TYPES OF PROGRAMMING LANGUAGES

PRINCIPLES OF PROGRAMMING LANGUAGES

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Dalhousie University

REASONS TO CHOOSE A PARTICULAR PROGRAMMING LANGUAGE

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- Easy to express complex ideas
- Easy to control exactly how the computation is carried out
- Rich set of data types
- Extensive (standard) library
- Active, friendly community
- Was used for this project before I joined
- Good compiler support
- Open-source

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- Corporate pressure

GENERAL PURPOSE VS SPECIAL PURPOSE

General-purpose programming language:

Special-purpose programming language:

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- Turing-complete

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C++

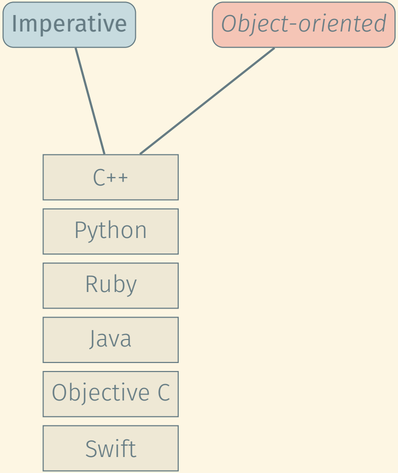
Python

Ruby

Java

Objective C

Swift


Imperative
Object-oriented
C++
Python
Ruby
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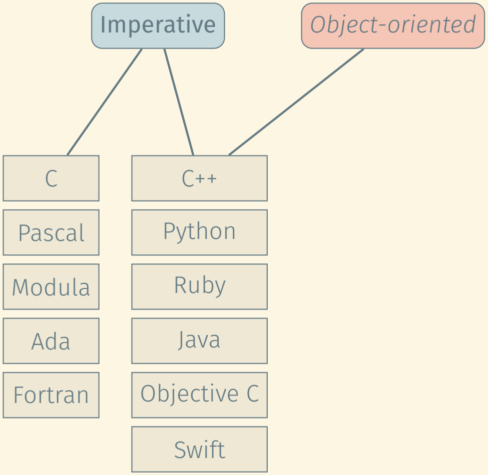

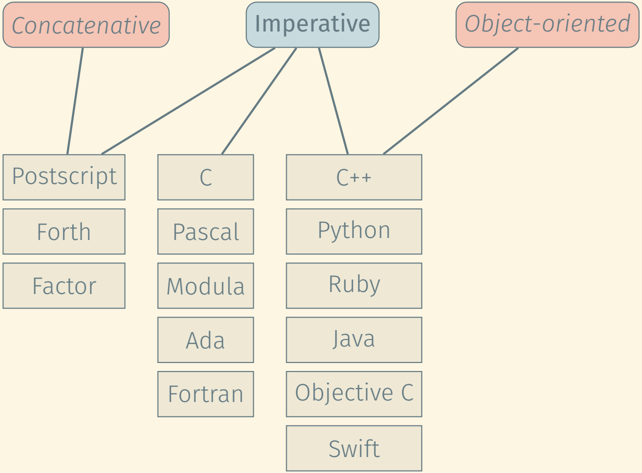
Concatenative
Imperative
Object-oriented
Postscript
Forth
Factor
C
Pascal
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Ruby
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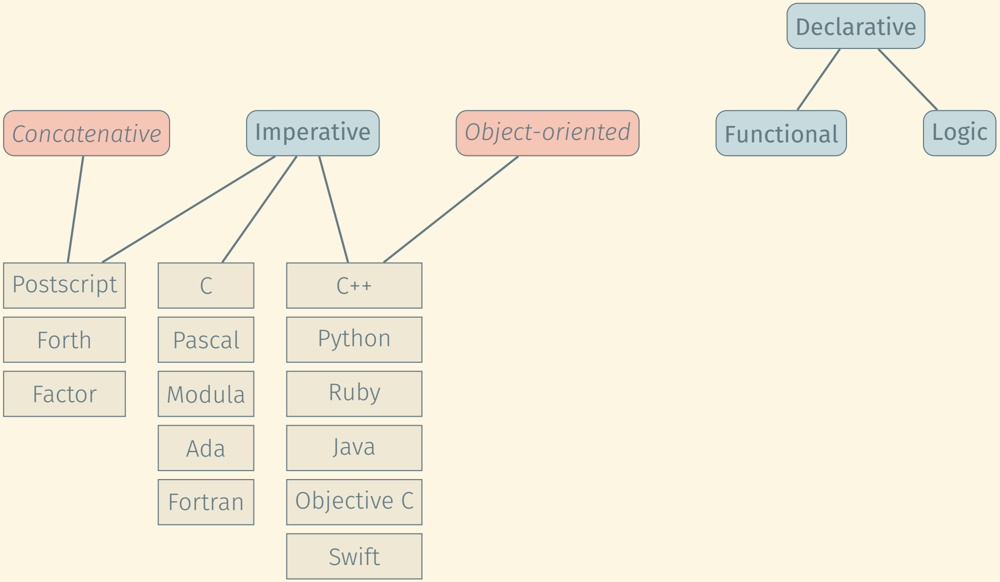

