CS450
Structure of Higher Level Languages
Lecture 33: PhD in CS/Pattern matching
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Today we will learn...

- What is a PhD
- Research in the Software Verification Lab
- Learn about pattern matching
What is a Ph.D.?
What is a Ph.D.?

An academic degree where you must:

1. Master a subject completely
2. Advance the state of the art

- **Meaning:** Doctor of Philosophy
- **Importance:** The highest academic degree
- **Rarity:** Specialized workforce (4.5% of the population)
- **Prestige:** The title of Doctor

Source: [www.cs.purdue.edu/homes/dec/essay.phd.html](http://www.cs.purdue.edu/homes/dec/essay.phd.html)
Overview: What is a Ph.D.?

1. Why join graduate school?
2. Why not join graduate school?
3. Why a graduate degree in CS?
4. What is the structure of a PhD?
5. How do the a PhD effectively?
Why join graduate school?
Why join graduate school?

- **Intellectual curiosity:** the challenge of learning, the culture of seeking and *sharing* knowledge
- **Specialized degree:** after graduation you will be a better professional
- **Autonomy:** you want time to develop your own project
- **Better paying work prospects:** a graduate degree is a good investment

PhD degrees are generally fully-funded!
Why not join graduate school?

- **5-year investment:** You will not be paying tuition, grants and serving as a teaching assistant (TA) will pay you a stipend. However, this stipend is significantly lower than working in the industry!
- **Higher workload:** Graduate course are more rigorous than undergraduate courses. You will need to juggle TA with courses and research.
- **5-year commitment:** You will be working on the same subject for 5 years.
- **Autonomy required:** A PhD degree is not structured like a BSc. There is no exact formula for an effective PhD degree. More freedom, more responsibility.
- **Travelling required:** You will need to travel internationally.
- **Public speaking:** A crucial part of the PhD is public speaking.

I am using 5 years as an approximate duration to conclude a PhD degree.
Why join graduate school?

Average Salary (Degree in CS)

- BSc: $82,000/year
- MSc: $100,000/year
- PhD: $128,000/year

Source: Payscale.com, 2019
Why a graduate degree in CS?

Why a graduate degree in CS?

During your Ph.D. you must:

1. Master a subject completely
2. Advance the state of the art
The PhD degree

1. How to master a subject?

- Take **graduate courses**
- **Read** the literature: peer-reviewed scientific papers, books
- Attend **conferences**: meet top experts
- Attend **summer schools**: learn from world-class scholars
- Visit universities
- Do internships

What are peer-reviewed papers? Scientific articles are submitted to other scientists experts in the field, who attest the scientific accuracy of the article. Articles may also be presented in a conference.
The PhD degree

2. How to advance the state of the art?

Complete a PhD thesis manuscript

- **Novel:** the contribution must be completely new
- **Impact:** the contribution must have a useful impact to society

Skills

- explore, investigate, contemplate
- conceptualize, find issues, solve problems

You will be the *world expert* on a subject!
Let us say you are here

Source: matt.might.net/articles/phd-school-in-pictures/
Step 1: complete PhD courses (MSc)

Source: matt.might.net/articles/phd-school-in-pictures/
Step 2: master a subject completely

Source: matt.might.net/articles/phd-school-in-pictures/
Step 3: advance the state of the art

Source: matt.might.net/articles/phd-school-in-pictures/
Pursuing a Ph.D. effectively

A PhD adviser shall...

- **Advise the student.** Help find a thesis topic, teach how to do research, write papers, give talks, etc.
- **Protect the student.** Provide protection from and information about funding concerns.
- **Inform the student.** Proactively provide realistic, honest advice about post-Ph.D. career prospects.
- **Frame student’s work.** Provide early and clear guidance about the time frames and conditions for graduation.

A PhD student shall...

- **Get educated about career prospects post-PhD.**
- **Determine if these career prospects match your expectations.**
- **A PhD is not just research.** There is coursework, quals, and writing a thesis.
- **Work hard and maintain a rhythm.**
- **Follow the PhD program.** You are responsible for meeting the program’s deadlines and requirements.
Research in the Software Verification Lab
Software Verification Lab

We make your programs run right

- We study how systems work
- We describe what we learned mathematically
- We understand why systems fail
- **We build tools** that help programmers
Software Verification Lab

The big picture

- We care about High Performance Computing (the backbone of scientific advancement)
- We focus on large-scale scientific workloads
- Our research improves the quality assurance of scientific codes
Looking for collaborators

- Summer research projects
- PhD students

Check out the more than 40 software open source projects, written in Python, C++, Java, OCaml, Coq, Racket, ...
What you will learn...

