CIS352 Course Wrapup

May 3, 2022

Projects

- Want to start by talking about project…
- Projects are the **core part** of the course
- Independent experience broadly related to the class
- Why do we do the projects?
    - Main goal: **require you to learn debugging**
    - The projects become conceptually nontrivial, and even the most experienced programmers will make mistakes
    - Understand how to make hypotheses about what may be buggy is crucial—I would like to do a better job of teaching this in subsequent (smaller) classes

Project Performance

- **Overall quite good project performance**
- About 85% of the class did P1
  - Almost everyone got ~100%
- About 85% of the class did P2
  - >75% of those got >85% (many >100)
- About 75% of the class did P3
  - 2/3 of those got >80%, rest got ~40-80
- About 70% of the class did P4
  - On average people did better than P3

Project Thoughts

- One was a warmup project with Racket / Autograder / …
  - Reiterating lessons of recursion, symbols, lists
- Two (PageRank) teaches three concepts:
  - Accumulating a hash—immutable maps are a key concept
- Three was a Scheme interpreter:
  - Functionally implement set! via “threading” store through recursive interpreter—this is an instance of the `State` monad (Haskell)
- Last, the Church encoder
  - Teaches concepts of compiler design: consume syntax as input, transform to new syntax to be executed as lambda calculus

Project Design Aspects

- Lots of the course was just **learning** Racket's mix of features
  - As a design feature of the course, this has upsides and downsides
- Projects get **harder** and **more open-ended** as they progress
  - Different students report different projects hardest
- I think the right order is:
  - P3 (hardest, coding-wise, lots of places to make mistakes)
  - P4 (easier coding, conceptually harder, *trickiest to debug*)
  - P1 (learning Racket is hard, can be tedious, fast-paced)
  - P2 (surprisingly, many find this easy once they understand folds)

http://coursefeedback.syr.edu/

Some Course Concepts

Program with **Expressions** rather than **Statements**

- One significantly underrated aspect of functional programming
- Which of the following looks better?

```
(define (foo x)
  (if x #t #f))

(define (foo x) x)
```

Why are we so tempted to write code that looks like the first?

(Potential) answer: common idiom from **statement-based** languages (Python/Java/…)—use sequence of `if`/`else`/`switch` to set a flag to return

Folds are specific kind of loop

- Folds are akin to a **for** loop that iterates over an **ordered sequence** and accumulates a value
  - Trivial extensions: iterate over a set (call set->list), accumulate a hash / pair / set of values

Every **fold** corresponds to a **for** loop and **tail-recursive** function

```
(define (rec-reverse l)
  (define (h l acc)
    (match l
      ['() acc]
      [`(,hd . ,tl) (h tl (cons hd acc))]))
  (h l '()))
```

Every **fold** corresponds to a **for** loop and **tail-recursive** function

```
(define (rec-reverse l)
  (define (h l acc)
    (match l
      ['() acc]
      [`(,hd . ,tl) (h tl (cons hd acc))]))
  (h l '()))
```

```
(define (fold-reverse l)
  (foldl (lambda (x acc) (cons x acc))
         '()
         l))
```

Every **fold** corresponds to a **for** loop and **tail-recursive** function

```
(define (for-reverse l)
  (define acc '())
  (for ([i l])
    (set! acc (cons i acc)))
  x)

;; (for-reverse '(1 2 3))
```

```
(define (rec-reverse l)
  (define (h l acc)
    (match l
      ['() acc]
      [`(,hd . ,tl) (h tl (cons hd acc))]))
  (h l '()))
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(define (fold-reverse l)
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```
(define (fold-reverse l)
  (foldl (lambda (x acc) (cons x acc))
         '()
         l))
```

Representing / Manipulating Syntax

- To define semantics / language features
- **Interpreters**—consume syntax and produce **values**
- **Compilers**—consume syntax and produce **programs**
  - Subsequently run via lower-level machine, preserve semantics

```
(define (scoped-λ-term? t ρ)
  (match t
    [(? symbol? x) (set-member? ρ x)]
    [`(,t0 ,t1)
     (and (scoped-λ-term? t0 ρ) (scoped-λ-term? t1 ρ))]
    [`(lambda (,(? symbol? xs) ...) ,e)
     (scoped-λ-term? e (set-union ρ (list->set xs)))]))

(scoped-λ-term? '(lambda (x) (x x)) (set))
(scoped-λ-term? '((lambda (x) (lambda (y) (y x)))
                  (lambda (z x y) (x y)))
                (set))
(scoped-λ-term? '((lambda (x) (lambda (y) (z x)))
                  (lambda (z x y) (x y)))
                (set))
```