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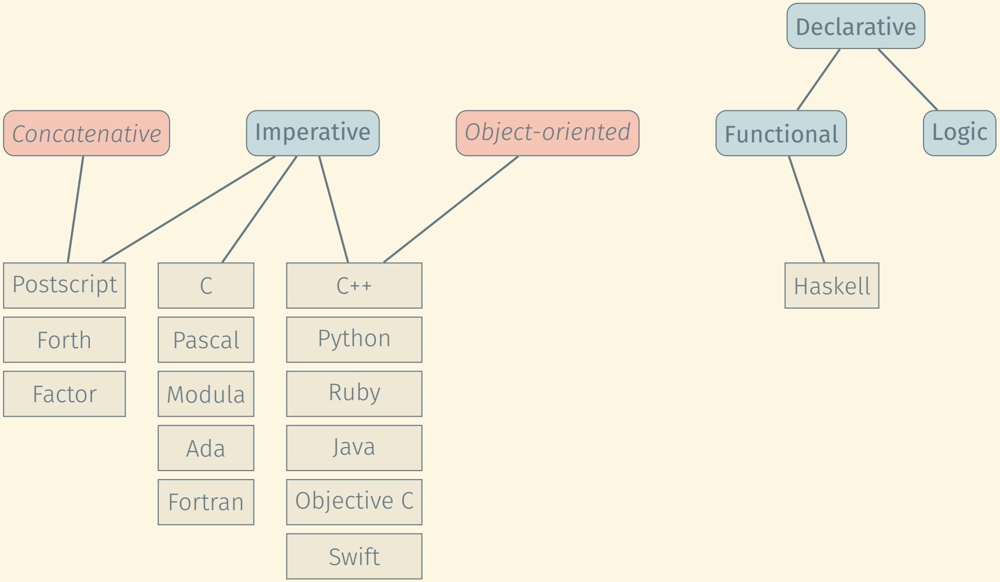

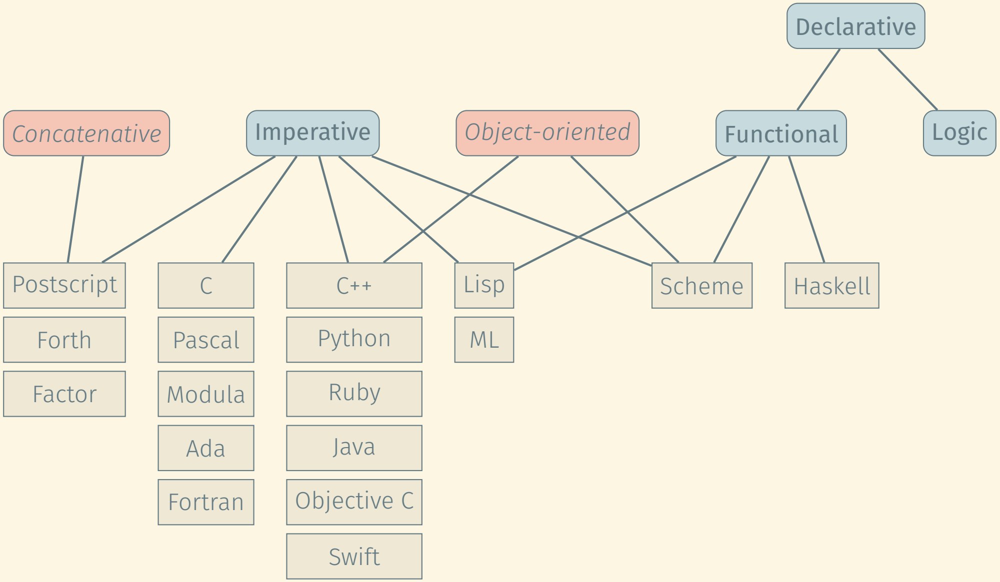
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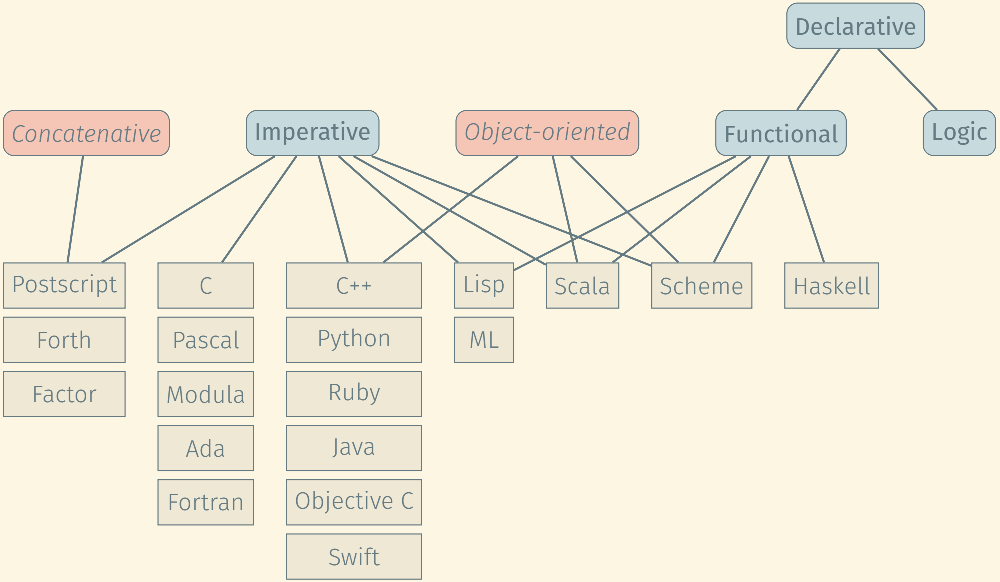