Intersection between

- Software Engineering
- Logic

Things you may learn

- Functional programming
- Multithreading/parallel programming
- Developing Continuous Integration pipelines
- Using super computers (clusters in national labs with 1000s of cores)
- Implementing compilers/interpreters/debuggers
- Programming proofs & proof engineering
- Using SAT/SMT solvers & model checkers
Pattern matching
Pattern matching

Operation `match` can perform pattern matching on the given argument. Think of it as a `switch` statement on steroids.

Without

```
(define (r:eval-builtin sym)
  (cond [(equal? sym '+) +]
        [(equal? sym '* ) *]
        [(equal? sym '- ) -]
        [(equal? sym '/ ) /]
        [else #f]))
```

With `match`

```
(define (r:eval-builtin sym)
  (match sym
    ['+  +]
    ['*  *]
    ['-  -]
    ['/  /]
    [_  #f]))
```

The underscore operator `_` means any pattern.
No-match exception

Operation `match` raises an exception when no pattern is matched, unlike `cond` that returns `#<void>`.

```
(match 1
 [10 #t])  ; Expecting 10, but given 1, so no match
; match: no matching clause for 1 [,bt for context]
```
Matching lists

With cond

```
(define (factorial n)
  (cond [ (= n 0) 1]
        [else (* n (factorial (- n 1)))]))
```

With match
Matching lists

With cond

```
(define (factorial n)
  (cond [(= n 0) 1]
        [else (* n (factorial (- n 1)))])
```

With match

```
(define (factorial n)
  (match n
    [0 1]
    [- (* n (factorial (- n 1))))])
```
Introducing define/match

The define and match pattern is so common that there is a short-hand version. *Notice the parenthesis!*

With define/match

```scheme
(define/match (factorial n)
  [(0) 1]
  [(-) (* n (factorial (- n 1)))]
)
```

With match

```scheme
(define (factorial n)
  (match n
    [(0) 1]
    [(-) (* n (factorial (- n 1)))]
  )
)
```

With cond

```scheme
(define (factorial n)
  (cond [(= n 0) 1]
        [else (* n (factorial (- n 1)))]
  )
)
```
List patterns

Lists are so common that they deserve a special range of patterns

(define (f l)
  (match l
    [(list) #f] ; Matches the empty list
    [(list 1 2) #t] ; Matches a list with exactly 1 and 2
    [(list x y) (+ x y)] ; Matches a list with any two elements
    [(list h t ... t)]) ; Matches a nonempty list

(check-equal? (f (list)) ???)
(check-equal? (f (list 1)) ???)
(check-equal? (f (list 1 2)) ???)
(check-equal? (f (list 2 3)) ???)
List patterns

Lists are so common that they deserve a special range of patterns

```
(define (f l)
  (match l
    [(list) #f]
    [(list 1 2) #t]
    [(list x y) (+ x y)]
    [(list h t ...) t]))

(check-equal? (f (list)) #f)
(check-equal? (f (list 1) (list))
(check-equal? (f (list 1 2) '#t)
(check-equal? (f (list 2 3) (+ 2 3)))
```
Example `map`

With `cond`

```
(define (map f l)
  (cond [(empty? l) l]
        [else (cons (f (first l)) (map f (rest l)))]))
```

With `match`
Example map

With cond

```lisp
(define (map f l)
  (cond [(empty? l) l]
        [else (cons (f (first l)) (map f (rest l)))]))
```

With match

```lisp
(define (map f l)
  (match l
    [(list) l]
    [(list h t ...) (cons (f h) (map f t))]))
```
The #:when clause

With match

```
(define (member x l)
  (match l
    [((list) #f)
     [(list h _ ...) #:when (equal? x h) #t]
     [(list _ t ...) (member x t)])
)
```

With cond

```
(define (member x l)
  (cond
    [(empty? l) #f]
    [(equal? (first l) x) #t]
    [else (member x (rest l))])
)
```