Metacircular Interpreters (P3)

- Write an interpreter for a target language in a source language reusing features of source language
- Upside: expressive, succinct, straightforward to implement
- Downsides: (may be) slow if defining (meta) language is slow

Metacircular Interpreters (P3)

- Write an interpreter for a target language in a source language reusing features of source language
- Upside: expressive, succinct, straightforward to implement
- Downsides: (may be) slow if defining (meta) language is slow
- Most dynamic languages (Pearl, Ruby, Python, …) have relatively-fast interpreters that use high-performance native (C++/Rust/…) data structures but follow these same principles
- Compilation has mostly focused on lower-level memory-unsafe languages (C++) with the addition of compilation to bytecode (compile to IR; interpret IR w/ very-efficient interpreter)

```
;; A language with two extra ops: getstk
;; and printstk.
;; Assume ρ is Variable -> Value
;; Value ::=
;;    (closure ρ e)
;;    (stack e ...)
;; e is source expressions
;; e ::= x
;;     | (e e)
;;     | (lambda (x) e)
;;     | (getstk)
;;     | (printstk e)
;; stk ::= list of expressions (stack e)
```

```
(define (eval-λ+stack e ρ stk)
  (match e
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(getstk) `(stack ,stk)]
    [`(printstk ,e+)
     (define stk-v (eval-λ+stack e+ ρ (cons e stk)))
     (displayln "Captured stack:")
     (for ([expr stk-v])
       (pretty-print expr))]
    [`(,e0 ,e1)
     (define v-e0 (eval-λ+stack e0 ρ stk))
     (match v-e0
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (eval-λ+stack e1 ρ stk))
        (eval-λ+stack e-body (hash-set ρ+ x v-a) (cons e stk))]
       [_ (error (format "can't apply ~a" v-e0))])]))
```

Debugging

We want you to form hypotheses for broken code

"When I have a piece of broken code, how can I interact with it to test a hypothesis about what it is doing?"

Why is this hard? A: debugging difficulty / frustration is often related to the amount of time between experiments

May have to modify code multiple times, hence multiple interactions

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (- (bad-eval e0 ρ))]))
```

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (- (bad-eval e0 ρ))]))
```

```
(bad-eval '((lambda (x) (+ x 2)) (+ 1 2)) (hash))
;; 5
```

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (- (bad-eval e0 ρ))]))
```

Looks good; but crucially broken.

```
(bad-eval '((lambda (x) (+ x 2)) (+ 1 2)) (hash))
;; 5
```

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (- (bad-eval e0 ρ))]))
```

This must fail!

But how!?

How could this happen?

```
(bad-eval '((lambda (x) (+ (- x) 2)) (+ 1 2)) (hash))
;; hash-ref: no value found for key!
```

Now we look at the term and think: when does this case happen?

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (- (bad-eval e0 ρ))]))
```

Based on the fact **hash-ref** is in the **symbol** case, it must be **this subexpression**

```
(bad-eval '((lambda (x) (+ (- x) 2)) (+ 1 2)) (hash))
```

But why would this cause problems?

Now we ask: what is the right thing that should happen?

We think: "**it should be executing the - branch**."

To **test** this hypothesis we **edit** the code…

```
(define (bad-eval e ρ)
 (match e
   [(? number? n) n]
   [(? symbol? x) (hash-ref ρ x)]
   [`(lambda (,x) ,e-body)
    `(closure ,e ,ρ)]
   [`(,e0 ,e1)
    (match (bad-eval e0 ρ)
      [`(closure (lambda (,x) ,e-body) ,ρ+)
       (define v-a (bad-eval e1 ρ))
       (bad-eval e-body (hash-set ρ+ x v-a))])]
   [`(+ ,e0 ,e1)
    (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
   [`(- ,e0)
    (displayln "(evaluating (- …))")
    (- (bad-eval e0 ρ))]))
```

