Not All Programming Languages are Created Equal: Using Functional Languages in Introductory Computer Science Classes.

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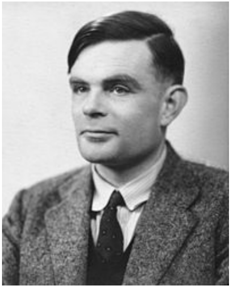
Curious facts about my research

- My research is in programming languages.
- In the past: some theoretical and practical work on how to make programs run faster while getting the same behavior (program optimization).
- Recently: **exploring use of a new programming language Clojure in introductory CS classes.**
- Clojure: a functional programming language released on October 16, 2007.

Foundations of computing systems: how it all started.



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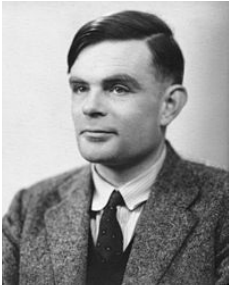

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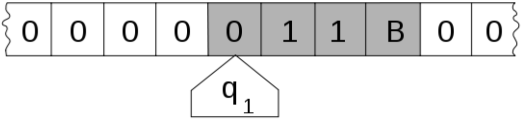
Alan Turing 1936: *Turing machine*: an abstract computing device.



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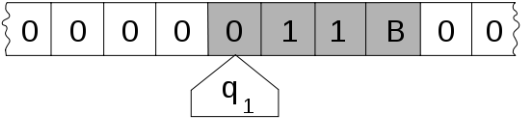

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Turing machine: an abstract computing device.

Consists of an infinite tape (*memory*) and a movable read/write head that reads and writes symbols on the type: (*direct changes in memory*).

Executes rules, e.g. *if the current memory cell has 0, write 1 and move left.*

Internal architecture of a computer, such as CPU (central processing unit) and memory, are based on concepts of the Turing machine.

Source: `http://en.wikipedia.org/wiki/Alonzo_Church`

Foundations of computing systems: how it all started.

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Alonzo Church (Alan Turing's thesis adviser).
1930s: *the lambda calculus (λ-calculus)*: a system in mathematical logic that describes computations.

A computation is a sequence of function applications, similar to $f(g(x))$.
Functions: $\lambda x.x + 1$ is a function that adds 1 to its argument.
λx means that a function takes one argument x, and $x + 1$ is the value that the function computes.
Does not deal with details of implementation or memory manipulation.

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Church-Turing thesis: the Turing machine and the λ-calculus can both perform all possible algorithms that can be described by computable functions.
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All languages are equivalent. Are they equal?.

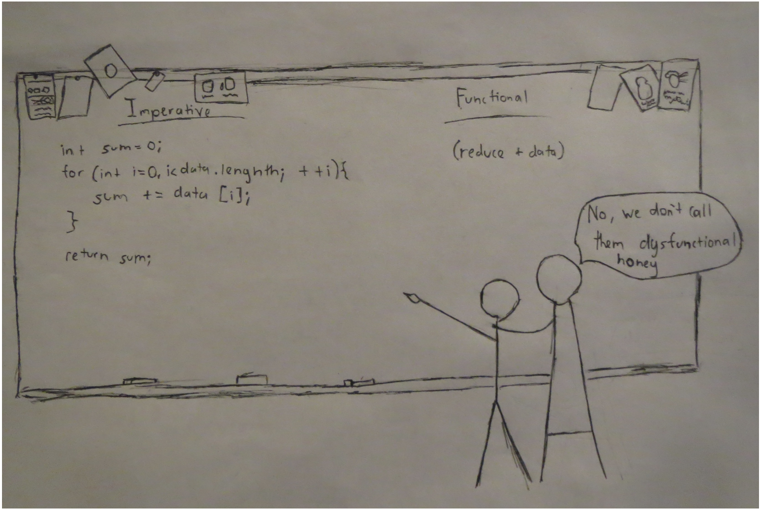
First programming languages.

First computers were programmed only by machine instructions.
High-level programming languages appeared so that programs can be understandable to humans.
First high-level languages:

- 1957: **Fortran** (**For**mula **Tran**slator), based on memory manipulation (like a Turing machine),
- 1958: **Lisp** (**Lis**t **P**rocessing), based on function composition (like the λ-calculus),
- 1959: **Cobol** (**Co**mmon **B**usiness-**O**riented **L**anguage), based on memory manipulation (like a Turing machine).

Languages that are like the λ-calculus are called *functional*.
Languages that are like a Turing machine are called....

Functional vs imperative.



Credit: Leonid Scott.

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Languages that are like a Turing machine are called *imperative*.

