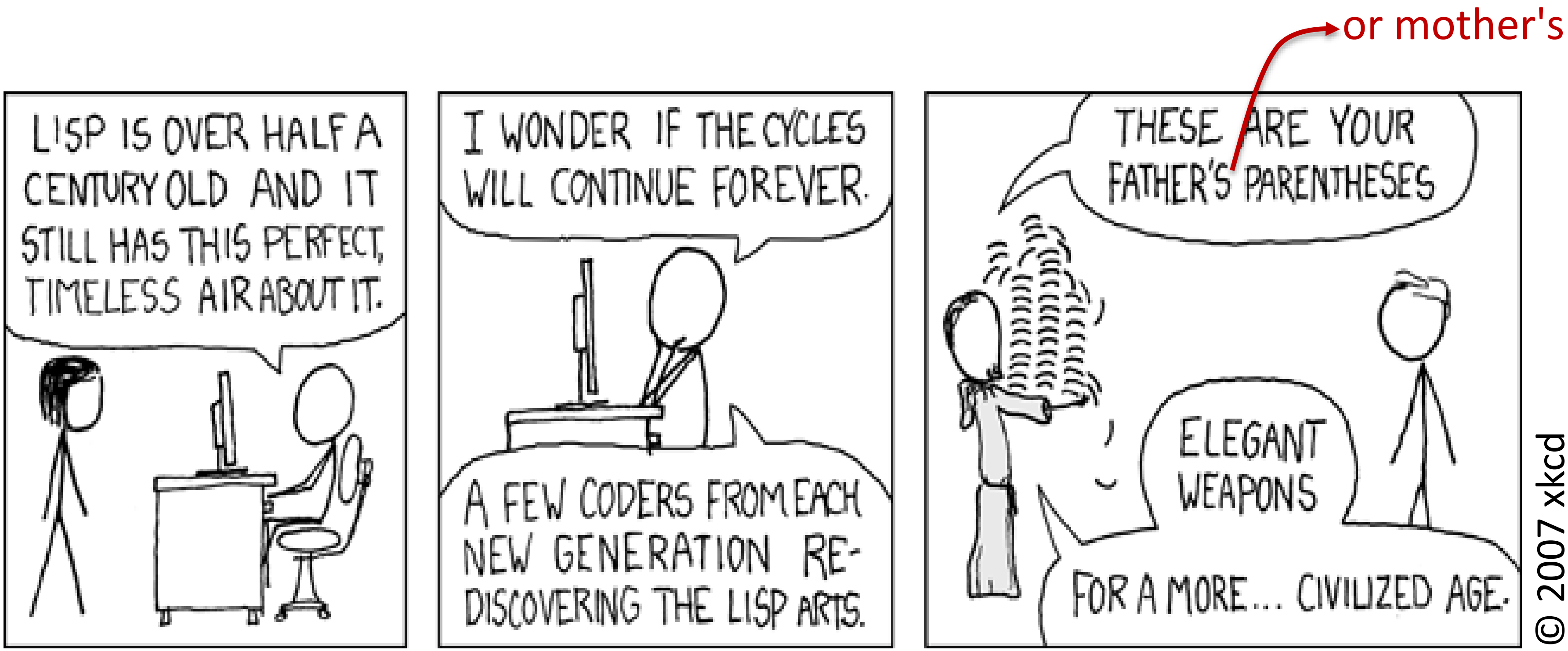


COS 326 Functional Programming: An elegant weapon for the modern age

Andrew Appel

Princeton University

Alonzo Church, 1903-1995
Princeton Professor, 1929-1967

In 1936, Alonzo Church invented the lambda calculus. He called it a logic, but it was a language of pure functions -- the world's first programming language.

He said:

"*There may, indeed, be other applications of the system than its use as a logic.*"

Alonzo Church, 1903-1995
Princeton Professor, 1929-1967

nted

Greatest technological understatement of the 20th century?

He said:

"*There may, indeed, be other applications of the system than its use as a logic.*"