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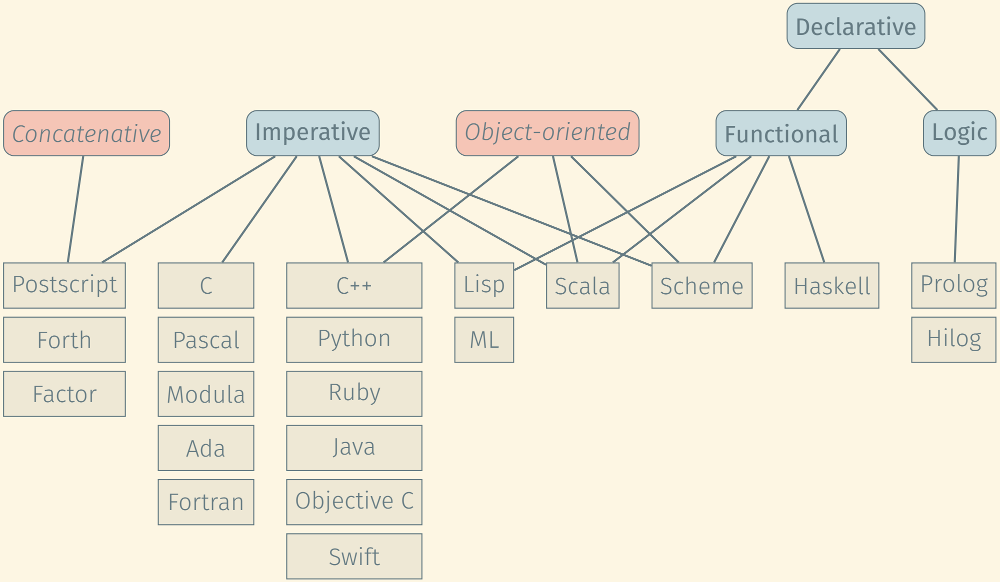

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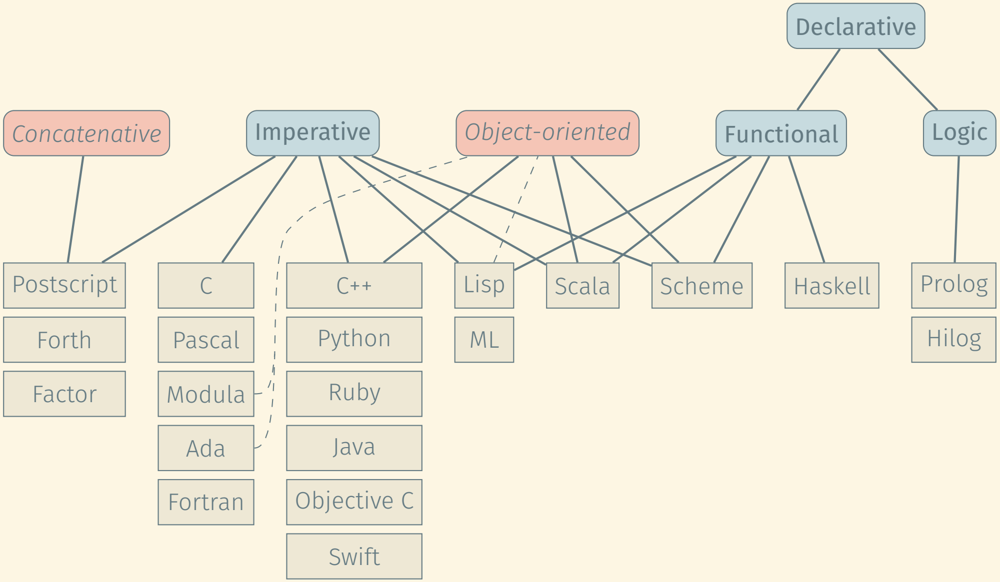

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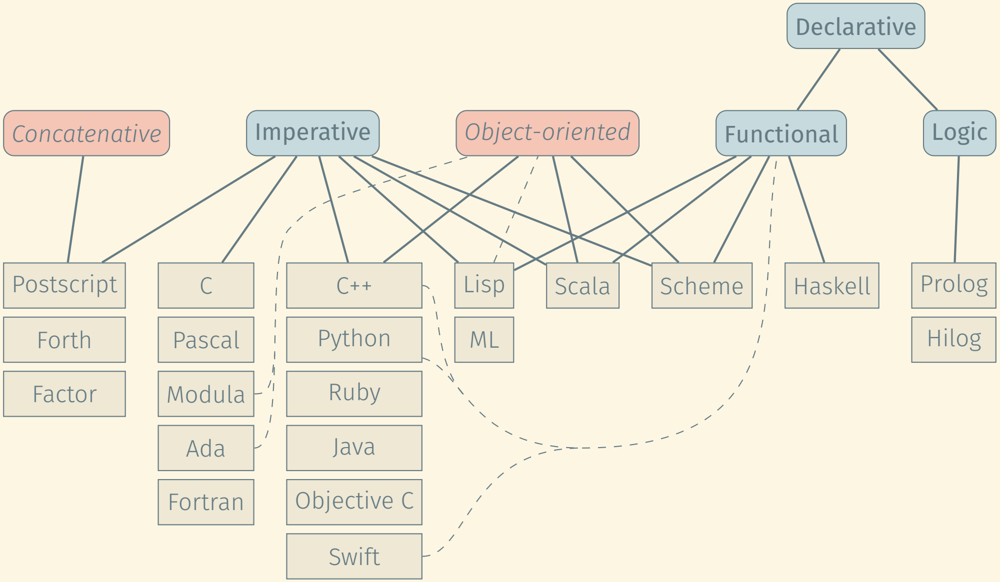

