# Introduction to Research in Computer Science

Lewis University

Spring 2022

# Outline

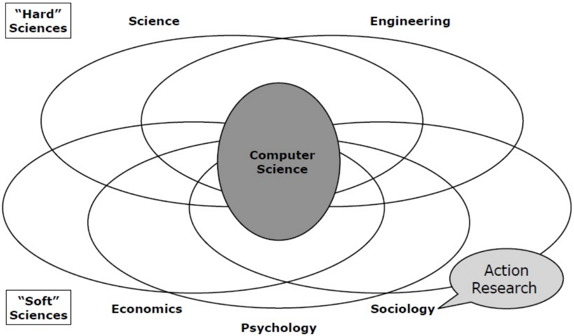
# Course Objectives

- Gain an appreciation for the diverse areas encompassing modern computer science
- Understand different approaches to research in computer science, including proofs, observational studies, and implementation-driven research
- Be able to read and ask questions of a computer science research paper
- Present and answer questions about a technical paper
- Explore formal verification as a researh area in computer science

# Course Administration

- Method of Delivery: Synchronous (live) and Asynchronous (Pre-recording)
- Assessment:
  - Class Contribution (Discussions on BB): 15%
  - Assignments (2 to 3): 35%
  - Course Project (Presentation 15%, Project 35%): 50%
- All assignments and Project (Report and Presentation) should be done in Latex
- Compulsory Readings: Weekly reading, how to read scientific paper links
- Project Proposal's due date: Week #3

# What is Computer Science?



# What is Computer Science?

- Some combination of:
  - Science
  - Engineering
  - Mathematics
- More precisely
  - “Computer Science” is a name of a field
  - Computer science is a the scientific endeavor relating to computing

# Areas of Research in Computer Science

- Abundant-data applications, algorithms, and architectures
- Artificial intelligence and robotics
- Verification, proofs, and automated debugging of hardware designs, software, networking protocols, mathematical theorems, etc
- Bio-informatics and other uses of CS in biology, biomedical engineering, and medicine
- Databases, data centers, information retrieval, and natural-language processing

# Areas of Research in Computer Science

- Emerging technologies for computing hardware, communication, and sensing
- Human-computer interaction
- Large-scale networking
- Limits of computation and communication
- Multimedia
- Programming languages and environments
- Security of computer systems and support for digital democracy

# Algorithms

A skilled programmer must have good insight into algorithms.

At bachelor level you were offered courses on basic algorithms: searching, sorting, pattern recognition, graph problems, ...

You learned how to detect such subproblems within your programs, and solve them effectively.

You are trained in algorithmic thought for uniprocessor programs (e.g. divide-and-conquer, greedy, memorization).

# Algorithms

Consider the following template C code posted on BB.

What algorithm is being implemented here? Write a program in the language of your choice to test this algorithm.

There are three desirable properties for a good algorithm. ...........

# Algorithms: Discussion

What are three desirable properties for a good algorithm?

Designing correct, efficient and implementable algorithms for real-world problem requires access to two distinct bodies of knowledge:

- *Techniques.................................*
- *Resources.................................*
- **Lesson:** There is a fundamental difference between algorithms, which always produce a correct result, and heuristics, which may usually do a good job but without providing guarantee.

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# Algorithms: Analysis - Big O notation

Complexity measures state how resource consumption (messages, time, space) grows in relation to input size.

For example, if an algorithm has a worst-case message complexity of $O(n^2)$, then for an input of size $n$, the algorithm in the worst case takes *in the order of* $n^2$ messages.

Let $f, g : \mathbb{N} \to \mathbb{R}_{>0}$.

$f = O(g)$ if, for some $C > 0$, $f(n) \leq C \cdot g(n)$ for all $n \in \mathbb{N}$.

$f = \Theta(g)$ if $f = O(g)$ and $g = O(f)$.

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# Distributed systems

A distributed system is an interconnected collection of autonomous processes.

Motivation:

- information exchange
- resource sharing
- parallelization to increase performance
- replication to increase reliability
- multicore programming

# Distributed versus uniprocessor

Distributed systems differ from uniprocessor systems in three aspects.