A few designers of functional programming languages

Alonzo Church:
λ-calculus, 1934

John McCarthy
(PhD Princeton 1951)
LISP, 1958

Guy Steele & Gerry Sussman:
Scheme, 1975

A few designers of functional programming languages

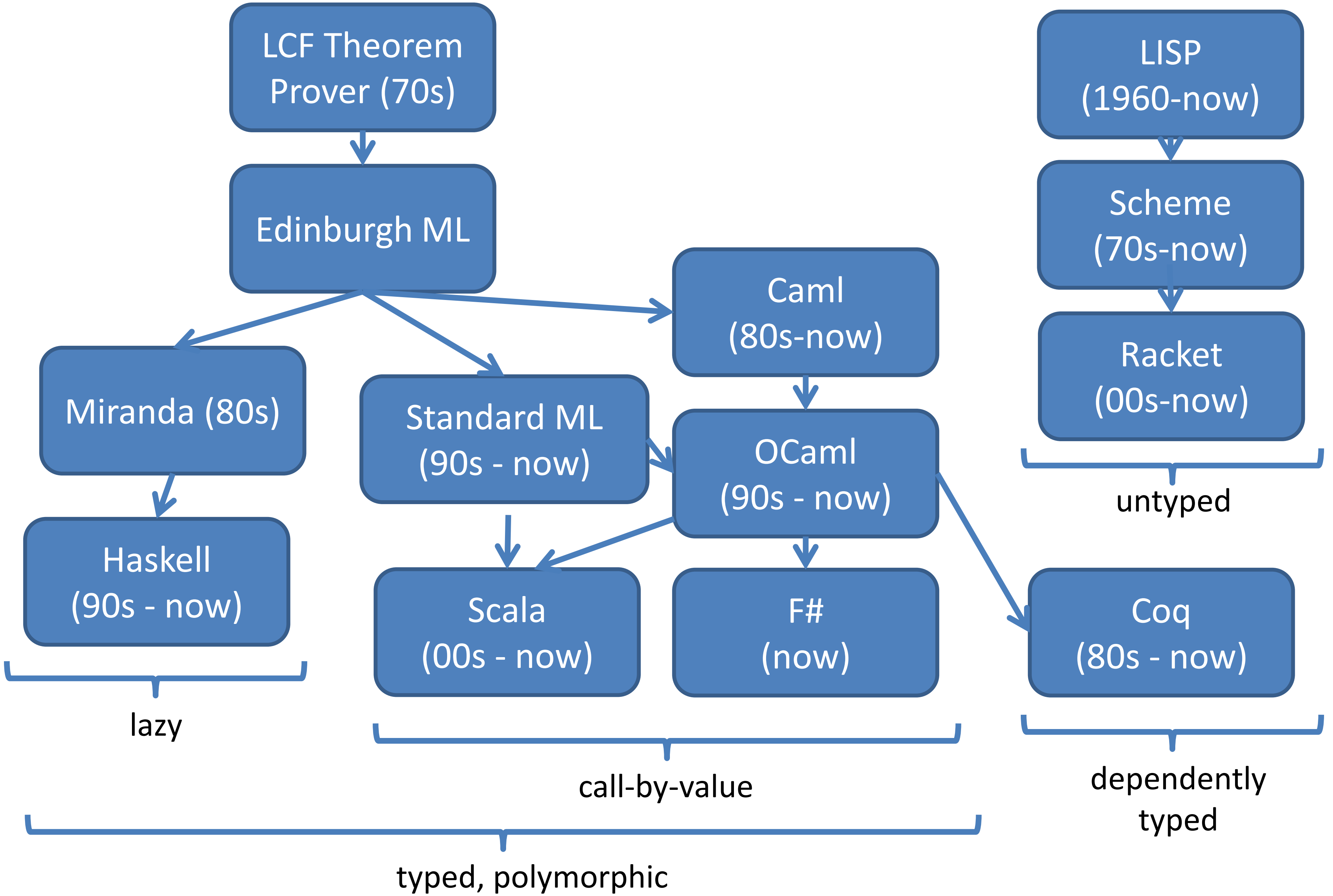
Alonzo Church:
λ-calculus, 1934

Robin Milner
ML, 1978

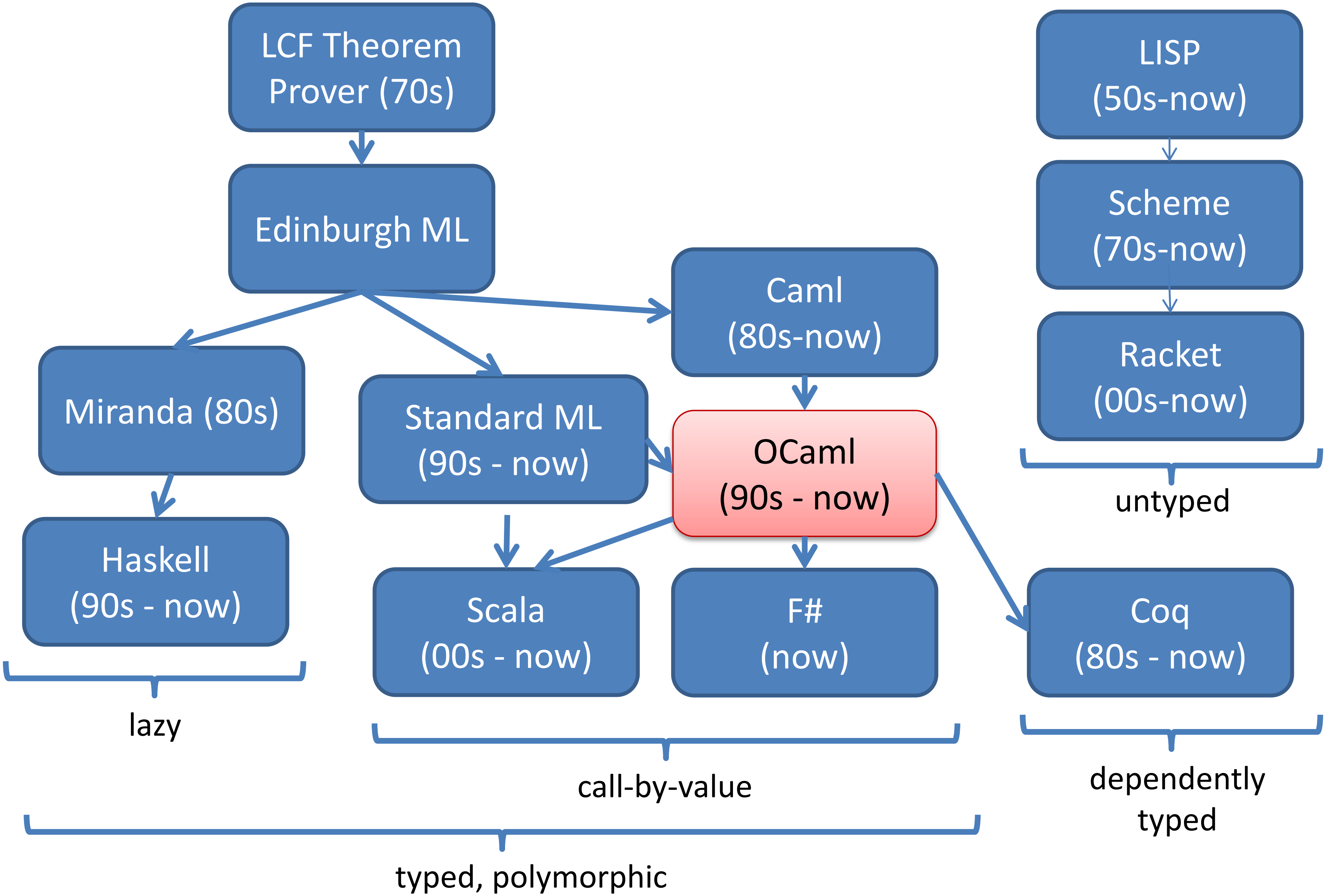
Appel & MacQueen: SML/NJ, 1988

Xavier Leroy: Ocaml, 1990’s

Vastly Abbreviated FP Genealogy



Vastly Abbreviated FP Geneology



Functional Languages: Who's using them?

map-reduce in their data centers → Google

Twitter ← Scala for correctness, maintainability, flexibility

Facebook ← Erlang for concurrency, Haskell for managing PHP, OCaml for bug-finding

Microsoft — Be what's next. ← F# in Visual Studio

mathematicians ← Coq (re)proof of 4-color theorem

bluespec ← Haskell to synthesize hardware

BARCLAYS ← Haskell for specifying equity derivatives

www.artima.com/scalazine/articles/twitter_on_scala.html
www.infoq.com/presentations/haskell-barclays
www.janestreet.com/technology/index.html#work-functionally
msdn.microsoft.com/en-us/fsharp/cc742182
research.google.com/archive/mapreduce-osdi04.pdf
www.lightbend.com/case-studies/how-apache-spark-scala-and-functional-programming-made-hard-problems-easy-at-barclays
www.haskell.org/haskellwiki/Haskell_in_industry

COURSE LOGISTICS

Course Staff

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email: appel@cs

Joomy Korkut
Preceptor
office: CS 214
email: joomy@cs

Resources

- coursehome:
  - http://www.cs.princeton.edu/~cos326
- Lecture schedule and readings:
  - $(coursehome)/lectures.php
- Assignments:
  - $(coursehome)/assignments.php
- Precepts
  - useful if you want to do well on exams and homeworks
- Install OCaml: $(coursehome)/resources.php