THE LANGUAGES I USE

Rust or C++

- When I need performance

C

- When I feel nostalgic

Haskell

- When I want to have fun and write elegant code that I trust

Prolog

- When I want to solve puzzles

Python

- When I need to write a prototype quickly

Scala

- When I'm told to use Java

Java

- Never

Scheme

- When I'd rather teach you Haskell

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- Focus on telling the computer exactly which steps to execute
- Close to the machine
- Difficult to analyze/ automatically optimize
- Functions called for
  - Return values
  - Side effects

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... are the only reason we compute at all:

- Taking input and communicating results requires side effects.

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Cons:

- Can be less efficient than well-designed imperative code
- Some imperative data structures are inherently more efficient than their purely functional counterparts

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- Database of facts, represented as logical predicates
- Rules for deducing new facts from known facts
- Execution driven by queries whether certain facts are true

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- In theory, no need to worry about execution details at all

Cons:

- In practice, need to understand execution details enough to
  - Avoid infinite loops in deduction
  - Obtain efficient programs

INTERMISSION: SCHEME AND PROLOG TUTORIALS

C++:

```
template <typename It>
void merge_sort(const It &begin, const It &end) {
  auto n = end - begin;
  if (n < 2)
    return;
  auto mid = begin + n / 2;
  merge_sort(begin, mid);
  merge_sort(mid, end);
  std::vector<std::iterator_traits<It>::value_type>
    left(begin, mid);
  std::vector<std::iterator_traits<It>::value_type>
    right(mid, end);
  merge(left, right, begin);
}
```

AN EXAMPLE WHERE FUNCTIONAL PROGRAMMING SHINES: MERGE SORT (2)

```
template <typename It>
void merge(
  const std::vector<std::iterator_traits<It>::value_type> &left,
  const std::vector<std::iterator_traits<It>::value_type> &right,
  It out) {
  auto l = left.begin(), r = right.begin();
  while (l != left.end() && r != right.end()) {
    if (*r < *l)
      *out++ = *r++;
    else
      *out++ = *l++;
  }
  while (l != left.end())
    *out++ = *l++;
  while (r != right.end())
    *out++ = *r++;
}
```

Haskell:

```
mergeSort :: Ord t => [t] -> [t]
mergeSort []  = []
mergeSort [x] = [x]
mergeSort xs  = merge (mergeSort ls) (mergeSort rs)
    where n        = length xs
          (ls, rs) = splitAt (n `div` 2) xs

merge :: Ord t => [t] -> [t] -> [t]
merge []         rs         = rs
merge ls         []         = ls
merge ls@(l:ls') rs@(r:rs') | r < l     = r : merge ls  rs'
                            | otherwise = l : merge ls' rs
```

AN EXAMPLE WHERE FUNCTIONAL PROGRAMMING SHINES: MERGE SORT (4)

Prolog:

```
list_sorted([], []).
list_sorted([X], [X]).
list_sorted(List, Sorted) :-
  list_left_right(List, Left, Right),
  list_sorted(Left, LeftSorted),
  list_sorted(Right, RightSorted),
  merged_left_right(Sorted, LeftSorted, RightSorted).

merged_left_right(Left, Left, []).
merged_left_right([R|Right], [], [R|Right]).
merged_left_right([L|Merged], [L|Left], [R|Right]) :-
  L #=< R, merged_left_right(Merged, Left, [R|Right]).
merged_left_right([R|Merged], [L|Left], [R|Right]) :-
  R #< L, merged_left_right(Merged, [L|Left], Right).
```

```
list_left_right(List, Left, Right) :-
  phrase(parse_half(List, Left), List, Right).

parse_half([], []) --> [].
parse_half([_], []) --> [].
parse_half([_,_|List], [L|Left]) --> [L], parse_half(List, Left).
```

Problem: *Build a permutation of the integers* $\{0, 1, \ldots, n-1\}$ *specified by indicating, for each element, after which element it is to be inserted.*

Example:

	1	2	3	4	5	6	
Input:	0	0	1	0	3	2	
Output:	0	4	2	6	1	3	5

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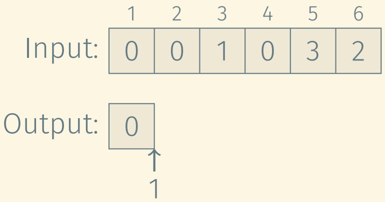

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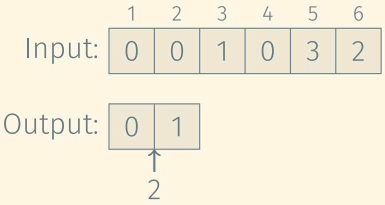