```
(bad-eval '((lambda (x) (+ (- x) 2)) (+ 1 2)) (hash))
```

Now we **run** the instrumented code with the **same** testcase

But we **never see our new code**

But how could *that* happen?

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (displayln "(evaluating (- …))")
     (- (bad-eval e0 ρ))]))
```

```
(bad-eval '((lambda (x) (+ (- x) 2)) (+ 1 2)) (hash))
```

Answer: our **match** statement is broken! Function application ***eagerly matches*** `(- x)`

Thus, - is looked up via the symbol case.. and crashes

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (displayln "(evaluating (- …))")
     (- (bad-eval e0 ρ))]))
```

```
(bad-eval '((lambda (x) (+ (- x) 2)) (+ 1 2)) (hash))
```

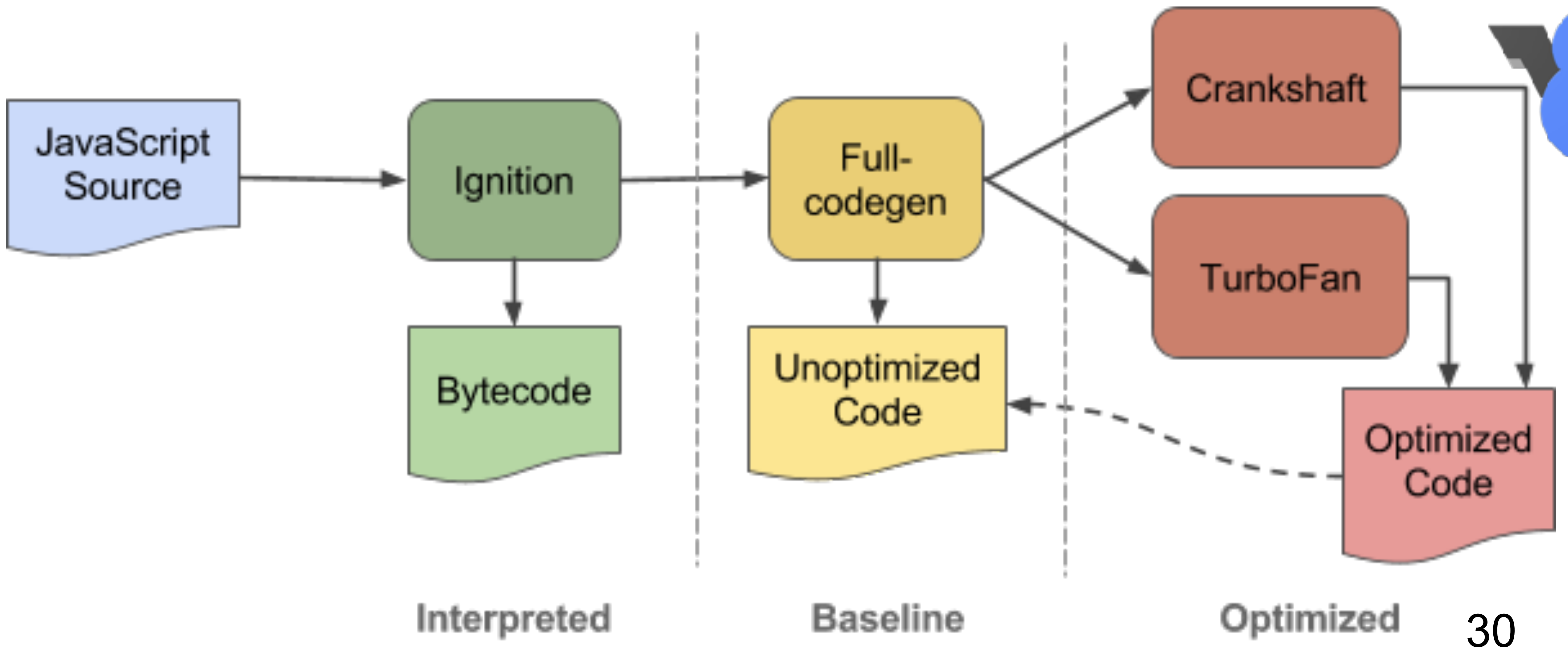
Fix: move our expression match case down, copy and pasting it