- Use the #:match clause to add a condition to the pattern
struct patterns

| Match also supports structs |

```
(struct foo (bar baz))
(define (f x)
  (match x
    [(foo a b) (+ a b)])
(check-equal? (f (foo 1 2)) 3)
```
Exercise \texttt{r:eval-exp}

With \texttt{cond}

\begin{verbatim}
(define (r:eval-exp exp)
  (cond
    ;; 1. When evaluating a number, just return that number
    [(r:number? exp) (r:number-value exp)]
    ;; 2. When evaluating an arithmetic symbol, return the respective arithmetic function
    [(r:variable? exp) (r:eval-builtin (r:variable-name exp))]
    ;; 3. When evaluating a function call evaluate each expression and apply
    ;;    the first expression to remaining ones
    [(r:apply? exp)
      ((r:eval-exp (r:apply-func exp))
       (r:eval-exp (first (r:apply-args exp)))
       (r:eval-exp (second (r:apply-args exp))))]
    [else (error "Unknown expression:" exp)])
\end{verbatim}
Example \texttt{r:eval-exp}

\begin{verbatim}
(define/match (r:eval-exp exp)
  ; 1. When evaluating a number, just return that number
  [((r:number n)) n]
  ; 2. When evaluating an arithmetic symbol, return the respective arithmetic function
  [((r:variable x)) (r:eval-builtin x)]
  ; 3. When evaluating a function call evaluate each expression and apply
  ; the first expression to remaining ones
  [((r:apply ef (list ea1 ea2))) ((r:eval-exp ef) (r:eval-exp ea1) (r:eval-exp ea2))]
  [(_ (error "Unknown expression:" exp))]
\end{verbatim}

Formalism

\[ n \Downarrow n \quad x \Downarrow \text{builtin}(x) \]
\[ e_f \Downarrow v_f \quad e_{a_1} \Downarrow v_{a_1} \quad e_{a_2} \Downarrow v_{a_2} \quad v = v_f(v_{a_1}, v_{a_2}) \]
\[ (e_f e_{a_1} e_{a_2}) \Downarrow v \]
Pattern matching

Pros

- Write less code
- Better safety (some languages support exhaustive pattern matching)

Cons

- Exposes your data as public (more maintenance)
- Any changes to your data, breaks patterns that match that data (tighter coupling)
Implementing match
Implementing match for list

```
(define (list-match l on-empty on-cons)
  (cond
   [(empty? l) (on-empty)]
   [(list? l) (on-cons (first l) (rest l))]
   [else (error "Not a list!")]
   ))

(define (length l)
  (list-match l
    (lambda () 0)
    (lambda (_ t) (+ 1 (length t)))))
```
Racket’s `match` is not exhaustive; we do get a runtime error if no branch is met. But how can we know if we are writing all branches?

We can implement a function that works like match with fixed branches.

```scheme
(define (s:value? v)
  (or (s:number? v)
      (s:void? v)
      (s:closure? v)))
(struct s:void () #:transparent)
(struct s:number (value) #:transparent)
(struct s:closure (env decl) #:transparent)
```
Implementing match for sets of structs

```
(define (match-s:value v on-number on-void on-closure)
  (cond [(s:number? v) (on-number (s:number-value v))]
        [(s:void? v) (on-void)]
        [(s:closure? v) (on-closure (s:closure-env v) (s:closure-decl v))])))

; Example:
(define (value-to-id v)
  (match-s:value v
    (lambda (x) 'number)
    (lambda () 'void)
    (lambda (env decl) 'closure)))
```

**Pros**

- The user **must** provide the code for every case

**Cons**

- The order of the branches is not easy to remember
Introducing keyword arguments

We can prefix a function parameter with a `#:symbol` to declare that the order of the arguments does not matter, the name of the parameter does (known as the keyword in Racket).

```racket
(define (match-s:value v #:number on-number #:void on-void #:closure on-closure)
  (cond [(s:number? v) (on-number (s:number-value v))]
        [(s:void? v) (on-void)]
        [(s:closure? v) (on-closure (s:closure-env v) (s:closure-decl v))])))

; Example:
(define (value-to-id v)
  (match-s:value v
    #:void (lambda () 'void)
    #:number (lambda (x) 'number)
    #:closure (lambda (env decl) 'closure)))
```

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