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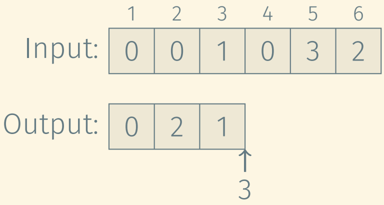

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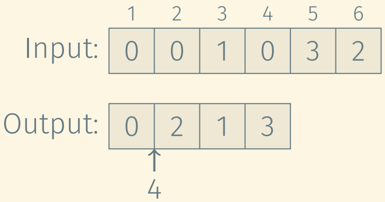

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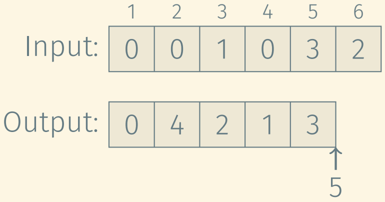

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std::vector<int> dynamic_permute(const std::vector<int> &refs) {
  int n = ref.size() + 1;
  std::list<int> seq;
  std::vector<std::list<int>::iterator> list_nodes(n);
  list_nodes[0] = seq.insert(seq.end(), 0);
  for (int i = 1; i < n; ++i)
    list_nodes[i] = seq.insert(next(list_nodes[ref[i]]), i);
  return std::vector<int>(seq.begin(), seq.end());
}
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  std::vector<std::list<int>::iterator> list_nodes(n);
  list_nodes[0] = seq.insert(seq.end(), 0);
  for (int i = 1; i < n; ++i)
    list_nodes[i] = seq.insert(next(list_nodes[ref[i]]), i);
  return std::vector<int>(seq.begin(), seq.end());
}
```

0

AN EXAMPLE WHERE IMPERATIVE PROGRAMMING SHINES: DYNAMIC DATA STRUCTURES (2)

C++: Linear time

```
std::vector<int> dynamic_permute(const std::vector<int> &refs) {
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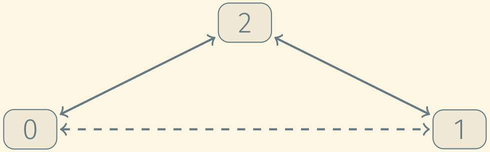

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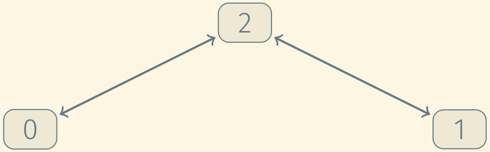

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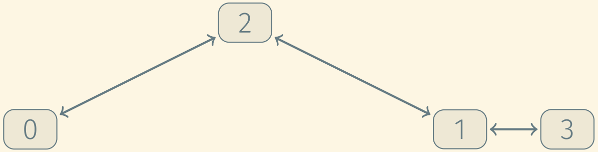

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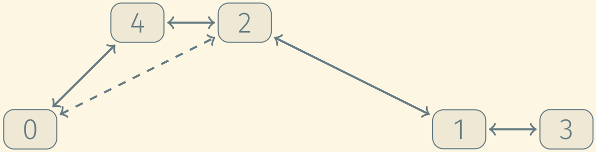

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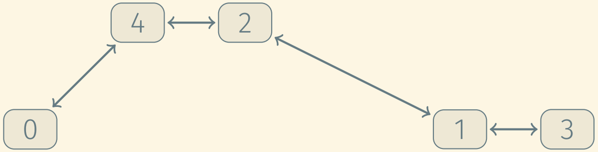

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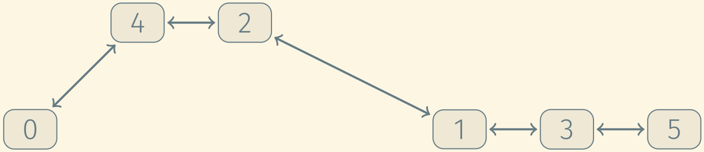

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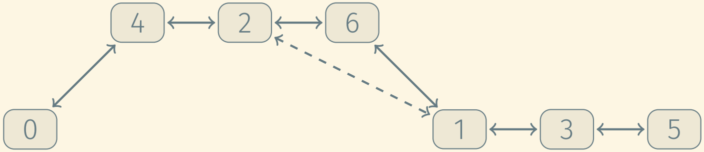

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}
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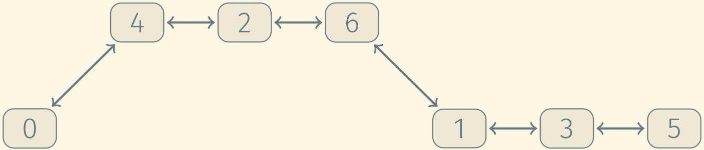

Doing this without mutation:

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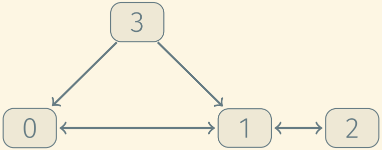
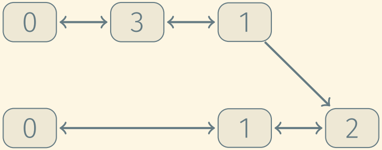


AN EXAMPLE WHERE IMPERATIVE PROGRAMMING SHINES: DYNAMIC DATA STRUCTURES (3)

Doing this without mutation:



AN EXAMPLE WHERE IMPERATIVE PROGRAMMING SHINES: DYNAMIC DATA STRUCTURES (3)

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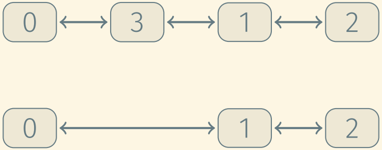

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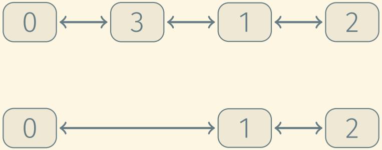
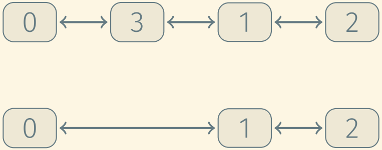


When “updating” any node in a functional data structure, all nodes with a path of pointers to it need to be replaced too.