```
(define (bad-eval e ρ)
  (match e
    [(? number? n) n]
    [(? symbol? x) (hash-ref ρ x)]
    [`(lambda (,x) ,e-body)
     `(closure ,e ,ρ)]
    [`(+ ,e0 ,e1)
     (+ (bad-eval e0 ρ) (bad-eval e1 ρ))]
    [`(- ,e0)
     (- (bad-eval e0 ρ))]
    [`(,e0 ,e1)
     (match (bad-eval e0 ρ)
       [`(closure (lambda (,x) ,e-body) ,ρ+)
        (define v-a (bad-eval e1 ρ))
        (bad-eval e-body (hash-set ρ+ x v-a))])]))
```

```
(bad-eval '((lambda (x) (+ (- x) 2)) (+ 1 2)) (hash))
;; -1 🎉
```

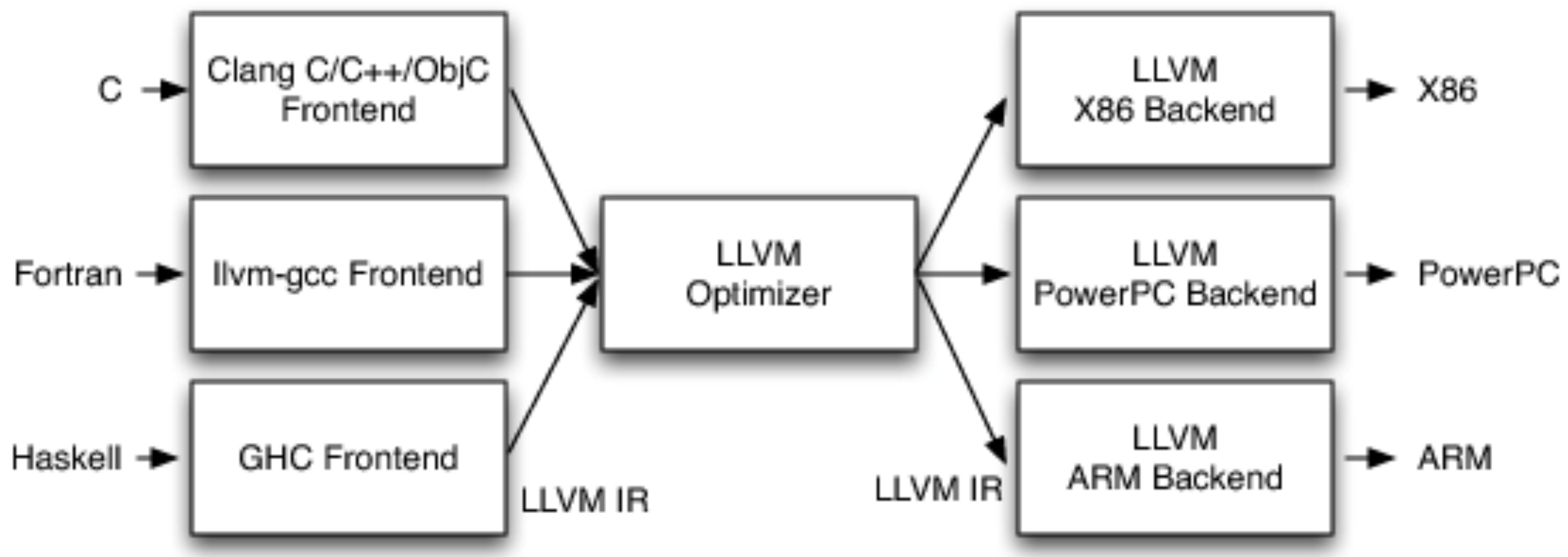
Compilers (P4)

- Traditionally, the C++-style compiler-engineering workforce was small
- As language technology evolves (Rust, WebAssembly, …), the language design landscape has become more granular
- Developers harness application-specific algorithmic and hardware features
  - Examples include GPGPU (General-Purpose GPU)



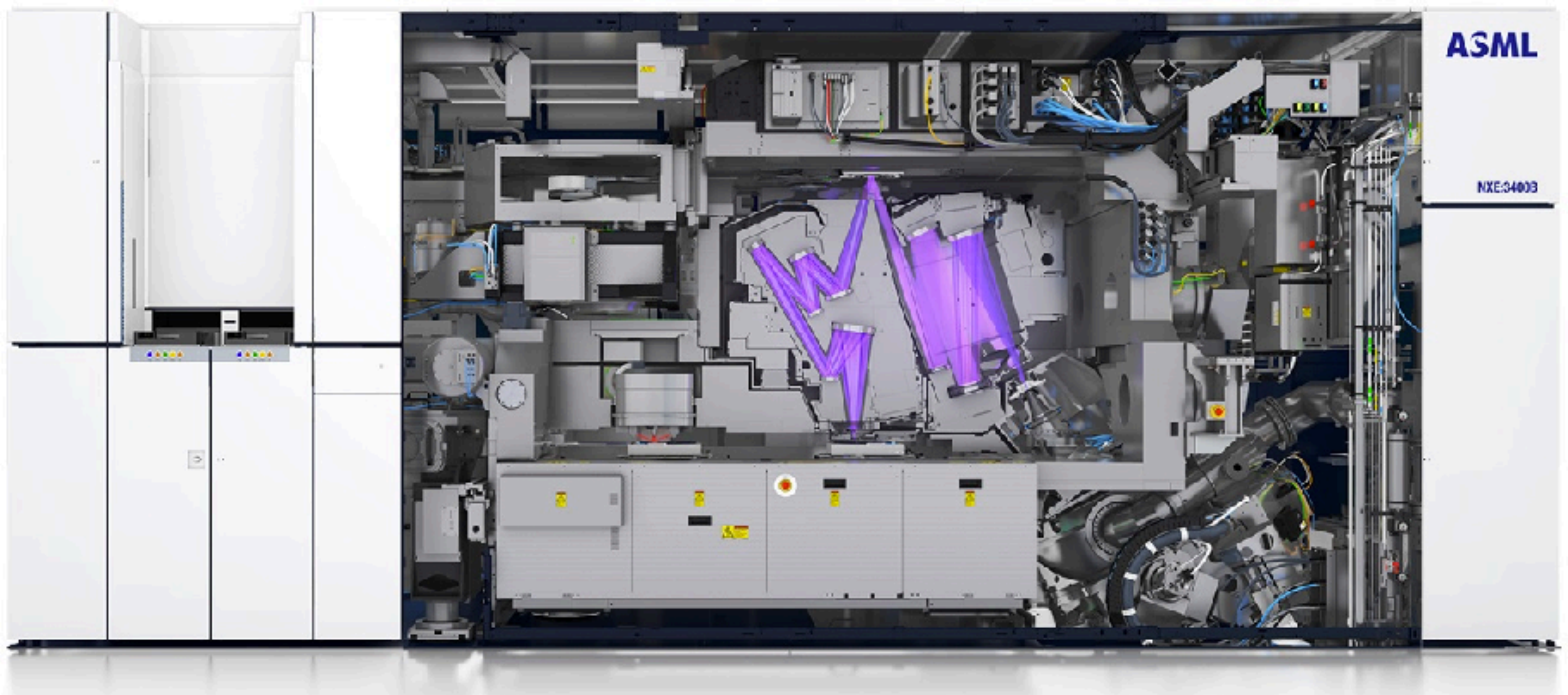
