - `(prime? 9) => #t` ✗

Regression Testing

- **Keep your test cases in your code**
- Whenever you find a bug, add a test case that exposes the bug
  `(prime? 4)`
- Whenever you change your code, run all your old test cases to make sure they still work (the code hasn't **regressed**, i.e. reintroduced an old bug)
- **Automated** (self-checking) test cases help a lot here:

```
(define (assert test-succeeded message)
  ; signal an error if and only if a test case fails.
  ; Type: boolean,string -> void
  (if (not test-succeeded) (error message)))
(assert (prime? 4) "4 failed")
(assert (not (prime? 7)) "7 failed")
(assert (not (prime? 0)) "0 failed")
```

- If your regression test cases are simply included in your code, then pressing Run will run them all automatically
  - If some test cases are **very** slow, you can comment them out