Collaboration Policy

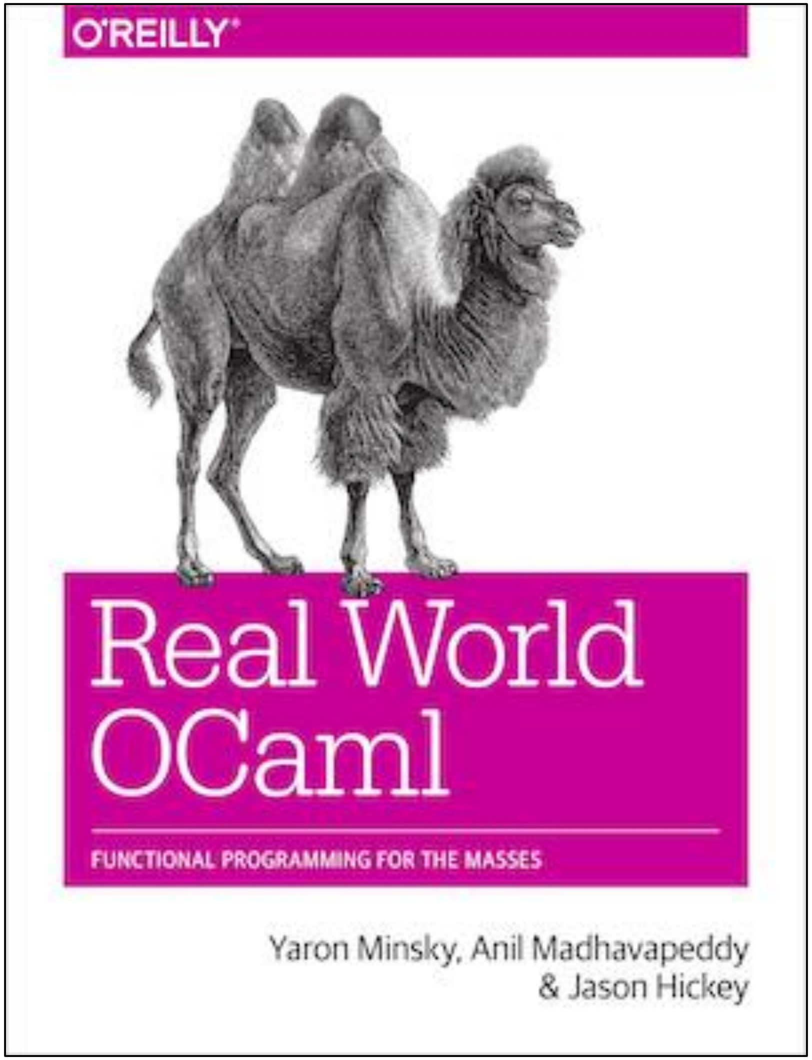
The COS 326 collaboration policy can be found here:

http://www.cs.princeton.edu/~cos326/info.php#collab

Read it in full prior to beginning the first assignment.

Please ask questions whenever anything is unclear, at any time during the course.

Course Textbook



http://realworldocaml.org/

Exams

Midterm

- take-home during midterm week

Final

- during exam period in January
- make your travel plans accordingly
- I have *no control at all* over when the exam occurs, the Registrar schedules exams.
- The final is ***not*** "cumulative" over the whole semester, it covers just "equational reasoning"

Assignment 0

Figure out how to download and install the latest version of OCaml
on your machine by the time precept begins tomorrow.
(or, how to use OCaml by ssh to Princeton University servers)

Resources Page:

http://www.cs.princeton.edu/~cos326/resources.php

Hint:

ocaml.org

Public Service Announcement

The Pen is Mighter than the Keyboard: Advantages of Longhand Over Laptop Note Taking

Pam Mueller (Princeton University)
Daniel Oppenheimer (UCLA)
Journal of Psychological Science, June 2014, vol 25, no 6

http://pss.sagepub.com/content/25/6/1159.fullkeytype=ref&siteid=sppss&ijkey=CjRAwmrlURGNw

https://www.scientificamerican.com/article/a-learning-secret-don-t-take-notes-with-a-laptop/

- You learn conceptual topics better by taking notes by hand.
  - We may need this experiment to be replicated a few more times to gain confidence in the result.
- Instagram and Fortnite distract your classmates.

A Functional Introduction

Thinking Functionally

In Java or C, you get (most) work done by *changing* something

```
temp = pair.x;
pair.x = pair.y;
pair.y = temp;
```

commands *modify* or *change* an existing data structure (like pair)

In ML, you get (most) work done by *producing something new*

```
let (x,y) = pair in
(y,x)
```

you *analyze* existing data (like pair) and you *produce* new data (y,x)

This simple switch in perspective can change the way you

think

about programming and problem solving.

