LANGUAGE BASED TECHNOLOGY FOR SECURITY

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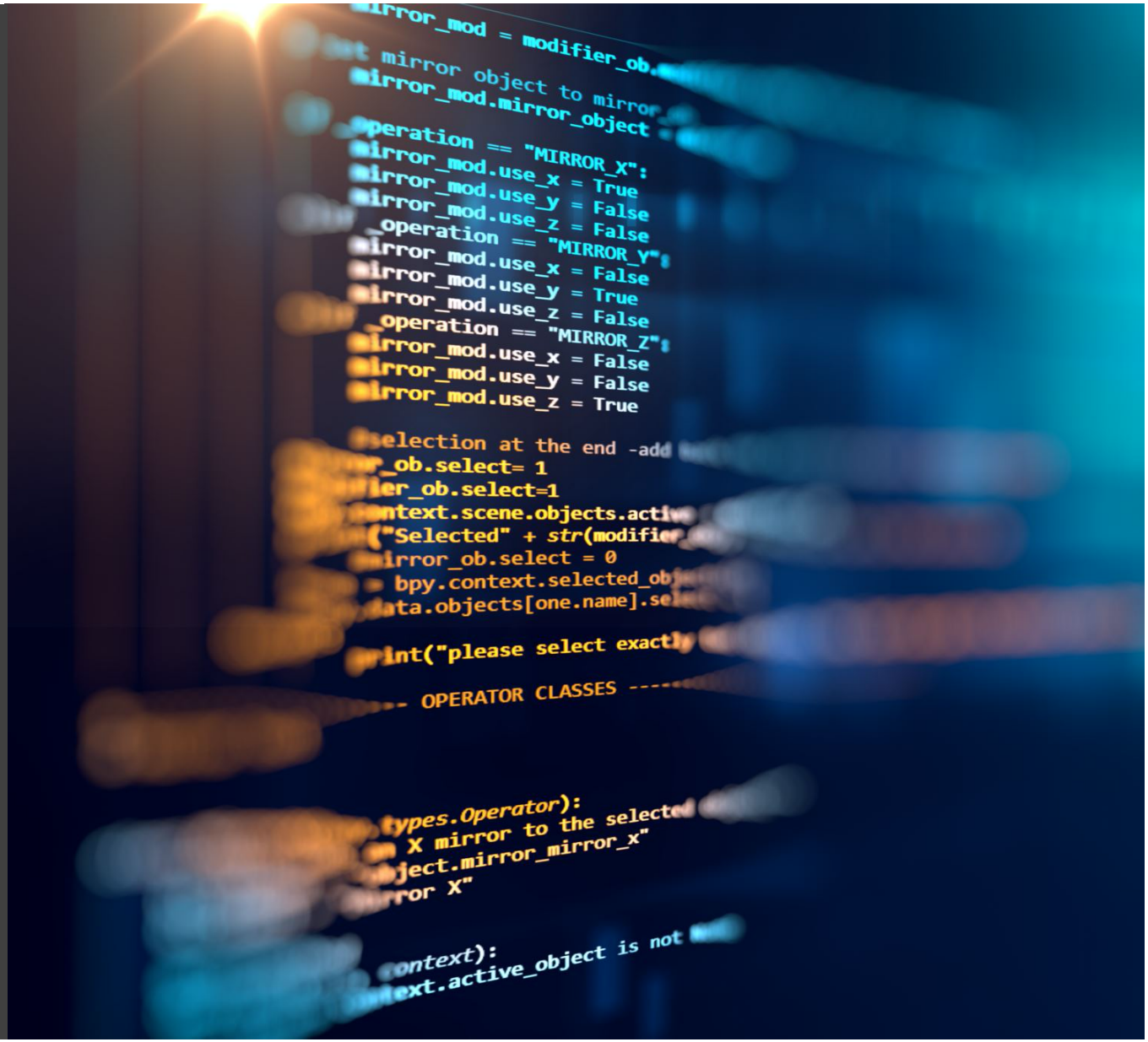
GIAN LUIGI FERRARI



PREREQUISITES

- If you've ever programmed in a variety of programming languages (C, Java, C++, OCaml, JavaScript etc.) then that will be a helpful skill.
- Also, if you know how programming languages are implemented, that will be quite useful too.

OUTLINE

- Course logistics
- Course objectives & Grading
- About us
- What is “Language-based Security”?

Course Information

- The teaching materials (lectures, readings and exercises) will be available on TEAMS
  - 714AA 20/21 - LANGUAGE-BASED TECHNOLOGY FOR SECURITY [WCY-LM]

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- Prof. Gian Luigi Ferrari – gian-luigi.ferrari@unipi.it
- Office hours: After classes

Course Objectives

- Issues
  - How does security typically fail in software?
  - Why does software often fail?
    - and what are the underlying root causes?
- What are ways to make software more secure?
  - principles, methods, tools & technologies
  - Secure programming languages (design and implementation)
  - practical experience with some of these

INTERMEZZO

TOP MAINSTREAM LANGUAGES (TIOBE INDEX)

Feb 2021	Feb 2020	Programming Language	Ratings	Change
1	2	C	16.34%	-0.43%
2	1	Java	11.29%	-6.07%
3	3	Python	10.86%	+1.52%
4	4	C++	6.88%	+0.71%
5	5	C#	4.44%	-1.48%
6	6	Visual Basic	4.33%	-1.53%
7	7	JavaScript	2.27%	+0.21%
8	8	PHP	1.75%	-0.27%
9	9	SQL	1.72%	+0.20%
10	12	Assembly language	1.65%	+0.54%

Same data 2013-2017- (http://nvd.nist.gov)

#5899 vulnerabilitis due to **buffer errors**

#5851 vulnerabilities due to **injection errors**

#3106 vulnerabillities due to **information leak**

#53% of softtware vulnerabilities in NVD were buffer errors, injections and information leaks

All of these are issues within the realm of Programming Language Design

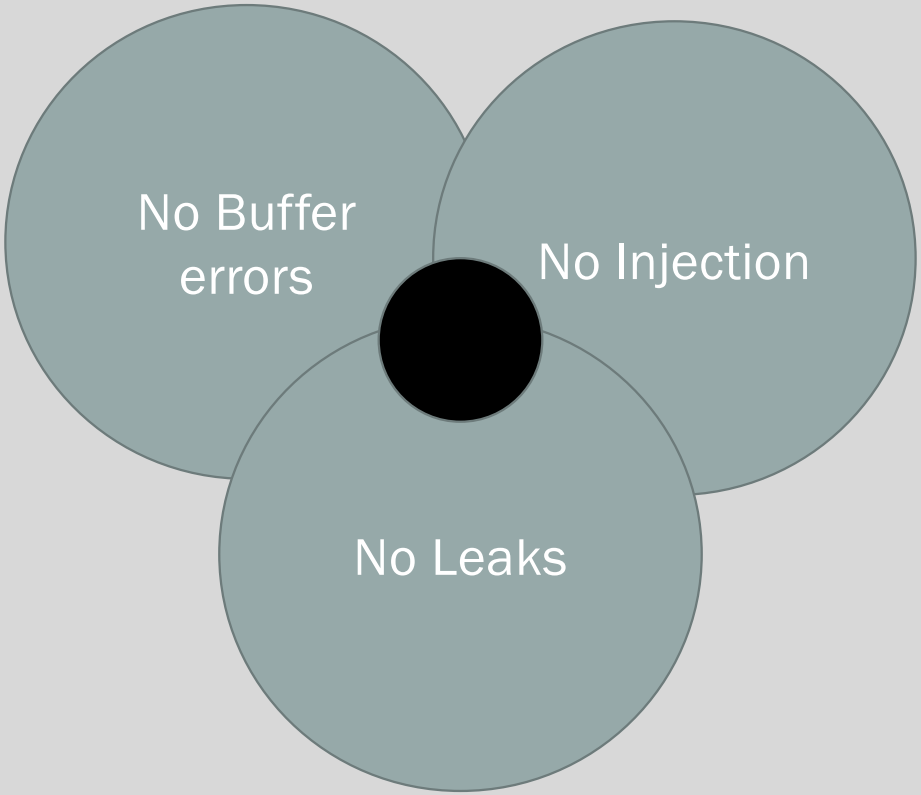
#5899 vulnerabilitis due to **buffer errors**

#5851 vulnerabilities due to **injection errors**

#3106 vulnerabillities due to **information leak**

#53% of software vulnerabilities in NVD were buffer errors, injections and information leaks

A Secure Programming Language is one that provides abstraction to avoid the three main categories of vulnerabilities



Avoid Buffer Errors Dynamicaly

John McCarthy 1958

- **Managed memory**
  - Garbage Collection introduced in LISP in 1958
- Now in
- OO Languages
  - Java, C# JavaScript, ...=
- Functional Languages
  - ML, Haskell, OCAML, F#, ...
- Dynamic Languages
  - Ruby, Perl, ...