Imperative	Functional
Most entities are changed (updated) in-place.	Most entities are immutable: a new entity is created upon an update.
Results are accumulated by updating a memory locations, often in a loop.	Results are accumulated as a sequence of function calls, e.g. recursion (a function calls itself).
Functions are defined before the program starts executing, encapsulate some functionality.	Functions are first-class citizens: can be anonymous, constructed "on-the-fly", passed to other functions, returned from other functions.
Built-in data structures are specified in terms of memory addresses (e.g. arrays: contiguous blocks of memory)	Built-in data structures are defined inductively, e.g. a part of a list is itself a list.

Sum up all the elements of a dataset `data`.

Imperative, a loop: `sum` is a variable to accumulate results, `i` is an index.

```
sum = 0;
for (i = 1; i < length(data); i = i + 1) {
    sum = sum + data[i];
}
```

Assume `data` is `5, 7, 3, ...`

Imperative vs functional: example

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Error-prone: when does the index change? Are we using the right element?

```
sum = 0;
for (i = 1; i < length(data); i = i + 1) {
    sum = sum + data[i];
}
```

Functional: *recursion*:

```
function sum (data):
  if isEmpty?(data) then 0
  else first(data) + sum(rest(data))
```

If data has no elements, the sum is 0, otherwise it's the result of adding the first element to the sum of the rest of data.

Imperative vs functional: example

```
sum = 0;
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Functional: *higher order functions*:

```
(reduce + data)
```

+ is a *function* (not an operation, as in imperative languages), we *pass it* to a function `reduce` that applies it to all elements.

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`(reduce minimum data)`

`minimum` is a function that finds the smaller of two elements.

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(reduce (lambda x y. if $x < 0$ then 0 else $(x + y)$) data)
Anonymous function adds up positive data elements only.

Imperative vs functional: tradeoffs

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1000 function calls = 1000 workspaces??? Isn't it slow and memory-intensive???

There are built-in optimizations in functional languages. Some degree of awareness of efficiency is required.

Imperative languages with a direct control of low-level memory access (e.g. C) can indeed be faster.

Imperative vs functional: tradeoffs (cont)

Functions as first-class citizens allow more modular and abstract code: no need to write a separate loop for adding all elements of a dataset and for multiplying since + and * (multiplication) can be passed to a function:

```
(reduce + list)
(reduce * list)
```

Functional languages promote writing shorter functions: it's easier to "separate concerns".

Imperative vs functional: tradeoffs (cont)

Effects of *immutability*:

- easier to develop correct programs: do not need to keep track of a changing state of entities in a program.
- more program optimization: knowing that a certain entity doesn't change allows remembering and pre-computing of parts of a program.
- functional programs are easier to run in parallel (multiple CPUs or distributed computation): since entities don't change, no need for access control to shared data since there's no risk of an accidental overwrite.
- functional languages explicitly make data mutable: easier to track.

Convenience for parallelization renewed interest in functional languages.

Current language landscape.

There are 100+ actively used programming languages.
Imperative are much more commonly used: *C*, *C++*, *Java*, *C#*, *python*, *JavaScript*, *php*, etc.
Several **functional** languages in active use: dialects of *Lisp (Common Lisp, Scheme, Clojure)*, *Haskell*, *Erlang*, *Scala*.
Functional languages are on the rise with parallel computation.
Mixed paradigm: many modern languages are imperative, but with some support for immutability and higher-order functions.

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Mixed paradigm: many modern languages are imperative, but with some support for immutability and higher-order functions.
Object-oriented languages: represent real-life entities as object in a program (modularity): Java, C++, C#, Scala.

Skills/background for CSci students.

Students entering computing industry...

- ...are expected to know at least one commonly used language (C++, Java, C#) well.
- ....will have to be learning new languages/paradigms as early as within the first week at work.
- ...will be working with multiple languages and systems at the same time.
- ...are expected to write well-organized clear program code.
- ...greatly benefit from knowing a variety of tools and approaches for collaborative software development process, testing, managing projects, professional communication skills.

Independent, self-directed learning, building upon a strong knowledge foundation and experience with collaborative work.

UMM curriculum structure.

Introductory courses. CSci 1201: python (imperative with functional elements) or CSci 1301 Racket (a functional language, dialect of Lisp).
Sophomore level. Course: CSci 2101 Data Structures: Java (imperative, object-oriented).
Sophomore/Junior level. Intro to operating systems, larger scale software development, algorithms development.
Junior/Senior level. Electives.

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- Immutability makes design easier: focus on concepts.
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- Focus on compact, logical code design.
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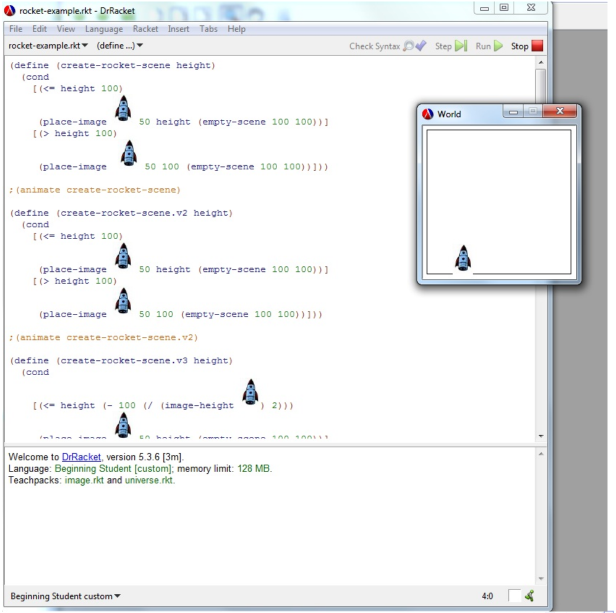
Students better learn more involved concepts (e.g. object-oriented approaches) with a strong base in general concepts.

Current CSci 1301: Racket programming language



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- A dialect of Lisp, specifically designed for teaching.
- Comes with an environment that allows students to easily write and execute their code.
- Has multiple levels: Beginner Student, Intermediate, Advanced. Lower levels make only a subset of features available to students, to avoid accidentally executable, but incorrect code. Also change the way output is formatted.
- Incorporates a system for working with images and allows students to provide functions for interactive environments ("when a key is pressed, do this") without dealing with back-end structures.

UMM has been using Racket, and its predecessor Scheme, in intro classes for about 15 years. It worked well.

The Clojure programming language.

Clojure is a new language in the Lisp family.

- Built-in immutability, for safe sharing during parallel processing.
- Built-in support for several models of mutability for cases when data needs to be concurrently modified.
- Running in the Java Virtual Machine: a well-developed engine for running Java: can piggy-back on its optimizations, interactions with the operating systems, etc.
- Fully interoperable with Java: can use all Java libraries.
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- Used in industry, has a large (and fast growing) community around it (conferences, meetups, open source projects,...)
- It's a nice language!

Clojure at UMM: faculty, students, alums

- First introduced by Brian Goslinga (UMM CSci'11)
- Made an appearance in parallel/distributed computing class (2011 Elena, 2013 Nic) and Programming Languages (2012).
- Three projects: improving Clojure error messages (Brian Goslinga UROP, Eugene Butler LSAMP), interoperability between Java and Clojure (Stephen Adams UROP), parallelization in Clojure (Joe Einertson UROP).
- An idea came up that we should try using Clojure in an introductory class.
- Starting Fall 2012, a joint work with Stephen Adams (UMM CSci 2012), Joe Einertson (UMM CSci 2013), plus a directed study with Paul Schliep and Max Magnuson (UMM CSci 2015).
- A presentation at Trends in Functional Programming in Education (TFPIE), May 2013.

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- A presentation at Trends in Functional Programming in Education (TFPIE), May 2013.
- We now have a name for this project: **ClojurEd**

Potential benefits of using Clojure in intro classes.

- If done right, we can get most of the same benefits as from using Racket.
- Additionally, it integrates nicely into future classes in the way Racket cannot.
- There is a large community around it: opportunities to get help or to jump into a project. Also, issues are fixed fast and the language support doesn't depend on a dozen of individuals.
- Allows fast parallel execution.
- It's a real-life language done well, and there aren't that many out there.

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What needs to be done before we can teach Clojure to intro students? **A lot!** Work in progress:

- Environment for beginners: looking for a beginner-friendly text editor, need to add a few things to make it automatically run Clojure with our libraries.
- Error messages in Clojure are not beginner-friendly. We have done some work on improvements.
- We are changing and adding Clojure functions to make them easier to use for beginners.
- Developing an approach to introducing Clojure abstractions to beginners.
- Exploring Clojure libraries for graphics that would allow students to work with images, similar to Racket.

Bits of the universe: a Clojure poem

```
nil
pop!
(time ())
empty?
atom
atom atom
atom atom atom atom atom
atom atom atom atom atom atom atom atom atom
(binding [atom [atom [atom [atom [atom]]]]])
make-hierarchy
repeat
repeatedly iterate sequence
constantly interleave
merge

replicate
parents
descendants
cycle
7000000000

true? false?
find identity
find name
symbol? number?
rational? odd?
resolve
future?
future-done?
future-cancelled?
reversible?
nil?
```