Thinking Functionally

pure, functional code:

```
let (x,y) = pair in
(y,x)
```

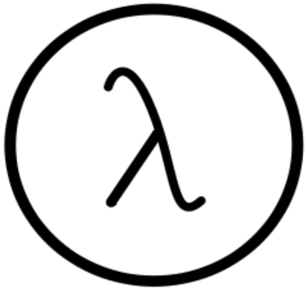
- *outputs are everything!*
- *output is function of input*
- *data properties are stable*
- *repeatable*
- *parallelism apparent*
- *easier to test*
- *easier to compose*

imperative code:

```
temp = pair.x;
pair.x = pair.y;
pair.y = temp;
```

- *outputs are irrelevant!*
- *output is not function of input*
- *data properties change*
- *unrepeatable*
- *parallelism hidden*
- *harder to test*
- *harder to compose*

Why OCaml?



Small, orthogonal core based on the *lambda calculus*.

- Control is based on (recursive) functions.
- Instead of for-loops, while-loops, do-loops, iterators, etc.
  - can be defined as library functions.
- Makes it easy to define semantics

Supports *first-class, lexically scoped, higher-order* procedures

- a.k.a. first-class functions or closures or lambdas.
- first-class: functions are data values like any other data value
  - like numbers, they can be stored, defined anonymously, ...
- lexically scoped: meaning of variables determined statically.
- higher-order: functions as arguments and results
  - programs passed to programs; generated from programs

These features also found in Scheme, Haskell, Scala, F#, Clojure, ...

Why OCaml?

Statically typed: debugging and testing aid

- compiler catches many silly errors before you can run the code.
  - A type is worth a thousand tests
- Java is also strongly, statically typed.
- Scheme, Python, Javascript, etc. are all strongly, *dynamically typed* – type errors are discovered while the code is running.

Strongly typed: compiler enforces type abstraction.

- cannot cast an integer to a record, function, string, etc.
  - so we can utilize *types as capabilities*; crucial for local reasoning
- C/C++ are *weakly typed* (statically typed) languages. The compiler will happily let you do something smart (*more often stupid*).