LLVM

- Compiler backend for C-like languages
  - If you run a Mac, this is your native build toolchain
  - Supersedes GCC in design methodology, robustness, & ease of extension
  - Common compiler target that abstracts around register allocation, etc…



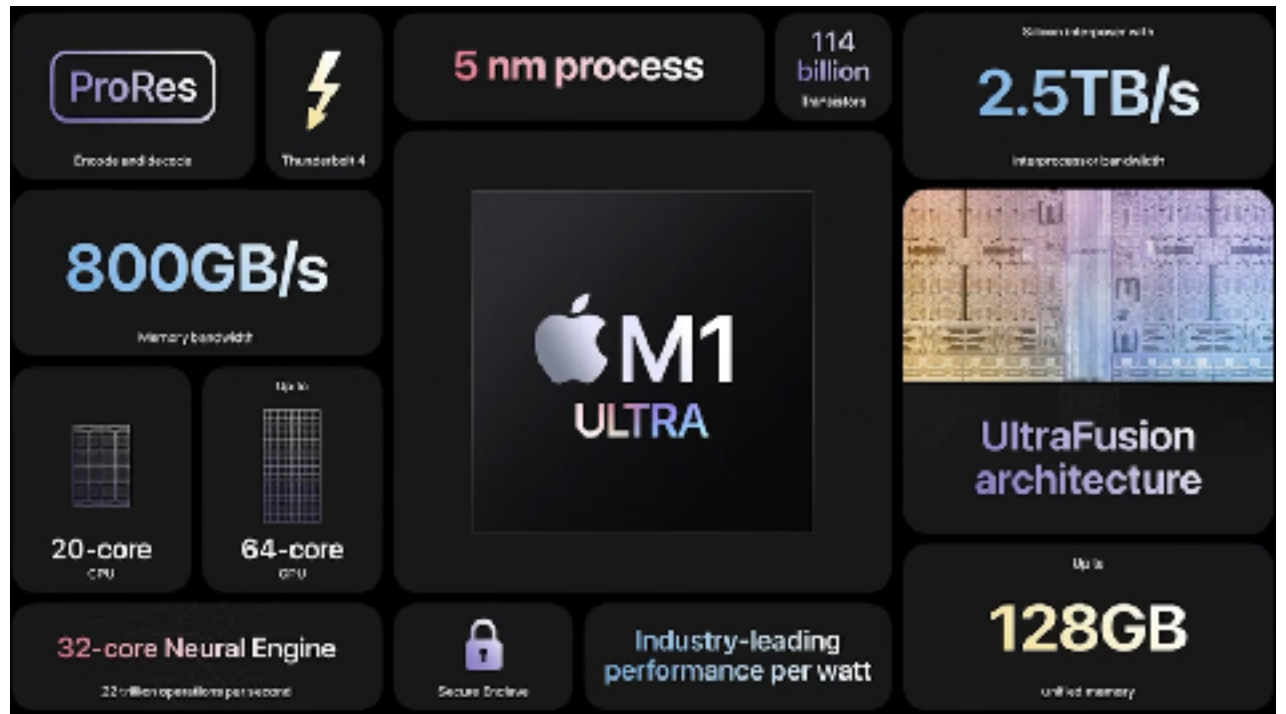
The future of Chips

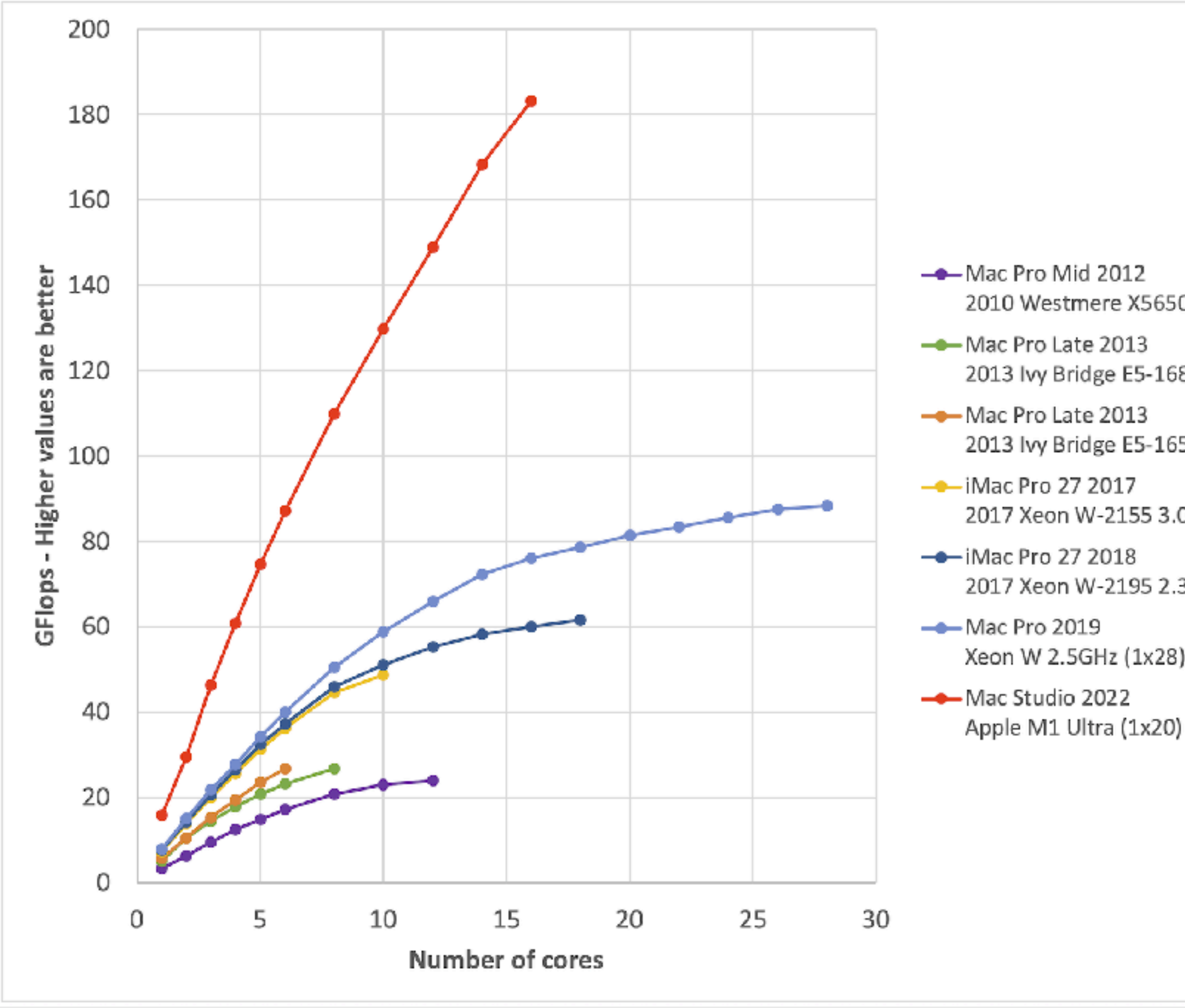
- All languages ultimately execute in native instruction set of some chip
- From 90s-2020: x86 (Pentium/Core iX/… chips), x86-64 (AMD64)
  - AMD chips currently offer leading core-density via manufacture at TSMC
- TSMC able to print chips at densest scale due to its use of ASML's Extreme UltraViolet (EUV) photolithography



M1 Ultra (Apple)

- Apple has designed world-class chips since their experience w/ iPhone
- Built on ARM, RISC assembly, much simpler than X86-64 (TSMC)
- Instruction decoding much cheaper