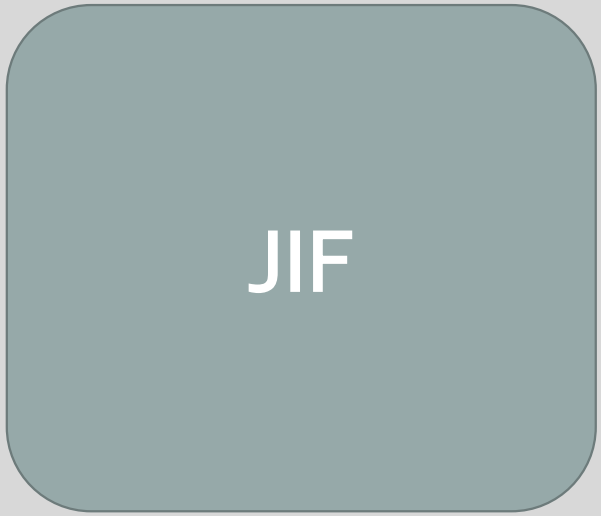
Avoid SQL Injection Statically

MICROSOFT 2007

- LINQ .NET's Language Integrated Query Framework
- LINQ to SQL manages relationa data as objects without losing the ability to query
  - Statically typed

Permette di essere utilizzato all'interno del run time di .NET in modo interoperabile per fare delle query alle basi di dati relazionali pur continuando a rimanere in un modello di programmazione ad oggetti.

Avoid Information Leaks Statically

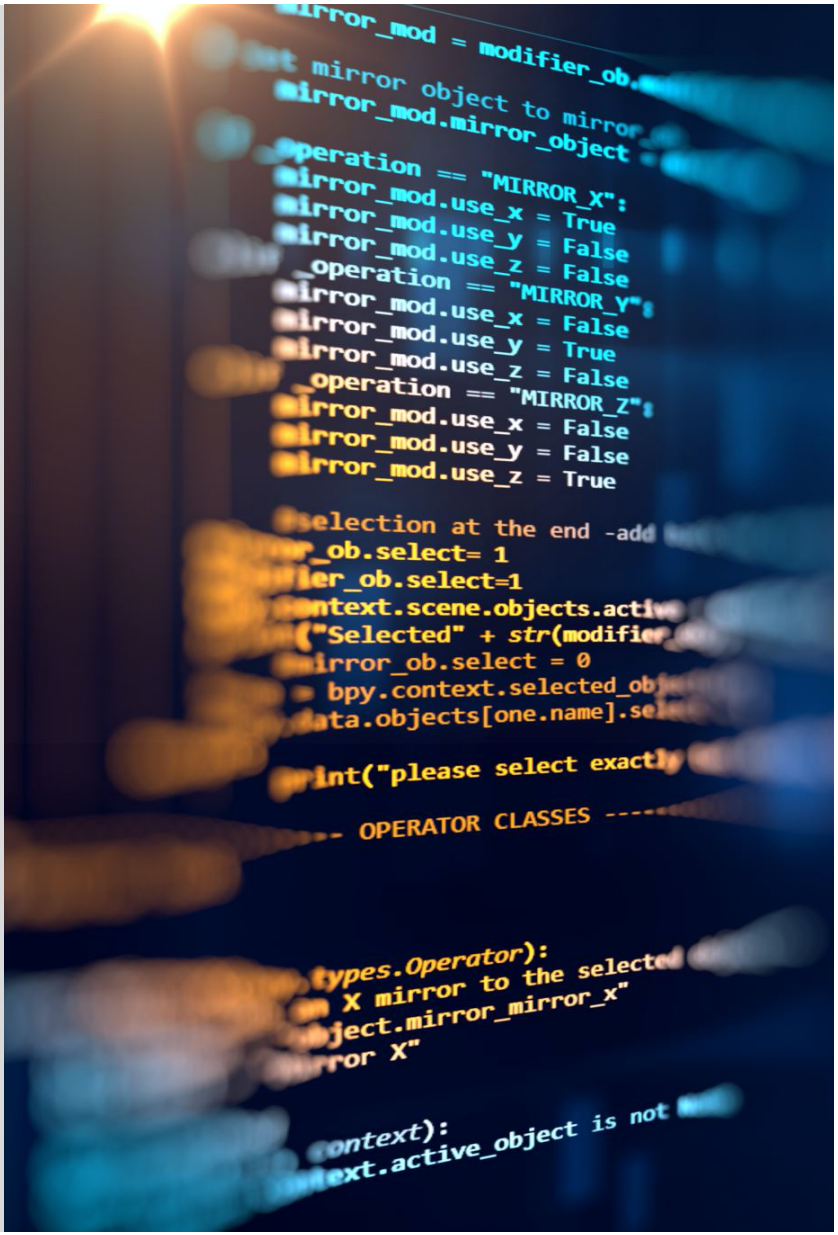


Andrew Myers, 2002

- Extends Java with information flow and access control enforced at compilke time and run time
  - Integrity
  - Confindentiality
  - Prevent infromation leaks

Controlla sia a livello statico usando i meccanismi tipici di analisi statica di Java che a tempo di esecuzione che non ci siano flussi di esecuzione scorretti.

TODAY MAIN STREAM PROGRAMMING LANGUAGES ARE NOT SECURE LANGUAGES



SECURE PROGRAMMING LANGUAGES PROVIDE ABSTRACTIONS AND TOOLKITS TO SUPPORT SECURE PROGRAMMING

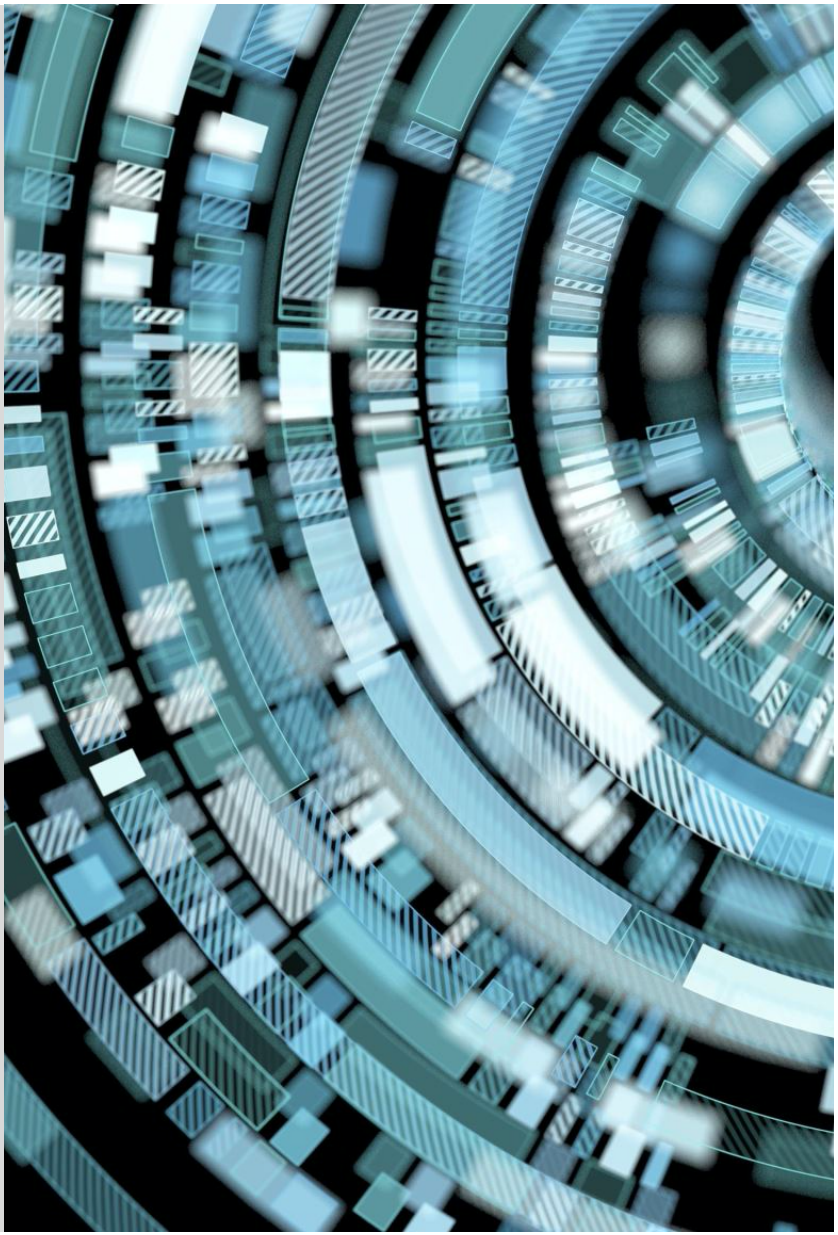
Vorremmo che i linguaggi di programmazione venissero progettati fin dall inizio sicuri e che la sicurezza non sia solo legata all'aspetto di path quando il software è prodotto, sia dal punto di vista delle tecniche di ingegneria del software sia dal punto di vista degli strumenti che vengono usati per programmare e dunque vorremmo che la sicurezza non fosse sacrificata sull'altare dell'efficienza.