Type inference: compiler fills in types for you

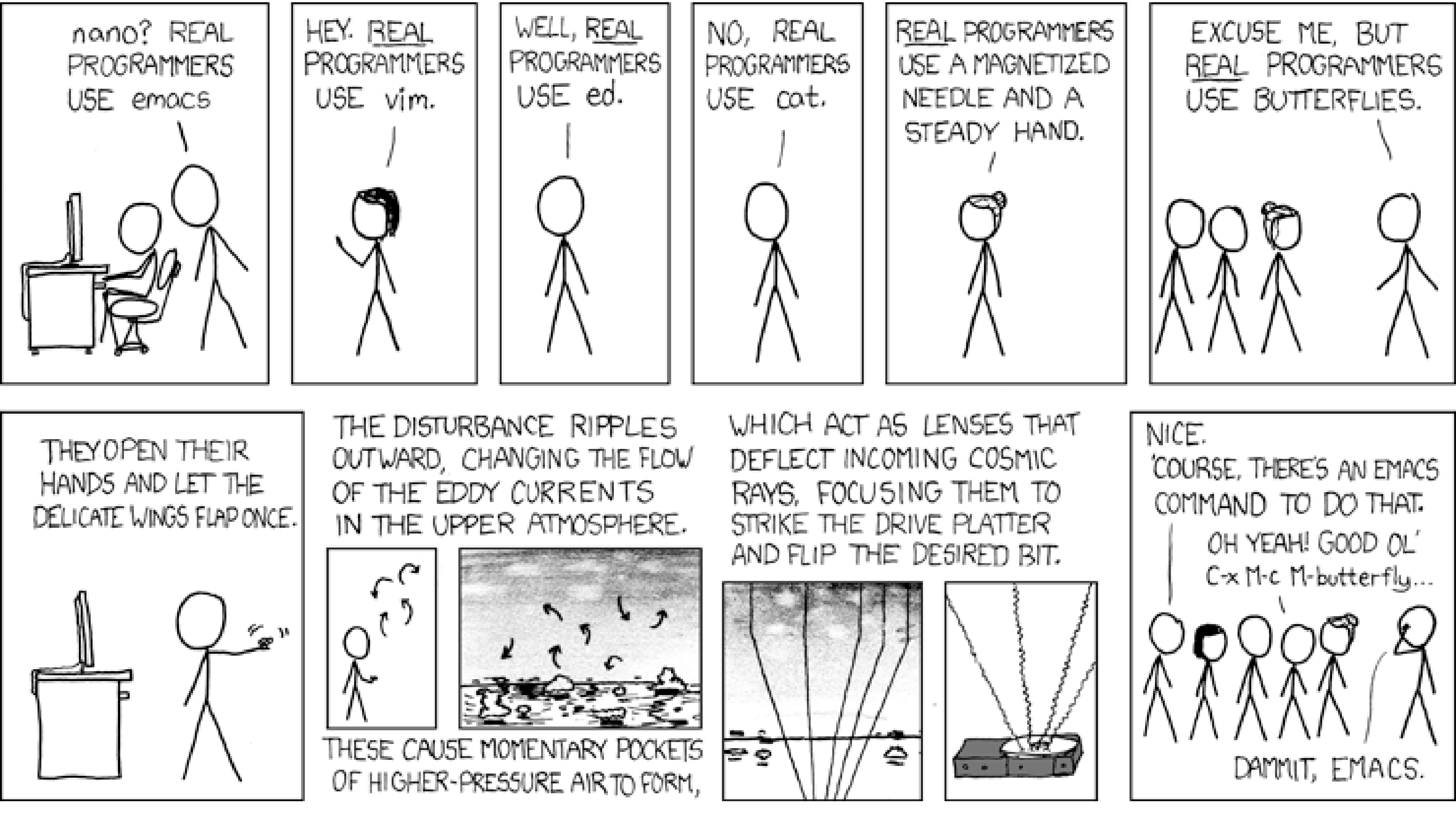
Installing, Running OCaml

- OCaml comes with compilers:
  - “ocamlc” – fast bytecode compiler
  - “ocamlopt” – optimizing, native code compiler
  - “ocamlbuild – a nice wrapper that computes dependencies
- And an interactive, top-level shell:
  - useful for trying something out.
  - “ocaml” at the prompt.
  - *but use the compiler most of the time*
- And many other tools
  - e.g., debugger, dependency generator, profiler, etc.
- See the course web pages for installation pointers
  - also OCaml.org

Editing OCaml Programs

- Many options: pick your own poison
  - Emacs
    - what I'll be using in class.
    - good but not great support for OCaml.
    - I like it because it's what I'm used to
    - (extensions written in elisp – a functional language!)
  - OCaml IDE
    - integrated development environment written in OCaml.
    - haven't used it, so can't comment.
  - Eclipse
    - I've put up a link to an OCaml plugin
    - I haven't tried it but others recommend it
  - Sublime, atom
    - A lot of students seem to gravitate to this

XKCD on Editors



AN INTRODUCTORY EXAMPLE (OR TWO)

OCaml Compiler and Interpreter

- Demo:
  - emacs
  - ml files
  - writing simple programs: hello.ml, sum.ml
  - simple debugging and unit tests
  - ocamlc compiler

A First OCaml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

A First OCaml Program

hello.ml:

```
print_string "Hello COS 326!!\n"
```

a function

its string argument enclosed in "..."

a program can be nothing more than just a single expression (but that is uncommon)

no parens. normally call a function f like this:

```
f arg
```

(parens are used for grouping, precedence only when necessary)

A First OCaml Program

hello.ml:

```
print_string "Hello COS 326!!\n"
```

compiling and running hello.ml:

```
$ ocamlbuild hello.d.byte
$ ./hello.d.byte
Hello COS 326!!
$
```

.d for debugging
(other choices .p for profiled; or none)

.byte for interpreted bytecode
(other choices .native for machine code)

A Second OCaml Program

a comment
(* ... *)

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

A Second OCaml Program

the name of the function being defined

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

the keyword “let” begins a definition; keyword “rec” indicates recursion

A Second OCaml Program

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

result type int

argument named n with type int

A Second OCaml Program

deconstruct the value n
using pattern matching

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

data to be deconstructed appears between key words “match” and “with”

A Second OCaml Program

vertical bar "|" separates the alternative patterns

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

deconstructed data matches one of 2 cases:
(i) the data matches the pattern 0, or (ii) the data matches the variable pattern n

A Second OCaml Program

Each branch of the match statement constructs a result

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

construct the result 0

construct a result using a recursive call to sumTo

A Second OCaml Program

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)

let _ =
  print_int (sumTo 8);
  print_newline()
```

print the result of calling sumTo on 8

print a new line

OCAML BASICS:
EXPRESSIONS, VALUES, SIMPLE TYPES

Terminology: Expressions, Values, Types

Expressions are computations

- 2 + 3 is a computation

Values (a subset of the expressions) are the results of computations

- 5 is a value

Types describe collections of values and the computations that generate those values

- int is a type
- values of type int include
  - 0, 1, 2, 3, …, max_int
  - -1, -2, …, min_int

Some simple types, values, expressions

<u>Type</u>:	<u>Values</u>:	<u>Expressions:</u>
`int`	`-2, 0, 42`	`42 * (13 + 1)`
`float`	`3.14, -1., 2e12`	`(3.14 +. 12.0) *. 10e6`
`char`	`'a', 'b', '&'`	`int_of_char 'a'`
`string`	`"moo", "cow"`	`"moo" ^ "cow"`
`bool`	`true, false`	`if true then 3 else 4`
`unit`	`()`	`print_int 3`

For more primitive types and functions over them, see the OCaml Reference Manual here:

http://caml.inria.fr/pub/docs/manual-ocaml/libref/Pervasives.html

Evaluation