AN EXAMPLE WHERE IMPERATIVE PROGRAMMING SHINES: DYNAMIC DATA STRUCTURES (3)

Doing this without mutation:



When "updating" any node in a functional data structure, all nodes with a path of pointers to it need to be replaced too.

This makes standard pointer-based data structures difficult/impossible to implement functionally.

WHAT ABOUT TRADITIONAL PERMUTING? (1)

Problem: *Given a list of elements, each annotated with its desired position in the output list, build an array storing each element in the desired position.*

Example:

Input:	(2, a)	(0, b)	(3, c)	(1, e)	(4, d)

Output:	b	e	a	c	d

WHAT ABOUT TRADITIONAL PERMUTING? (2)

C++:

```
template <typename T>
std::vector<T> permute(
  const std::vector<std::pair<int, T>> &input) {
  std::vector<T> output(input.size());
  for (auto &item : input)
    output[item.first] = item.second;
  return output;
}
```

C++:

```
template <typename T>
std::vector<T> permute(
  const std::vector<std::pair<int, T>> &input) {
  std::vector<T> output(input.size());
  for (auto &item : input)
    output[item.first] = item.second;
  return output;
}
```

Haskell:

```
permute :: [(Int, t)] -> [t]
permute xs = elems (array (0, len xs - 1) xs)
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (1)

4				2		6	1	
2	3		6		1	7		
	6	9	5			4		3
	9							4
	4	2				8	3	
8							9	
9		8			2	3	7	
		4	1		3		6	8
	1	6		7				2

4	8	7	3	2	9	6	1	5
2	3	5	6	4	1	7	8	9
1	6	9	5	8	7	4	2	3
6	9	1	7	3	8	2	5	4
5	4	2	9	1	6	8	3	7
8	7	3	2	5	4	1	9	6
9	5	8	4	6	2	3	7	1
7	2	4	1	9	3	5	6	8
3	1	6	8	7	5	9	4	2

Sudoku

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (2)

Prolog:

```
sudoku(Rows) :-
  transpose(Rows, Columns),
  rows_blocks(Rows, Blocks),
  append([Rows, Columns, Blocks], Sets),
  maplist(permutation([1, 2, 3, 4, 5, 6, 7, 8, 9]), Sets).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (2)

Prolog:

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sudoku(Rows) :-
  transpose(Rows, Columns),
  rows_blocks(Rows, Blocks),
  append([Rows, Columns, Blocks], Sets),
  maplist(permutation([1, 2, 3, 4, 5, 6, 7, 8, 9]), Sets).

rows_blocks([], []).
rows_blocks([R1,R2,R3|Rows], [B1,B2,B3|Blocks]) :-
  rows3_blocks3([R1,R2,R3], [B1,B2,B3]).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (2)

Prolog:

```
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  transpose(Rows, Columns),
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rows_blocks([R1,R2,R3|Rows], [B1,B2,B3|Blocks]) :-
  rows3_blocks3([R1,R2,R3], [B1,B2,B3]).

rows3_blocks3([[R11,R12,R13|R1], [R21,R22,R23|R2], [R31,R32,R33|R3]],
              [[R11,R12,R13,R21,R22,R23,R31,R32,R33|Bs]) :-
  rows3_blocks3([R1,R2,R3], Bs).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (2)

Prolog: Elegant but (ridiculously) slow

```
sudoku(Rows) :-
  transpose(Rows, Columns),
  rows_blocks(Rows, Blocks),
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rows3_blocks3([[R11,R12,R13|R1], [R21,R22,R23|R2], [R31,R32,R33|R3]],
              [[R11,R12,R13,R21,R22,R23,R31,R32,R33|Bs]) :-
  rows3_blocks3([R1,R2,R3], Bs).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (3)

Prolog: Elegant and fast

```
sudoku(Rows) :-
  transpose(Rows, Columns),
  append(Rows, Vs), Vs ins 1..9,
  maplist(all_distinct, Rows),
  maplist(all_distinct, Columns),
  Rows = [As,Bs,Cs,Ds,Es,Fs,Gs,Hs,Is],
  blocks(As,Bs,Cs), blocks(Ds,Es,Fs), blocks(Gs,Hs,Is),
  label(Vs).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (3)

Prolog: Elegant and fast

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sudoku(Rows) :-
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  blocks(As,Bs,Cs), blocks(Ds,Es,Fs), blocks(Gs,Hs,Is),
  label(Vs).
```

```
blocks([], [], []).
blocks([A1,A2,A3|As], [B1,B2,B3|Bs], [C1,C2,C3|Cs]) :-
  all_distinct([A1,A2,A3,B1,B2,B3,C1,C2,C3]), blocks(As,Bs,Cs).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (3)

Prolog: Elegant and fast

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sudoku(Rows) :-
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```

```
blocks([], [], []).
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  all_distinct([A1,A2,A3,B1,B2,B3,C1,C2,C3]), blocks(As,Bs,Cs).
```

What's different?

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (3)

Prolog: Elegant and fast

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sudoku(Rows) :-
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  label(Vs).

blocks([], [], []).
blocks([A1,A2,A3|As], [B1,B2,B3|Bs], [C1,C2,C3|Cs]) :-
  all_distinct([A1,A2,A3,B1,B2,B3,C1,C2,C3]), blocks(As,Bs,Cs).
```

What's different? This uses efficient constraint propagation.