Secure Programming Language Design: issues to consider

- Programming astraction for security
- Interoperability
- Virtual machines & Run time supports
- Compilation that preserves security abstraction
- Static techniques (types, control and data flow analysis)
- Run-time type checking
- :

END INTERMEZZO

IT'S TIME TO INTRODUCE SECURITY ABSTRACTIONS IN LANGUAGE DESIGN AND IMPLEMENTATION

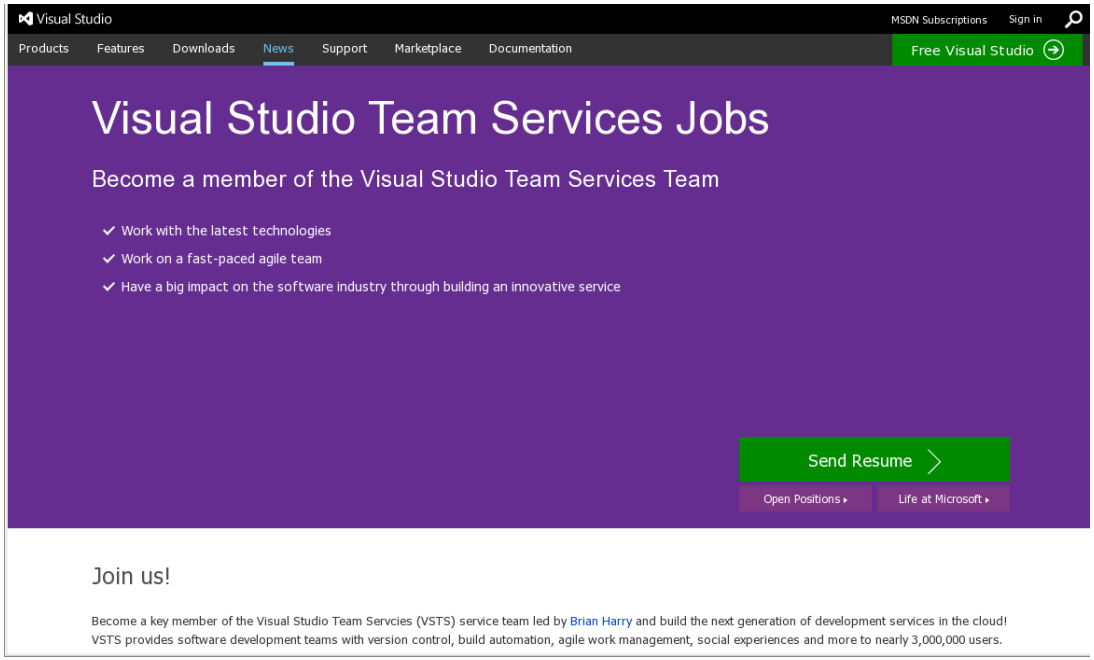


Who cares?

- In most cases, there is a clear mapping between top-level ICT professionals and jobs:
- Take Databases -> work at Oracle
- Take E-Commerce and services -> work at Amazon
- Take Networks -> work at Cisco
- Take Graphics -> work at Nvidia
- *…. Which companies develop compilers or interpreters?*

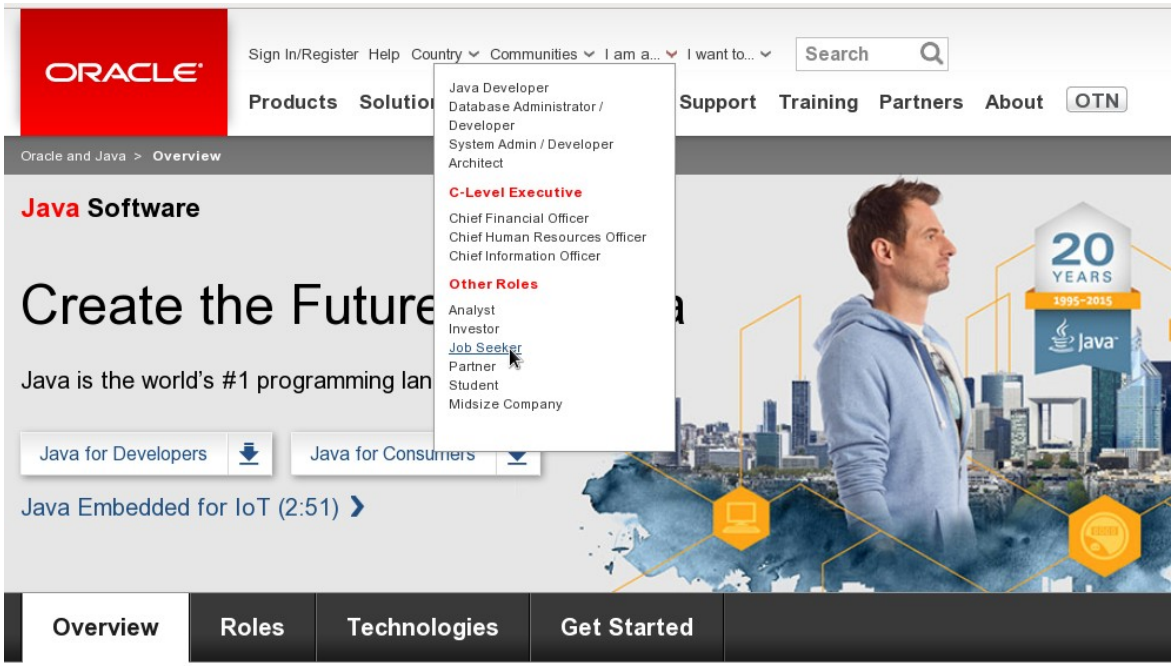
Microsoft

- Visual Studio, Excel, etc.