```
42 * (13 + 1)
```

Evaluation

```
42 * (13 + 1) -->* 588
```

Read like this: "the expression 42 * (13 + 1) evaluates to the value 588"

The "*" is there to say that it does so in 0 or more small steps

Evaluation

```
42 * (13 + 1) -->* 588
```

Read like this: “the expression 42 * (13 + 1) evaluates to the value 588”

The “*” is there to say that it does so in 0 or more small steps

Here I’m telling you how to execute an OCaml expression --- ie, I’m telling you something about the *operational semantics* of OCaml

More on semantics later.

Evaluation

```
42 * (13 + 1)                    -->*   588

(3.14 +. 12.0) *. 10e6           -->*   151400000.

int_of_char 'a'                  -->*   97

"moo" ^ "cow"                    -->*   "moocow"

if true then 3 else 4            -->*   3

print_int 3                      -->*   ()
```

Evaluation

`1 + "hello"` -->* ???

Evaluation

`1 + "hello"` -->* ???

"+" processes integers
"hello" is not an integer
evaluation is undefined!

Don't worry! This expression doesn't type check.

Aside: See this talk on Javascript:
https://www.destroyallsoftware.com/talks/wat

OCAML BASICS:
CORE EXPRESSION SYNTAX

Core Expression Syntax

The simplest OCaml expressions e are:

- values — *numbers, strings, bools, ...*
- id — *variables (x, foo, ...)*
- e_1 op e_2 — *operators (x+3, ...)*
- id e_1 e_2 … e_n — *function call (foo 3 42)*
- **let** id = e_1 **in** e_2 — *local variable decl.*
- **if** e_1 **then** e_2 **else** e_3 — *a conditional*
- (e) — *a parenthesized expression*
- (e : t) — *an expression with its type*

A note on parentheses

In most languages, arguments are parenthesized & separated by commas:

```
f(x,y,z)      sum(3,4,5)
```

In OCaml, we don't write the parentheses or the commas:

```
f x y z       sum 3 4 5
```

But we do have to worry about *grouping*. For example,

```
f x y z
f x (y z)
```

The first one passes three arguments to f (x, y, and z)

The second passes two arguments to f (x, and the result of applying the function y to z.)

OCAML BASICS: TYPE CHECKING

Type Checking

Every value has a type and so does every expression

This is a concept that is familiar from Java but it becomes more important when programming in a functional language

We write (e : t) to say that *expression* e *has type* t. eg:

2 : int

"hello" : string

2 + 2 : int

"I say " ^ "hello" : string

Type Checking Rules

There are a set of simple rules that govern type checking

- programs that do not follow the rules will not type check and O'Caml will refuse to compile them for you (the nerve!)
- at first you may find this to be a pain …

But types are a great thing:

- help us *think* about *how to construct* our programs
- help us *find stupid programming errors*
- help us track down errors quickly when we *edit our code*
- allow us to *enforce powerful invariants* about data structures

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

(2) "abc" : string (and similarly for any other string constant "…")

Type Checking Rules

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(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

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then e1 * e2 : int

(5) if e1 : string and e2 : string
then e1 ^ e2 : string

(6) if e : int
then string_of_int e : string

Type Checking Rules

Example rules:

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then string_of_int e : string

Using the rules:

2 : int and 3 : int. (By rule 1)

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

(2) "abc" : string (and similarly for any other string constant "…")

(3) if e1 : int and e2 : int
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Using the rules:

2 : int and 3 : int. (By rule 1)
Therefore, (2 + 3) : int (By rule 3)

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

(2) "abc" : string (and similarly for any other string constant "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

(5) if e1 : string and e2 : string
then e1 ^ e2 : string

(6) if e : int
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Using the rules:

2 : int and 3 : int. (By rule 1)
Therefore, (2 + 3) : int (By rule 3)
5 : int (By rule 1)

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

(2) "abc" : string (and similarly for a... ")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(5) if e1 : string and e2 : string
then e1 ^ e2 : string

...tring_of_int e : string

FYI: This is a ***formal proof*** that the expression is well-typed!

Using the rules:

2 : int and 3 : int. (By rule 1)
Therefore, (2 + 3) : int (By rule 3)
5 : int (By rule 1)
Therefore, (2 + 3) * 5 : int (By rule 4 and our previous work)

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

(2) "abc" : string (and similarly for any other string constant "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

(5) if e1 : string and e2 : string
then e1 ^ e2 : string

(6) if e : int
then string_of_int e : string

Another perspective:

???? * ???? : int

rule (4) for typing expressions
says I can put any expression
with type int in place of the ????

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

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Another perspective:

7 * ???? : int

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Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

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then e1 ^ e2 : string

(6) if e : int
then string_of_int e : string

Another perspective:

7 * (add_one 17) : int

rule (4) for typing expressions
says I can put any expression
with type int in place of the ????

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
        Objective Caml Version 3.12.0
#
```