- *Lack of knowledge on the global state*: A process has no up-to-date knowledge on the local states of other processes.

  Example: termination and deadlock detection become an issue.

- *Lack of a global time frame*: No total order on events by their temporal occurrence.

  Example: mutual exclusion becomes an issue.

- *Nondeterminism*: Execution of processes is nondeterministic, so running a system twice can give different results.

  Example: race conditions

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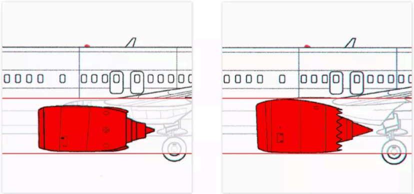
# Building Reliable Software

- Suppose you run a software company
- Support you've sunk 30+ person-years into developing the "next big thing":
  - ★ Boeing Dreamliner2 flight controller
  - ★ Autonomous vehicle control software for Tesla
  - ★ Gene therapy DNA tailoring algorithms
  - ★ Super-efficient green-energy power grid controller
- How do you avoid disasters?
  - ★ Turns out software endangers lives

# Boeing 737 Max Crashes

- Involved in two crashes
  - ✦ Lion Air Flight 610 on October 29, 2018 — 189 dead
  - ✦ Ethiopian Airlines Flight 302 on March 10, 2019 — 157 dead
- The crash is attributed to design errors including flight control software
  - ✦ The position of larger engines on 737 Max generated addition lift



*Engine placement on the third-generation 737 NG (left) versus the MAX (right).*

# Boeing 737 Max Crashes

- Manoeuvring Characteristics Augmentation System (MCAS)
  - Software to sense angle of attack (AoA) from a sensor and automatically compensate
- Crashes due to AoA sensor data but also due to MCAS software
- Every time MCAS was switched on and off again, it acted like first time pitching nose lower
  - incorrect spec not including history
- Max 0.8 degrees pitch during testing, which was changed to 2.4 after
  - Executing conditions not reflective of testing
- MCAS completely ignored that pilots were desperately pulling back on the yoke
  - Incorrect spec not considering environment

# Not an isolated incident

- NASA's Mars Climate Orbiter
  - A sub contractor on the engineering team failed to make a simple conversion from English units to metric
  - \$125 million
- Ariane 5 Flight 501
  - The software had tried to cram a 64-bit number into a 16-bit space.
  - Crashed both the primary and the backup computer
  - \$500 million payload lost + \$XXX to fix the flaw.
- Hawaii Sends Out a State-Wide False Alarm About a Missile Strike
  - there were "troubling" design flaws in the Hawaii Emergency Management Agency's alert origination software.
- The Equifax social security hack
  - 143 million of their consumer records (names, SSN, credit card numbers) were stolen by attackers.

# Approaches to Validation

- Social
  - Code reviews
  - Extreme/pair programming
- Methodological
  - Design patterns
  - Test-driven development
  - Version control
  - Bug Tracking
- Technological
  - Static analysis
  - Fuzzers
- Mathematical
  - Sound Type Systems
  - Formal verification

Less formal: Techniques may miss problems in programs

All of these methods should be used!

Even the most formal can still have holes:

- did you prove the right thing?
- do your assumptions match reality?

More formal: eliminate *with certainty* as many problems as possible.

# Software: first failure cause of computing systems

**Size:** from some (tens) of thousands of code lines to some millions of code lines

**Development effort:**

0,1-0,5 person.year / KLOC (large software)
5-10 person.year / KLOC (critical software)

**Share of the effort devoted to fault removal:**

45-75%

**Fault density:**

10-200 faults / KLOC created during development

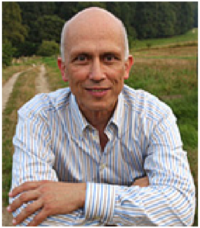
- static analysis
- proof
- model-checking
- *testing*

0,01-10 faults / KLOC residual in operation

# The Quest for Software Correctness

**Speech@50-years Celebration CWI Amsterdam**

"It is fair to state, that in this digital era correct systems for information processing are more valuable than gold."