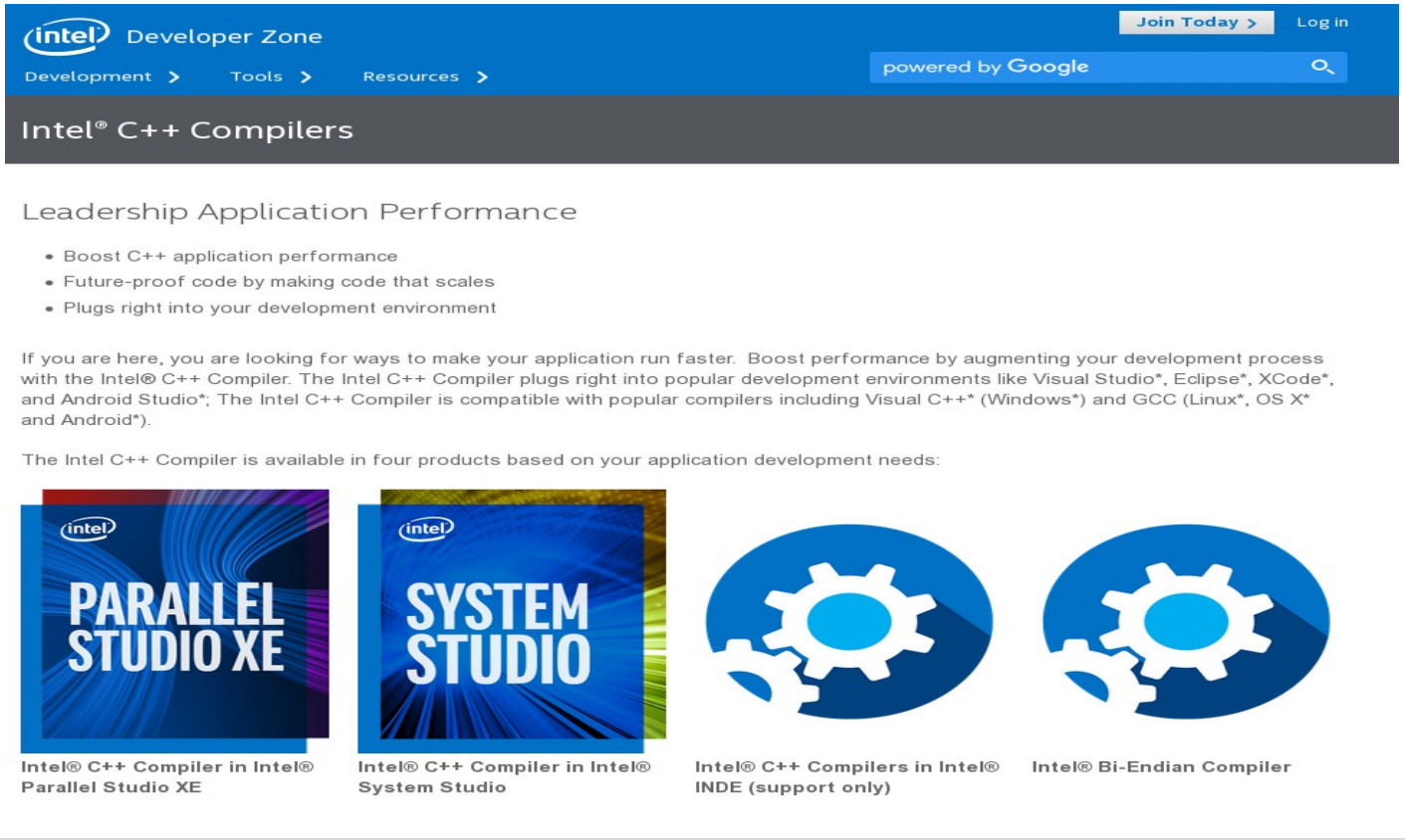


Oracle

- Java Compiler, Java Virtual Machine



Intel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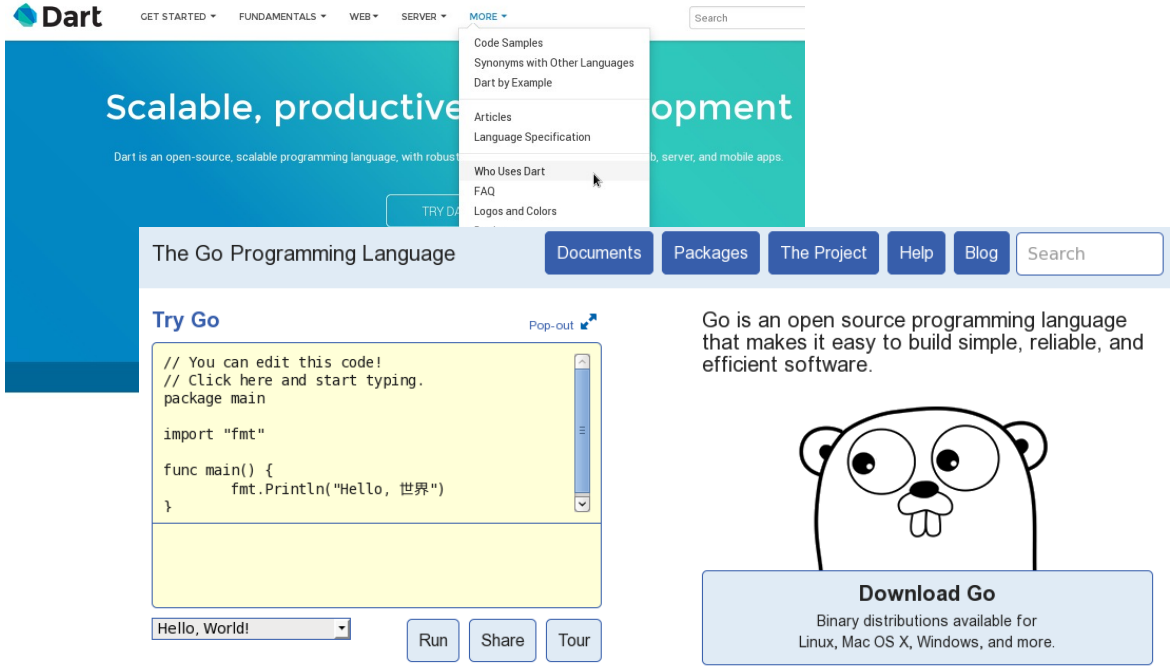
If you are here, you are looking for ways to make your application run faster. Boost performance by augmenting your development process with the Intel® C++ Compiler. The Intel C++ Compiler plugs right into popular development environments like Visual Studio*, Eclipse*, XCode*, and Android Studio*; The Intel C++ Compiler is compatible with popular compilers including Visual C++* (Windows*) and GCC (Linux*, OS X* and Android*).
The Intel C++ Compiler is available in four products based on your application development needs:
PARALLEL STUDIO XE
SYSTEM STUDIO
Intel® C++ Compiler in Intel® Parallel Studio XE
Intel® C++ Compiler in Intel® System Studio
Intel® C++ Compilers in Intel® INDE (support only)
Intel® Bi-Endian Compiler

Google

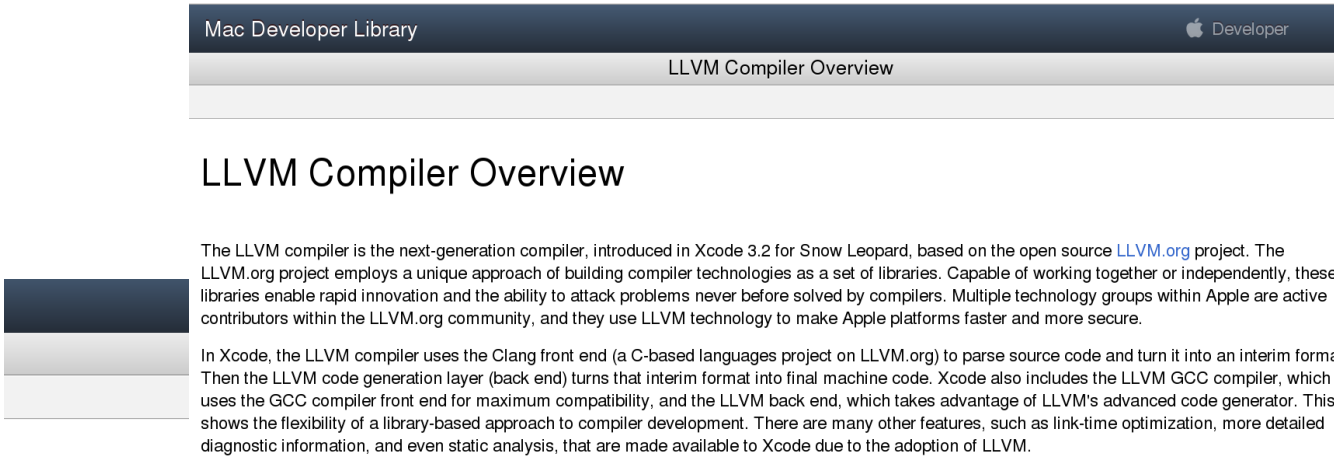
Go, Dart, etc.



Apple

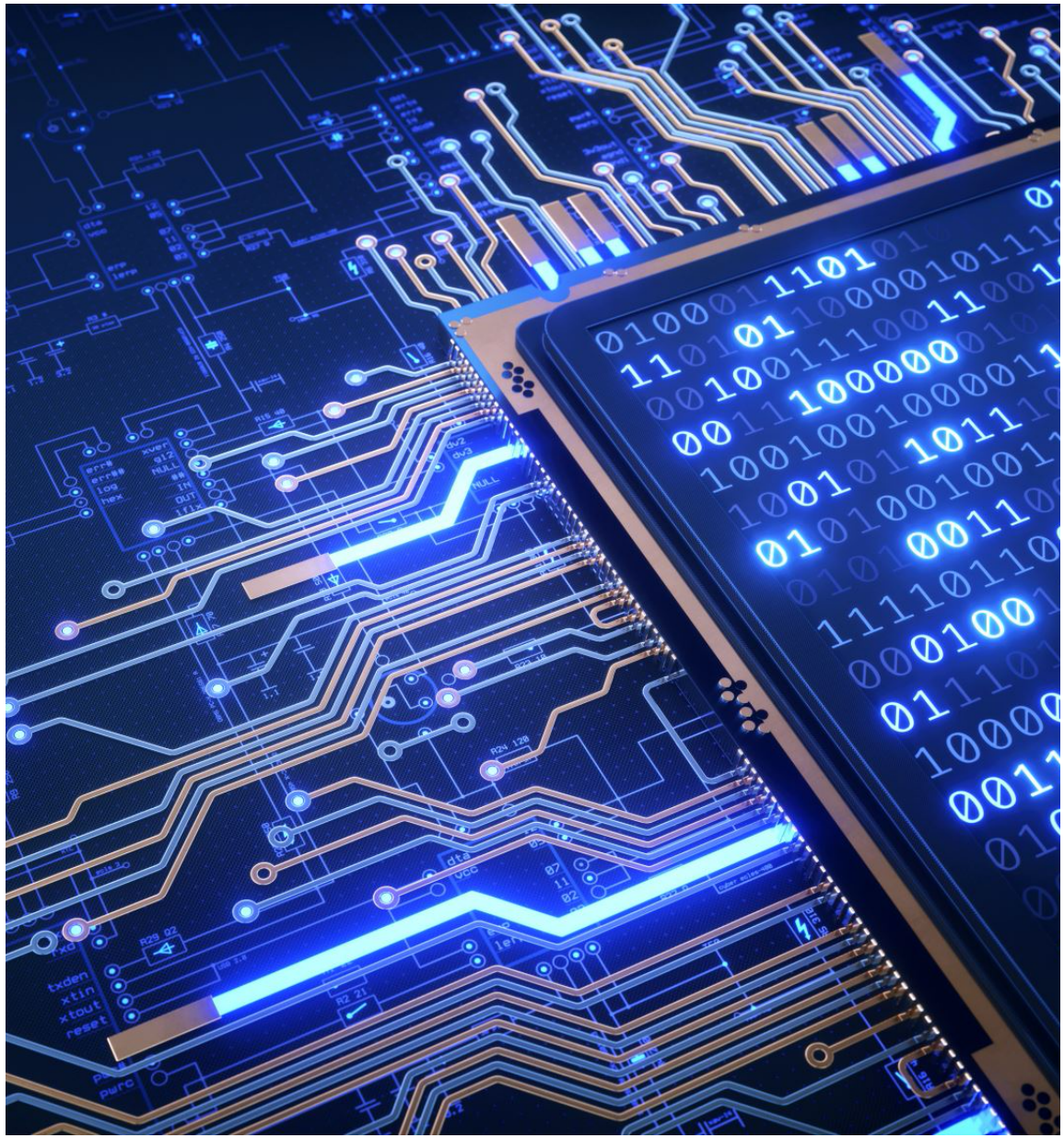
- Objective-C. LLVM.