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (4)

Prolog:

- 12 LOC
- Instantaneous answer
- SWI Prolog
  - Free, well maintained, feature-rich, ISO compliant
  - Much slower than SICSTUS Prolog (commercial)

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (4)

Prolog:

- 12 LOC
- Instantaneous answer
- SWI Prolog
  - Free, well maintained, feature-rich, ISO compliant
  - Much slower than SICSTUS Prolog (commercial)

Python:

- SAT solver (250 LOC)
- Encode puzzle as CNF (100 LOC)
- Instantaneous answer
- Could get faster if
  - Implemented in C++
  - Using state-of-the-art SAT solver

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (5)

	0			1				0					
1			0		1					1	1		
			0				1						
		1											
			0				0		1		1		1
				0							1		
1		1			1				1				
1		1					1					0	
				1			1						
						0				0	0		
		1	1							0	0		1
	0	0						0					
						1							1

⟶

1	0	0	1	1	0	1	1	0	1	0	0	1	0
1	1	0	0	1	1	0	0	1	0	1	1	0	0
0	1	1	0	0	1	0	1	1	0	0	1	0	1
0	0	1	1	0	0	1	0	0	1	1	0	1	1
1	0	0	1	1	0	0	1	1	0	1	0	1	0
0	1	1	0	0	1	0	0	1	1	0	1	0	1
0	1	0	1	0	0	1	1	0	0	1	1	0	1
1	0	1	0	1	1	0	0	1	1	0	0	1	0
1	0	1	1	0	0	1	1	0	0	1	1	0	0
0	1	0	0	1	0	1	1	0	0	1	1	0	1
1	1	0	0	1	1	0	0	1	1	0	0	1	0
0	0	1	1	0	1	0	0	1	1	0	0	1	1
1	0	0	1	1	0	1	1	0	0	1	1	0	0
0	1	1	0	0	1	1	0	0	1	0	0	1	1

Binary Puzzle

- No two identical rows/columns
- #0s = #1s in each row/column
- No three consecutive 0s or 1s in any row or column

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (6)

```
binary(Rows) :-
  append(Rows, Vs), Vs ins 0..1,
  transpose(Rows, Columns),
  maplist(no_triplets, Rows),
  maplist(no_triplets, Columns),
  maplist(zero_one_balance, Rows),
  maplist(zero_one_balance, Columns),
  phrase(pairs(Rows), Row_Pairs),
  phrase(pairs(Columns), Column_Pairs),
  maplist(not_same, Row_Pairs),
  maplist(not_same, Column_Pairs),
  label(Vs).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (6)

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  phrase(pairs(Columns), Column_Pairs),
  maplist(not_same, Row_Pairs),
  maplist(not_same, Column_Pairs),
  label(Vs).

no_triplets(List) :-
  length(List,L), L < 3.
no_triplets([A,B,C|List]) :-
  A+B+C #> 0, A+B+C #< 3,
  no_triplets([B,C|List]).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (6)

```
binary(Rows) :-
  append(Rows, Vs), Vs ins 0..1,
  transpose(Rows, Columns),
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```

```
zero_one_balance(List) :-
  length(List,L), Half is L // 2,
  sum(List, #= Half).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (6)

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binary(Rows) :-
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  maplist(zero_one_balance, Columns),
  phrase(pairs(Rows), Row_Pairs),
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```

```
zero_one_balance(List) :-
  length(List,L), Half is L // 2,
  sum(List, #= Half).

not_same((List1,List2) :-
  maplist(diff, List1, List2, Diffs),
  sum(Diffs, #>, 0).

diff(A, B, Diff) :-
  Diff #<==> A #\= B.
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (6)

```
binary(Rows) :-
  append(Rows, Vs), Vs ins 0..1,
  transpose(Rows, Columns),
  maplist(no_triplets, Rows),
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  label(Vs).

no_triplets(List) :-
  length(List,L), L < 3.
no_triplets([A,B,C|List]) :-
  A+B+C #> 0, A+B+C #< 3,
  no_triplets([B,C|List]).
```

```
zero_one_balance(List) :-
  length(List,L), Half is L // 2,
  sum(List, #= Half).

not_same((List1,List2) :-
  maplist(diff, List1, List2, Diffs),
  sum(Diffs, #>, 0).

diff(A, B, Diff) :-
  Diff #<==> A #\= B.

pairs([_]) --> [].
pairs([X|List]) -->
  pairs_(X, List), pairs(List).

pairs_(_, []) --> [].
pairs_(X, [Y|List]) -->
  [(X,Y)], pairs_(X,List).
```