- Modern system-on-chips (M1 Ultra) integrate CPU+GPU to achieve awesome speeds
- Application-specific instructions + toolchain integration (supports emulation)





http://hrtapps.com/blogs/20220427/

Languages Into the Future

- Fast, high-level abstractions
  - Highly-dynamic langs (Perl) intrinsically slow, good in-between spots (Rust)
  - Application-specific acceleration via GPUs/ISA/…
- Safety generally prevails once runtime overhead effectively mitigated
  - Garbage-collected langs: once GC fast enough
  - "Fancy types for memory" languages (Rust)—once community built / good compiler error msgs for type / borrow issues, etc…
- "Desktop OS" idea will become less dominant
  - Every app compiles its OS in, runs on a hypervisor situated on cloud/local server
  - Common components (libraries, runtime, GC) shared

Exams and Participation

- Quizzes can be stressful, but designed to be checkpoints to motivate you to study topics on a specific timeline
- Many students did corrections, almost all got 10/10
- Overall, most students averaging B to B- on exams
- Final will have 10 questions (like Q4)—up to 8 answers
  - **Monday, May 9, LSC 105 (normal room), 5:15 to 7:15 PM**
- Roughly half of students will get bump to + for participation, other half will see no change, very few will (possibly) get a -

Final Logistics

- Last call for **projects** is **May 8, 2022 @ 11:59PM**
- Consult grade calculator, may trade up to 15 points between categories
    - In practice, I may average (i.e., let you take as many points as useful) the two categories
- I will be flexible on grading in practice, but when bumping students up I will prefer those with higher project grades vs. exam grades
    - I may overlook late projects if they are otherwise correct
- I expect many As, many Bs, some Cs, and (possibly) a few <C-
- Great job in the course!