LLVM è un framework per progettare compilatori di macchine astratte, dunque è uno strumento con all'interno una quantità di meccanismi per analizzare il codice prodotto



About Objective-C

Objective-C is the primary programming language you use when writing software for OS X and iOS. It's a superset of the C programming language and provides object-oriented capabilities and a dynamic runtime. Objective-C inherits the syntax, primitive types, and flow control statements of C and adds syntax for defining classes and methods. It also adds language-level support for object graph management and object literals while providing dynamic typing and binding, deferring many responsibilities until runtime.



In a nutshell

- Skills on the design and Implementation of secure programming languages is one notch more than a standard ICT professional skills

How programming languages are implemented?

Two major strategies (roughly specking!!!!)

- interpreters (take source code and run it)
- Compilers (translate source code, run result)

Interpreters run programs “as is”

- Little or no static analòysis and static optimization

Compilers do extensive static analysis

Most implementations use mixed techniche (interpreter+compiler)

Why study the design and implementattion of secure programming languages

- Prepare for many good jobs
- Improve understanding the security issues of program behavior:
  - Know how things work “under the hood”
- Increase ability to learn new languages
- Learn to build a large and secure system
- See many basic concepts of computer science jointly at work
- Computers are the only tools that increase cognitive power, so learn to control them

le vulnerabilità verranno viste con la lente di un progettista di nuovi linguaggi di programmazione oppure progetta i compilatori per i nuovi linguaggi, dunque dal punta di vista del linguaggio --> primitive del linguaggio + strumenti di implementazione

Then … what will we do in this class

- **Learn** about different kinds of **software vulnerabilities** and **how** they can be handled by designing and implementing programming languages
- This will permit to gain **exposure to new ideas** in programming language design and implementation
- … **Lab to** get your hands dirty
  - You will design and implement your own programming language
  - **Do not be afraid: a simple interpreter**!!

Course Objectives (cont.)

- Cutting-edge research
  - Learn how to extract (the important) info from security-related research articles
  - Learn about modern efforts toward a science of computer security
- Many problems/questions are open-ended. We will be exploring the known issues together.

Grading

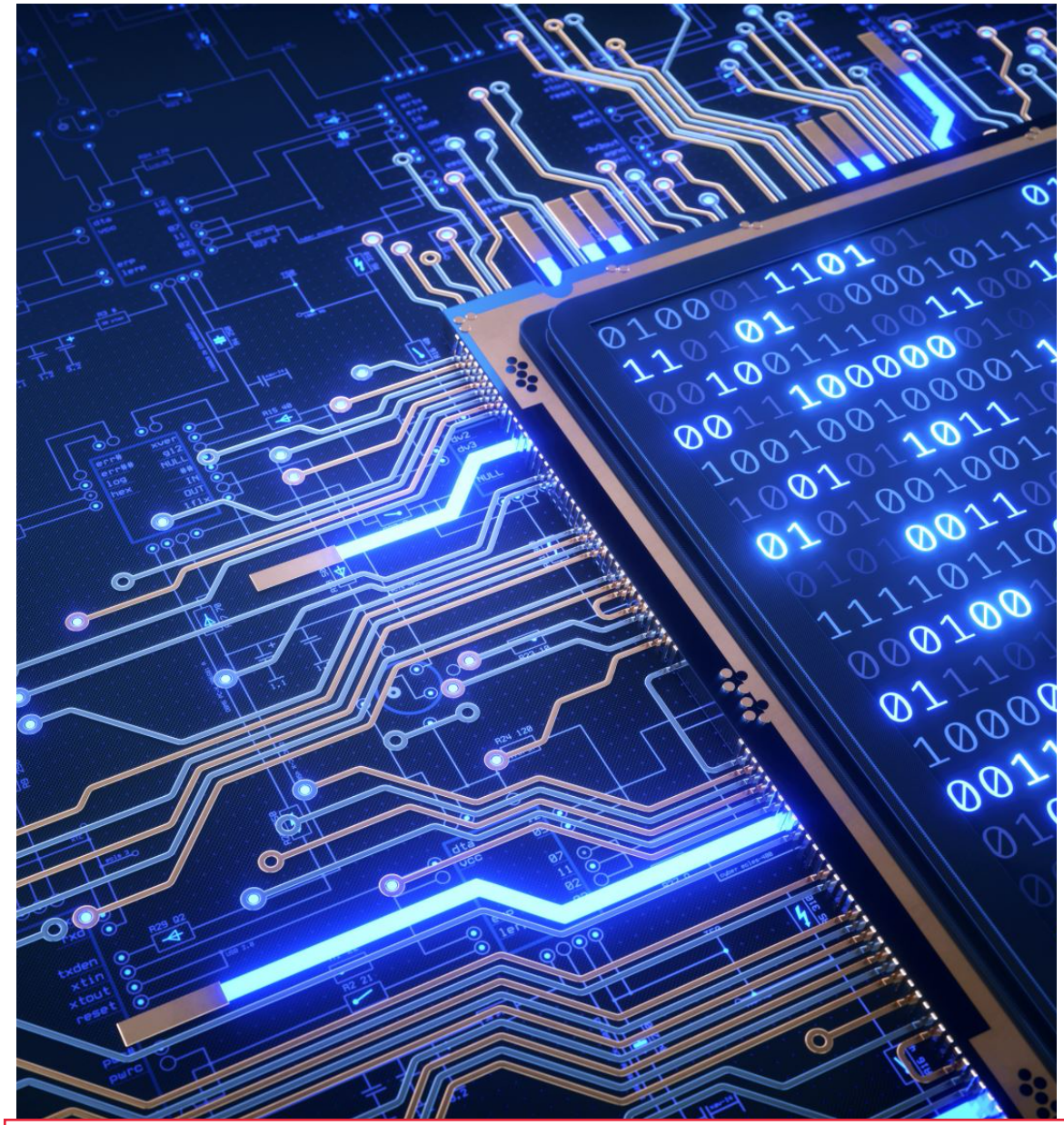
- Class participation (20%)
  - discuss topics, articles & ask questions
- Project work (40%)
  - Project proposal and implementation during last 4 weeks of course
- Written exam (40%)
  - main concepts
  - Feasibility, main limitations, pros/cons
  - A few harder in-depth questions to test whether you caught subtle but essential details

What is "Language Based Security"

- Leveraging theory of programming language design and compiler construction to enforce software security
- Two issues
  - new languages/tools for creating secure software
  - securing legacy code (e.g., written in C)
- Three stages of enforcement
  - static (find & fix vulnerabilities before runtime)
  - dynamic (detect and block attacks at runtime)
  - audit (recover and assign blame after an attack)

Challenges

- Is it possible to develop secure software that is guaranteed to be vulnerability-free?
- Scenario: You are hired to write the control software for self driving cars
  - it must NEVER fail (several lifes at stake)
  - it must cope with adversarial conditions (operate in a dynamic environment, have to work in all weather conditions anywhere on the planet)
  - it must be efficient (too slow = lifes at stake)
- Traditional approaches
  - test a lot (“It didn’t crash today…”)
  - write a proof (consisting of about 10K pages of math)



Challenges

- Dipartimento delle informazioni per la sicurezza (DIS) wants secure software on their office workstations.
  - need web browsers, document readers, etc.
  - need internet connectivity
  - stores and/or reads top secret documents
- not feasible to rebuild the entire universe of software from the ground up
- software is proprietary (and usually closed-source)
- How to stop secrets from leaking?

Avere dei linguaggi per il coordinamento del software che permettono di comporre assieme software sviluppato sicuro con software legacy garantendo le proprietà di sicurezza ovviamente potrebbe aiutare.

Scienza della sicurezza significa avere dei meccanismi con cui sono in grado di stabilire scientificamente cosa vuol dire avere una politica di sicurezza, quali sono le sue proprietà e come posso avere dei meccanismi di enforcement

A Science of security

- Can we develop a **science of security** like we have for math or physics?
  - Are there **certified** “proofs” of security?
  - What does it even mean for a system to be “secure”?
- Can we determine that one software system is “more secure” than other?
- Are there some security policies that are provably unenforceable?
- Can we prove that certain enforcement mechanisms can enforce certain classes of policies and not others?