AN EXAMPLE WHERE LOGIC PROGRAMMING SHINES: CONSTRAINT SATISFACTION (7)

Prolog:

- 31 LOC
- Around 7 secs to solve
- SWI Prolog
  - Free, well maintained, feature-rich, ISO compliant
  - Much slower than SICSTUS Prolog (commercial)

Python:

- SAT solver (250 LOC)
- Encode puzzle as CNF (150 LOC)
- Around 70 secs to solve
- Could get faster if
  - Implemented in C++
  - Using state-of-the-art SAT solver

EXPRESSIVENESS OF PROGRAMMING LANGUAGES

We want expressive programming languages that make programming easy:

- Concise
- Help to avoid common bugs
- Help to express exactly what we want

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Fine-grained control ⟷ High-level abstractions

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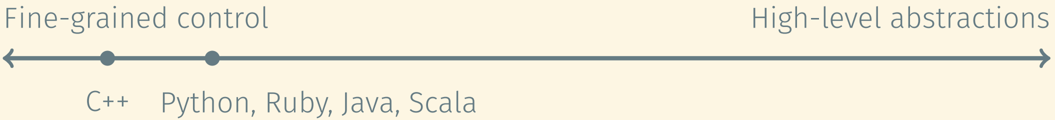

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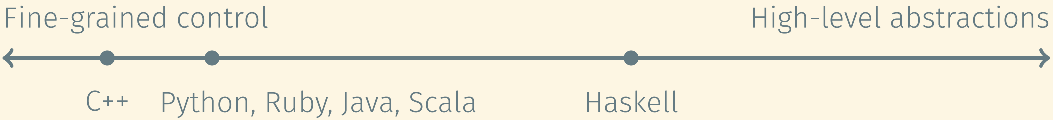

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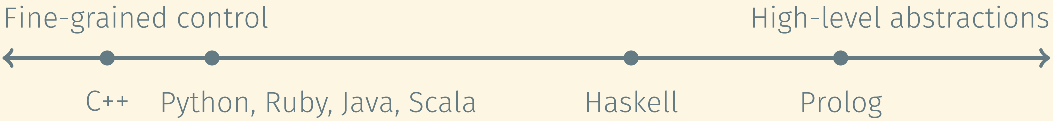

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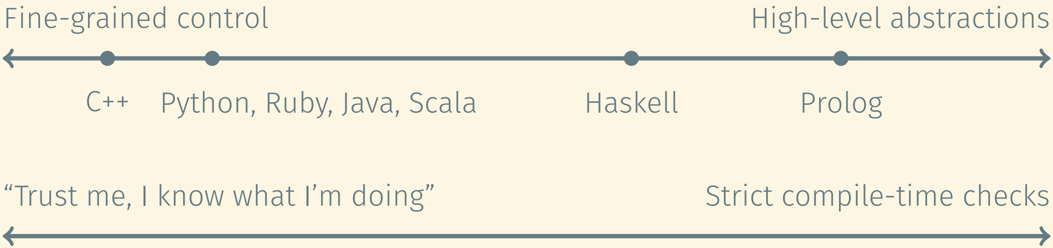

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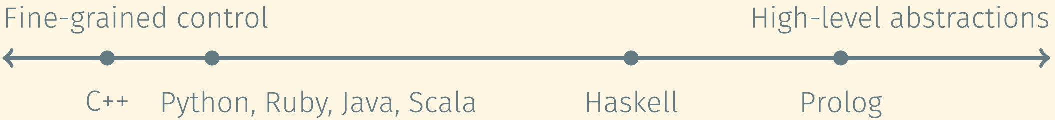

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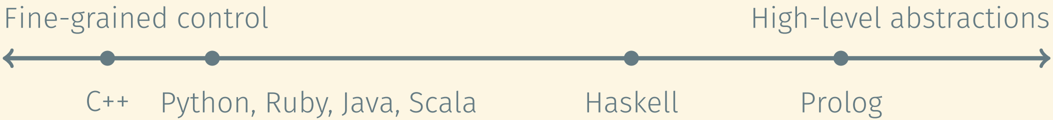

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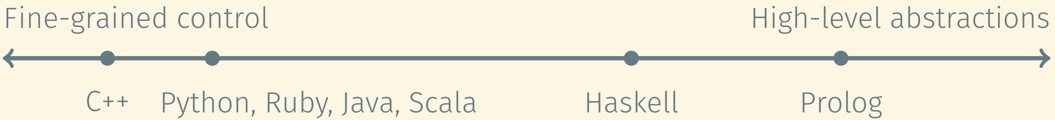

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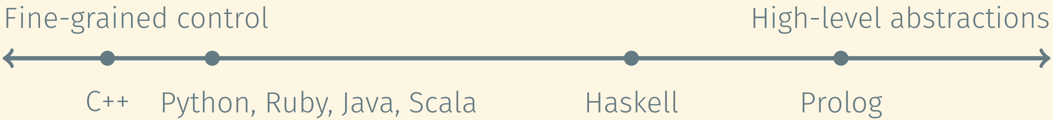

SUMMARY

Programming languages are the tools we use to express computations.

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Different programming languages may be better for different jobs.

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Different programming languages may be better for different jobs.

Be eager to explore new programming languages!

- Outside your comfort zone!
- It's fun.
- It makes you a better programmer, even in your favourite language.
- Your favourite language may change.