Henk Barendregt

# The Importance of Software Correctness

## Rapidly increasing integration of ICT in different applications

- embedded systems
- communication protocols
- transportation systems

$\Rightarrow$ reliability increasingly depends on software!

## Defects can be fatal and extremely costly

- products subject to mass-production
- safety-critical systems

# What is System Verification?

## Folklore "definition"

System verification amounts to check whether a system fulfills the qualitative requirements that have been identified

## Verification $\neq$ validation

- Verification = "check that we are building the thing right"
- Validation = "check that we are building the right thing"

# Software Verification Techniques

## Peer reviewing

- static technique: manual code inspection, no software execution
- detects between 31 and 93% of defects with median of about 60%
- subtle errors (concurrency and algorithm defects) hard to catch

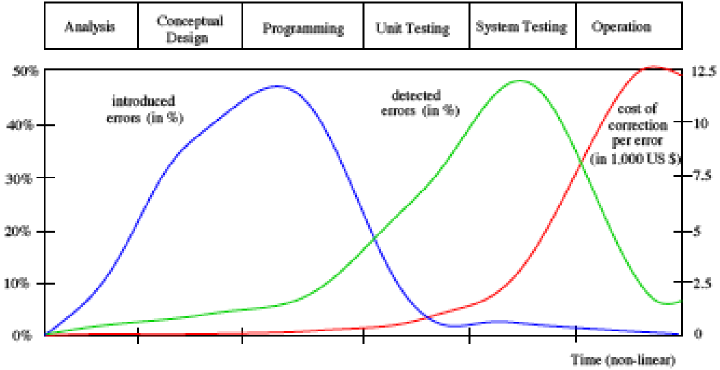
## Testing

- dynamic technique in which software is executed

## Some figures

- 30% to 50% of software project costs devoted to testing
- more time and effort is spent on validation than on construction
- accepted defect density: about 1 defects per 1,000 code lines

# Bug Hunting: the Sooner, the Better



# Formal Methods

## Intuitive description

Formal methods are the

"applied mathematics for modelling and analysing ICT systems"

## Formal methods offer a large potential for:

- obtaining an early integration of verification in the design process
- providing more effective verification techniques (higher coverage)
- reducing the verification time

## Usage of formal methods

Highly recommended by IEC, FAA, and NASA for safety-critical software

# Formal Verification Techniques for Property $P$

## Deductive methods

- method: provide a formal proof that $P$ holds
- tool: theorem prover/proof assistant or proof checker
- applicable if: system has form of a mathematical theory

## Model checking

- method: systematic check on $P$ in all states
- tool: model checker (SPIN, NUSMV, UPPAAL, ...)
- applicable if: system generates (finite) behavioural model

## Model-based simulation or testing

- method: test for $P$ by exploring possible behaviours
- applicable if: system defines an executable model

# Simulation and Testing

## Basic procedure:

- take a model (simulation) or a realisation (testing)
- stimulate it with certain inputs, i.e., the tests
- observe reaction and check whether this is "desired"

## Important drawbacks:

- number of possible behaviours is very large (or even infinite)
- unexplored behaviours may contain the fatal bug

## About testing ...

testing/simulation can show the presence of errors, not their absence

# Milestones in Formal Verification

- Mathematical program correctness (Turing, 1949)
- Syntax-based technique for sequential programs (Hoare, 1969)
  - for a given input, does a computer program generate the correct output?
  - based on compositional proof rules expressed in predicate logic
- Syntax-based technique for concurrent programs (Pnueli, 1977)
  - handles properties referring to states during the computation
  - based on proof rules expressed in temporal logic
- Automated verification of concurrent programs
  - model-based instead of proof-rule based approach
  - does the concurrent program satisfy a given (logical) property?

# Which Approach Should We Consider?

Correctness vs Efficiency: What Comes first?

Are your Undergraduate Knowledge of Algorithms still relevant to the analysis of distributed systems?

Urgent Need to have a formal framework for describing Algorithms: Uniprocessor or distributed systems

In this course, we will analyze correctness proofs = Formal methods as the main support for your introduction to research in computer science.

Possible Themes for research initiation: Verification, proofs, and automated debugging of hardware designs, software, networking protocols, formal methods for complex systems, and mathematical theorems.