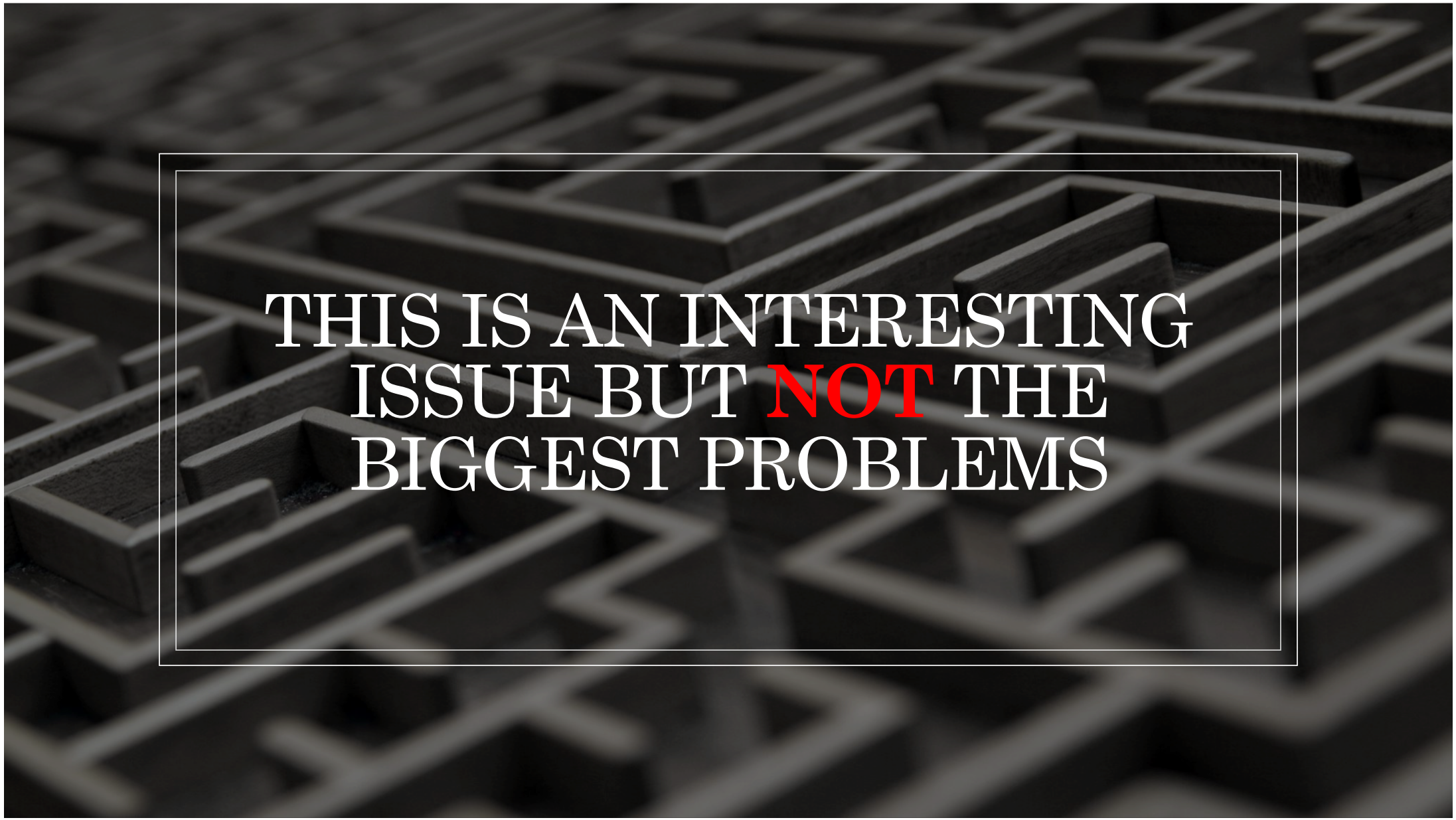

MOTIVATIONS

Why Software Security

- Software plays a major role in providing security and is the major source of security problems.
- Software is the weakest link in the security chain, with the possible exception of “the human factor”
- Software security does not get much attention
  - in programming courses,
- or indeed, in much of the security literature!

Many discussions of security begin with Alice and Bob

How can Alice communicate securely with Bob,
when Eve can modify or eavesdrop on the communication?


THIS IS AN INTERESTING
ISSUE BUT NOT THE
BIGGEST PROBLEMS

Se usiamo un canale sicuro, magari i dati arrivano correttamente da una parte all'altra però quello che ci dovremmo domandare è: abbiamo dei meccanismi per essere sicuri che il computer di Alice non è attaccato e quindi non c'è qualcun altro che ne sta prendendo il controllo? Risolvere il problema della comunicazione è sicuramente importante ma non affronta il problema di avere degli attacchi dovuti a degli input maliziosi che possono viaggiare su canali di comunicazione sicura.

Alice's computer is communicating with *another computer*

possibly malicious input

How can we prevent Alice's computer from being hacked, when it communicates with some other computer?

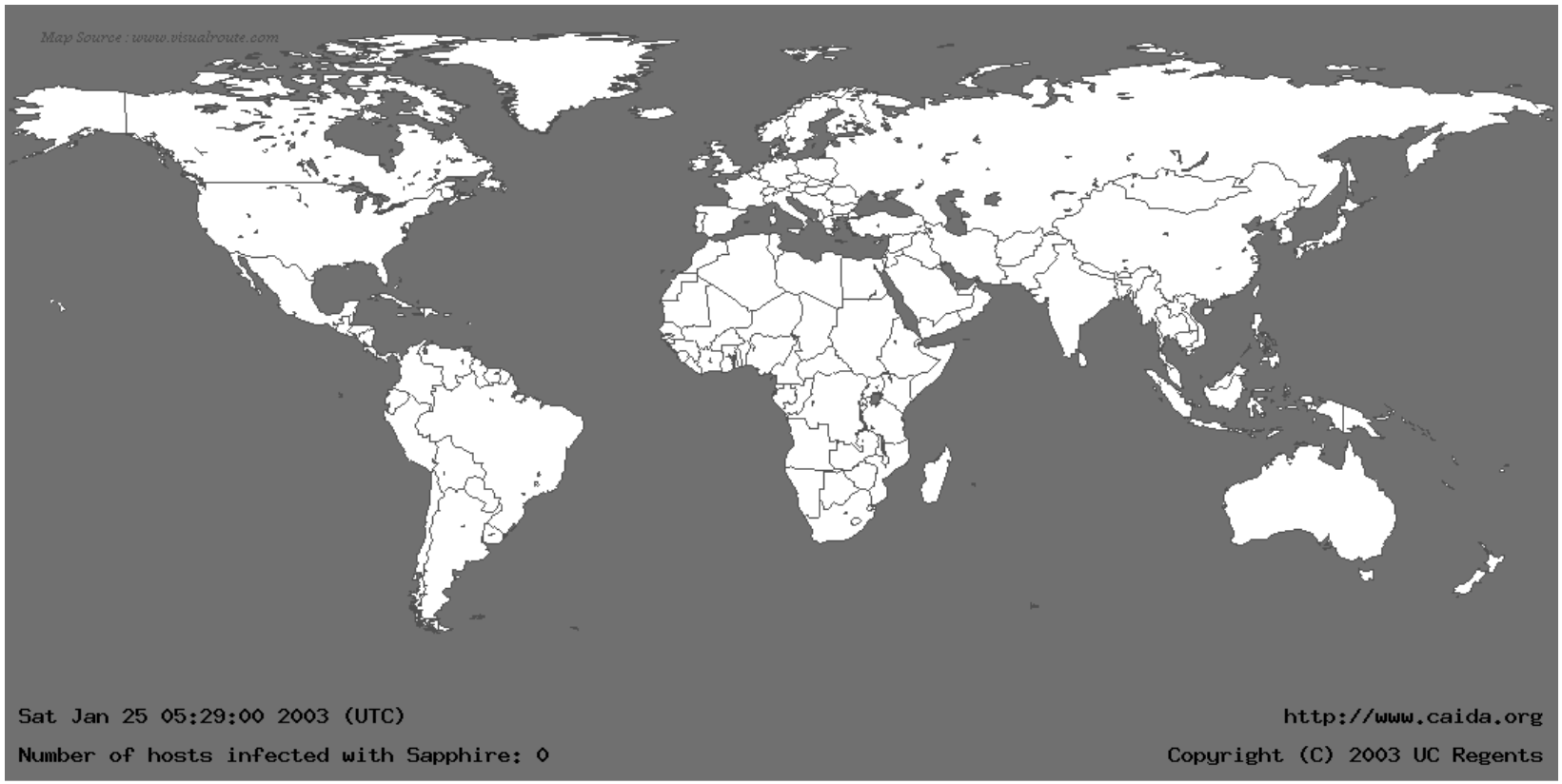
Or detect this? And then react ?

Solving the 1st problem - securing the communication - does *not* help!