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
       Objective Caml Version 3.12.0
# 3 + 1;;
```

use ";;" to end a phrase in the top level

(";;" can also end a top-level phrase in a file, but I'm going to avoid using it there because then some of you will confuse it with a ";" ....)

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
        Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
#
```

press return and you find out the type and the value

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
# “hello ” ^ “world”;;
- : string = “hello world”
#
```

press return and you find out the type and the value

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
        Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
# "hello " ^ "world";;
- : string = "hello world"
# #quit;;
$
```

Type Checking Rules

Example rules:

(1) 0 : int (and similarly for any other integer constant n)

(2) "abc" : string (and similarly for any other string constant "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

(5) if e1 : string and e2 : string
then e1 ^ e2 : string

(6) if e : int
then string_of_int e : string

Violating the rules:

"hello" : string (By rule 2)
1 : int (By rule 1)
1 + "hello" : ?? (NO TYPE! Rule 3 does not apply!)

Type Checking Rules

Violating the rules:

```
# "hello" + 1;;
Error: This expression has type string but an
expression was expected of type int
```

The type error message tells you the type that was expected and the type that it inferred for your subexpression

By the way, this was one of the nonsensical expressions that did not evaluate to a value

It is a ***good thing*** that this expression does not type check!

"Well typed programs do not go wrong"

Robin Milner, 1978

Type Checking Rules

Violating the rules:

```
# "hello" + 1;;
Error: This expression has type string but an
expression was expected of type int
```

A possible fix:

```
# "hello" ^ (string_of_int 1);;
- : string = "hello1"
```

One of the keys to becoming a good ML programmer is to understand type error messages.

Type Checking Rules

What about this expression:

```
# 3 / 0 ;;
Exception: Division_by_zero.
```

Why doesn't the ML type checker do us the favor of telling us the expression will raise an exception?

Type Checking Rules

What about this expression:

```
# 3 / 0 ;;
Exception: Division_by_zero.
```

Why doesn't the ML type checker do us the favor of telling us the expression will raise an exception?

- In general, detecting a divide-by-zero error requires we know that the divisor evaluates to 0.
- In general, deciding whether the divisor evaluates to 0 requires solving the halting problem:

```
# 3 / (if turing_machine_halts m then 0 else 1);;
```

There are type systems that will rule out divide-by-zero errors, but they require programmers supply proofs to the type checker

Isn’t that cheating?

“Well typed programs do not go wrong”

Robin Milner, 1978

(3 / 0) is well typed. Does it “go wrong?” Answer: No.

“Go wrong” is a technical term meaning, “have no defined semantics.” Raising an exception is perfectly well defined semantics, which we can reason about, which we can handle in ML with an exception handler.

So, it’s not cheating.

(Discussion: why do we make this distinction, anyway?)

Type Soundness

"Well typed programs do not go wrong"

Programming languages with this property have *sound* type systems. They are called *safe* languages.

Safe languages are generally *immune* to buffer overrun vulnerabilities, uninitialized pointer vulnerabilities, etc., etc. (but not immune to all bugs!)

Safe languages: ML, Java, Python, …

Unsafe languages: C, C++, Pascal

Well typed programs do not go wrong

Robin Milner

Turing Award, 1991

"For three distinct and complete achievements:

1. LCF, the mechanization of Scott's Logic of Computable Functions, probably the first theoretically based yet practical tool for machine assisted proof construction;

2. ML, the first language to include polymorphic type inference together with a type-safe exception-handling mechanism;

3. CCS, a general theory of concurrency.

In addition, he formulated and strongly advanced full abstraction, the study of the relationship between operational and denotational semantics."

"Well typed programs do not go wrong"

Robin Milner, 1978

OVERALL SUMMARY:
A SHORT INTRODUCTION TO FUNCTIONAL PROGRAMMING

OCaml

OCaml is a *functional* programming language

- Java gets most work done by *modifying* data
- OCaml gets most work done by producing *new*, *immutable* data

OCaml is a *typed* programming language

- the *type* of an expression *correctly predicts* the kind of *value* the expression will generate when it is executed
- types help us *understand* and *write* our programs
- the type system is *sound*; the language is *safe*