The Slammer Warm (2003)

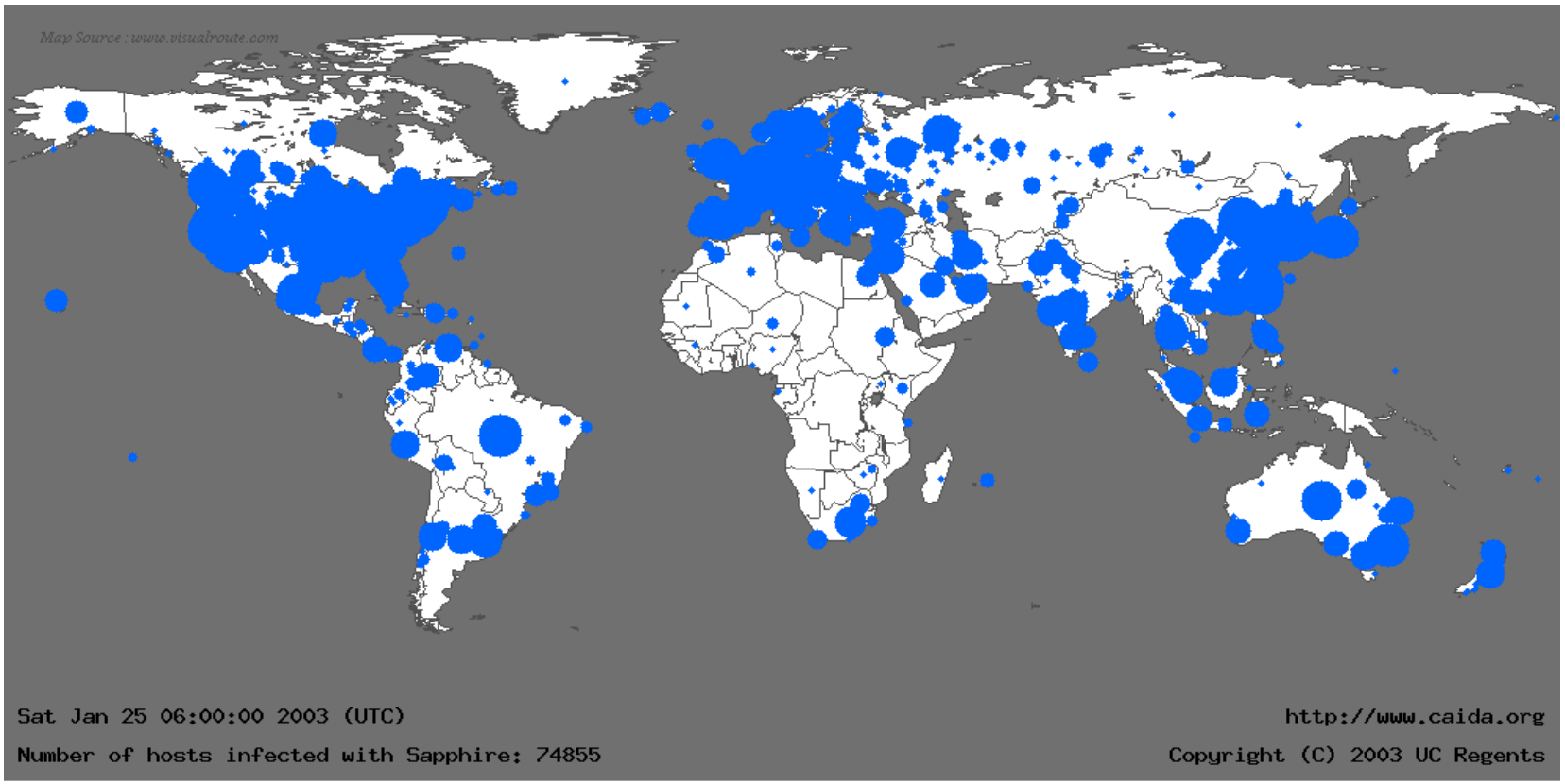
- Slammer is a 2003 computer worm that caused a denial of service on some Internet hosts and dramatically slowed general Internet traffic.
- It spreads rapidly, infecting most of its 75,000 victims within ten minutes.

FIGURA PRIMA CHE IL WORM EFFETTUASSE IL SUO ATTACCO



From *The Spread of the Sapphire/Slammer Worm*, by David Moore et al.

DOPO AVER EFFETTUATO L'ATTACCO



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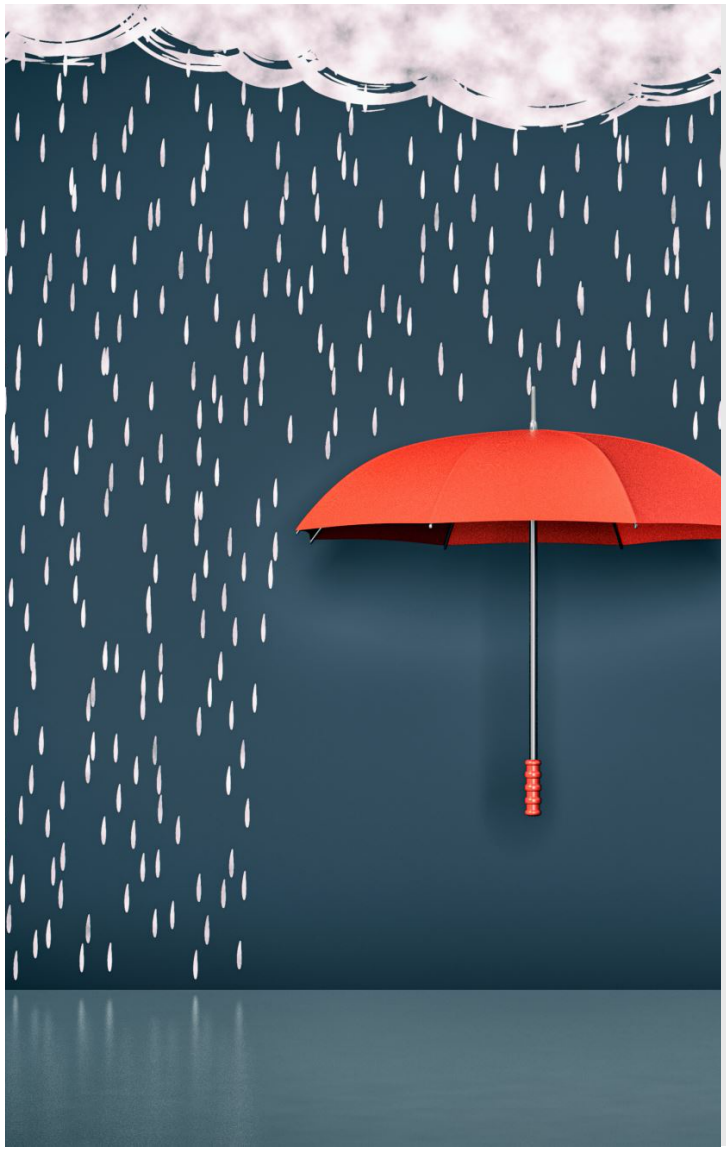


Security Problems

- To get an impression of the problem, have a look at

- US-CERT bulletins
- http://www.us-cert.gov/ncas

- CVE (Common Vulnerability Enumeration)
- https://cve.mitre.org/cve/

- NIST's vulnerability database
- https://nvd.nist.gov/vuln/search

Attackers

- Traditionally, hackers are amateurs motivated by fun
  - publishing attacks for the prestige
- Increasingly, hackers are professional
  - attackers go underground
  - zero-day exploits are worth money
  - attackers include organized crime with lots of money and (hired) expertise
- Ransomware is an important game changer, as it allows attackers to monetise nearly anything.

Software (in)security

- There are no silver bullets!
- Crypto or special security features do not magically solve all problems
  - if you think your problem can be solved by cryptography, you do not understand cryptography and you do not understand your problem" [Bruce Schneier]
- Security is an emergent property of entire system
  - (Non-functional) security aspects should be integral part of the design, right from the start

Software Security is often a secondary concern

- Security is always a secondary concern
  - Primary goal of software is to provide functionality& services;
  - Managing associated risks is a derived/secondary concern
- There is often a trade-off/conflict between
  - Security
  - Functionality
- where security typically loses out

Functionality vs Security

- Functionality is about what software should do,
- Security is (also) about what it should not do
- Unless you think like an attacker, you will be unaware of any potential threats

Lost Battles?

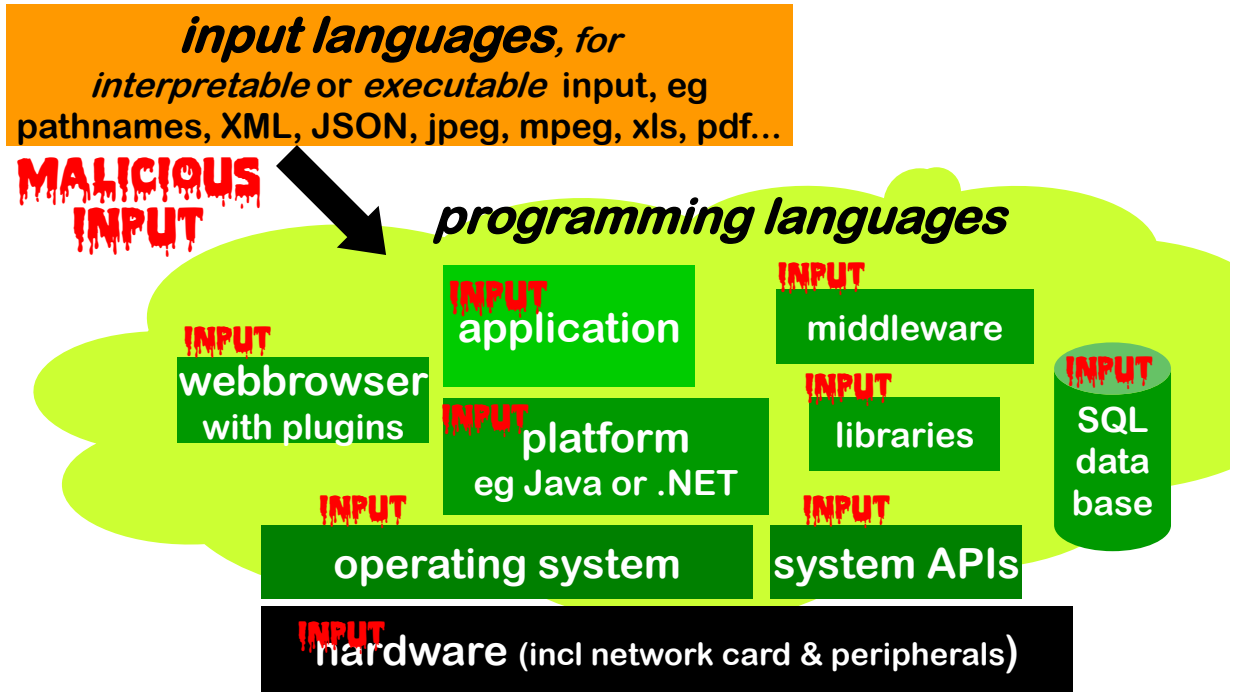
- operating systems (OSs)
  - with huge OS, with huge attack surface
- Traditional programming languages PENSATI PER ESSERE EFFICIENTI MA NON SICURI
  - with easy to use, efficient, but very insecure and error-prone mechanisms
- web browsers
  - with JavaScript, plug-ins for Flash & Java, access to microphone, web cam, location, ...
- email clients
  - which automatically cope with all sorts of formats & attachments

"After writing PHP forum software for three years now, I've come to the conclusion that it is basically impossible for normal programmers to write secure PHP code.

It takes far too much effort. .... PHP's raison d'etre is that it is simple to pick up and make it do something useful. There needs to be a major push ... to make it safe for the likely level of programmers - newbies.

Newbies have zero chance of writing secure software unless their language is safe. ... "

[Source http://www.greebo.cnet/?p=320]



THE SOFTWARE WEAKNESS

The weakness in depth

- Software runs on a huge, complicated infrastructure
  - HW, OS, platforms, web browser, lots of libraries & APIs, …
- Software is built using complicated languages
  - programming languages and input languages (SQL, HTML, XML, mp4, …)
- using various tools
  - compilers, IDEs, pre-processors, dynamic code downloads
- All of these may have security holes, or may make the introduction of security holes very easy & likely

Software Security: Recap

- A variety of problems are due to
  - lack of awareness of threats, but also of what should be protected
  - lack of knowledge of potential security problems, but also of solutions
- people choosing functionality over security
- compounded by complexity of software written in a variety of programming languages, using unsecure compilers, using large APIs, and running on huge infrastructure

Flaws vs Vulnerability

- security weaknesses / flaws:
  - things that are wrong or could be better done
- security vulnerabilities
  - Flaws that can actually be exploited by an attacker
  - Flaws are accessible: attacker has to be able to get at it
  - Flows are exploitable: attacker has to be able to do some damage with it
- Example: turning off Wifi and BlueTooth network connection, many security vulnerabilities become flaws

Design vs Implementation Flaws

Design flaws

- vulnerability in the design

Implementation flaws aka code-level defects

- vulnerability in the software introduced during coding (either by the programmer or by the compiler tool chain)

Overall consensus: implementation flaws and design flaws roughly equally common

- Vulnerabilities also arise on other levels
  - configuration flaws when installing software on a machine
  - unforeseen consequence of the intended functionality (eg spam)

Implementation flaws

- For flaws introduced during coding, we can distinguish
- Flaws that can be understood looking at the program itself
  - simple typos, confusing two program variables, off-by-one
  - error in array access, errors in the program logic,...
- Flows due to the interaction with the underlying platform or other systems (compilers) and services
  - buffer overflows in C(++) code
  - SQL injection, XSS, CSRF,.... in web-applications
  - Deserialisation attacks in many programming languages

Example: compilation

```
1 package Bank;
2
3 public class Account{
4   private int balance = 0;
5
6   public void deposit( int amount ) {
7     this.balance += amount;
8   }
9 }
```

Listing 1. Example of Java source code.

Immaginando di compilare il codice precedente in C, si ottiene che la classe viene implementata in termini di una struct, questa struct ha il campo balance a 0 e ha la possibilità di avere un puntatore al codice di una funzione che fa il deposito. La privacy del balance in questo caso non è più garantita,è possibile accedere al balance e si può assegnare un nuovo metodo allo struct al posto di quello definito dal programmatore.

Example compilation (cont.)

```
1 typedef struct account_t {
2   int balance = 0;
3   void ( *deposit ) ( struct Account*, int ) = deposit_f;
4 } Account;
5
6 void deposit_f( Account* a, int amount ) {
7   a→balance += amount;
8   return;
9 }
```

Listing 2. C code obtained from compiling the Java code of Listing 1.

Example Compilation (Cont)

When the Java code in Listing 1 interacts with other Java code, the latter cannot access the contents of `balance` since it is a private field. However, when the Java code is compiled into the C code in Listing 2 and then interacts with arbitrary C code, the latter can access the contents of `balance` by doing simple pointer arithmetic. Given a pointer to a C `Account` **`struct`**, an attacker can add the size (in words) of an **`int`** to it and read the contents of `balance`, effectively violating a confidentiality property that the source program had.

BISOGNA LAVORARE NON SOLO A LIVELLO DELLA PROGETTAZIONE DEL LINGUAGGIO DI PROGRAMMAZIONE MA ANCHE A LIVELLO DELLA STRUTTURA DEL RUN TIME E SUL PROCESSO DI COMPILAZIONE DUNQUE SULLE TECNICHE DI IMPLEMENTAZIONE DEL LINGUAGGIO DI PROGRAMMAZIONE.

Why?

This violation occurs because there is a discrepancy between what abstractions the source language offers and what abstraction the target language has.

The source languages provide powerful abstractions whose goal is allowing a programmer to write better code.

The source-level abstractions can be used to enforce security properties, but target languages that do not preserve such security properties are vulnerable to attacks.

Unfortunately, most target languages cannot preserve the abstractions of their source-level counterparts

Bad & Good News

- The bad news
  - people keep making the **same** mistakes
- The good news
  - people keep making the **same** mistakes
- **..... so we can do something about it!**

Java code: spot the (security) flaws

```
int balance;

void decrease(int amount)
 { if (balance <= amount)
       { balance = balance - amount; }
 else { printf("Insufficient funds\n"); }
 }

void increase(int amount)
 { balance = balance + amount;
}
```

Possibili difetti:
1) in increase() amount può essere negativo
2) inversione della direzione del confronto nell'if di decrease
3) balance non è inizializzato
4) balance non è privato
...

Java code: spot the (security) flaws

```
int balance;

void decrease(int amount)
 { if (balance <= amount)
       { balance = balance - amount; }
 else { printf("Insufficient funds\n"); }
 }

void increase(int amount)
 { balance = balance + amount;
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balance >= amount

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What if amount is negative?

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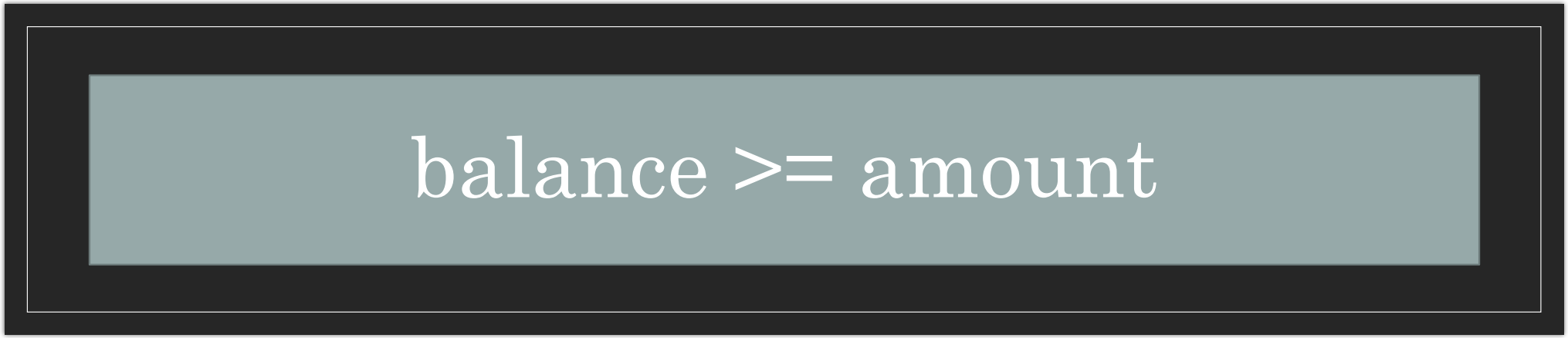
What if amount is negative?

What if balance + amount is too large for int?

What if amount is negative

lack of input validation of (untrusted) user input

could be a design flaw rather than an implementation flaw



Logical (design) error

What if balance + amount is too large for a 64 bit int?

Lower level error

Interaction with the underlying virtual machine

Dipende da cosa c'è sotto per essere in grado di risolvere anche questo tipologie di problemi.

DISCUSSION