Software architecture for reactive systems (introduction)

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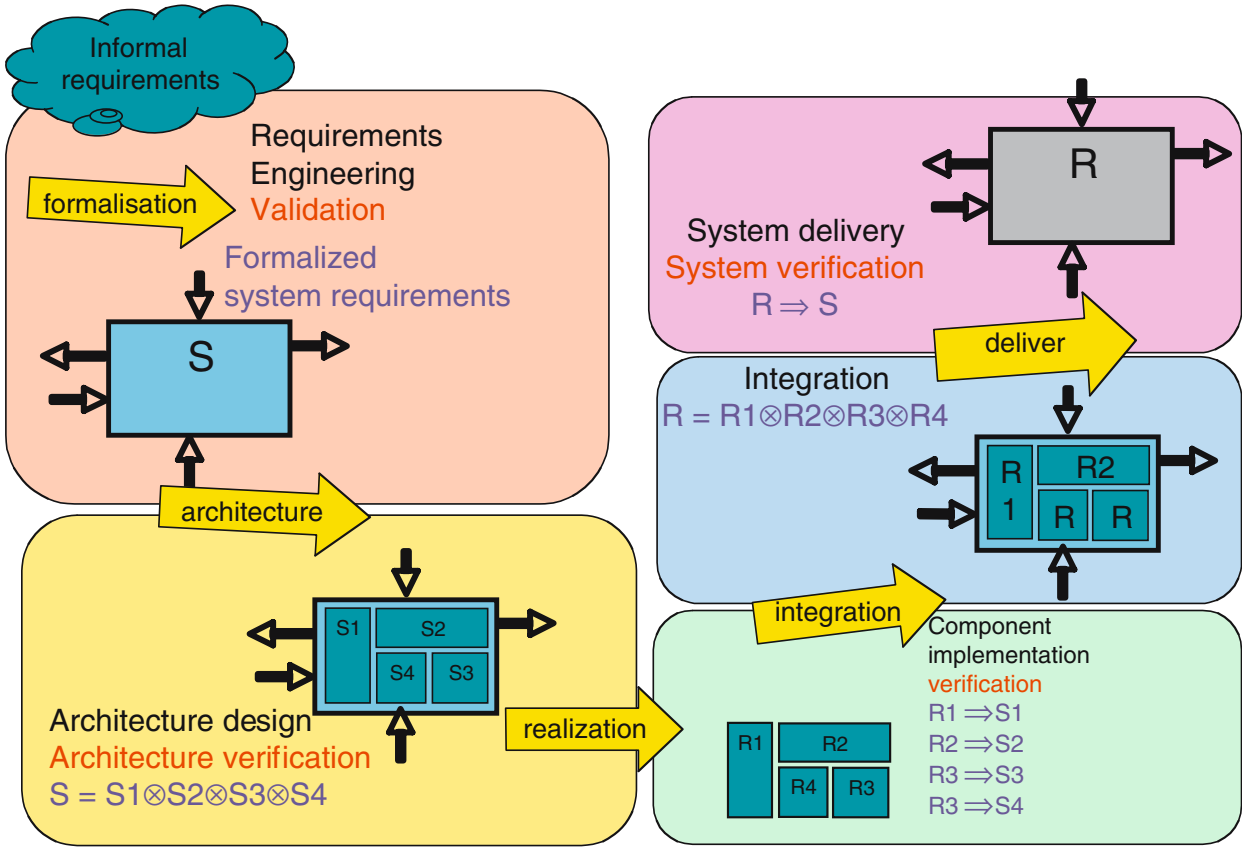
Software Engineering

Software development as one of the most complex but at the same time most effective tasks in the engineering of innovative applications:

- Software drives innovation in many application domains
- Appropriate software provides engineering solutions that can calculate results, communicate messages, control devices, animate and reason about all kinds of information
- Actually software is becoming everyware ...

Software Engineering



(illustration from [Broy, 2007])

Software Engineering

So, ... yet another module in the MFES profile?

Software architecture for reactive systems

characterised by

- a methodological shift: an architectural perspective
- a focus: on reactive systems

What is software architecture?

[Garlan & Shaw, 1993]

the systematic study of the overall structure of software systems

[Perry & Wolf, 1992]

SA = { Elements (*what*), Form (*how*), Rationale (*why*) }

[Kruchten, 1995]

deals with the design and implementation of the high-level structure of software

[Britton, 2000]

a discipline of generic design

What is software architecture?

[Garlan & Perry, 1995]

the structure of the components of a program/system, their interrelationships, and principles and guidelines governing their design and evolution over time

[ANSI/IEEE Std 1471-2000]

the fundamental organisation of a system, embodied in its components, their relationships to each other and the environment, and the principles governing its design and evolution.

[Garlan, 2003]

a bridge between requirements and code (...) a blueprint for implementation.

What is software architecture?

The architecture of a system describes its gross structure which illuminates the top level design decisions, namely

- how is it composed and of which interacting parts?
- where are the pathways of interaction?
- which are the key properties of the parts the architecture rely and/or enforce?

What is software architecture?

A framework to perform early verification of a system and ensure composability of separately developed parts, providing

- structural *vs* behavioural views
- hierarchical decomposition into interacting entities
- functional *vs* non functional properties
  (e.g. performance, reliability, dependability, portability, scalability, interoperability ...)
  to analyse schedulability, flow latency, memory consumption
- design guidelines (e.g. binding threads to processors to make the system schedulable)
- models for adaptation and reconfigurability
- ...

What is software architecture?

Which structure? $\rightsquigarrow$ Architectural views

- code-based structures: such as modules, classes, packages and relationships like uses, inherits from or depends on.
- run-time structures: such as object instances, clients, servers, databases, browsers, channels, broadcasters, software buses, ...
- allocation structures: intended to map code-based and run-time structures to external items, such as network locations, physical devices, managerial structures ...

This course

- focus on run-time structures
- and entails a particular view: components & glue

What is software architecture?

Components:

Loci of computation and data stores, encapsulating subsets of the system's functionality and/or data;
Equipped with run-time interfaces defining their interaction points and restricting access to those subsets;
May explicitly define dependencies on their required execution contexts;
Typically provide application-specific services

Connectors:

Pathways of interaction between components;
Ensure the flow of data and regulates interaction;
Typically provide application-independent interaction facilities;
Examples: procedure calls, pipes, wrappers, shared data structures, synchronisation barriers, etc.

What is software architecture?

Configurations:

Specifications of how components and connectors are associated;
Examples: relations associating component ports to connector roles, mapping diagrams, etc.

Properties:

Set of non functional properties associated to any architectural element;
Examples (for components): availability, location, priority, CPU usage, ...
Examples (for connectors): reliability, latency, throughput, ...

What is software architecture?

Constraints:

Represent claims about an architectural design that should remain true even as it evolves over time. Typical constraints include restrictions on allowable values of properties, topology, and design vocabulary. For example, the number of clients of a particular server is less than some maximum value.

Styles:

Styles represent families of related systems. A style defines a vocabulary of design element types and rules for composing them. Examples include dataflow architectures based on pipes and filters, blackboard architectures based on shared data space and a set of knowledge sources, and layered systems.

Two examples

from the micro level (a Unix shell script)

```
cat invoices | grep january | sort
```

- Application architecture can be understood based on very few rules
- Applications can be composed by non-programmers
- ... a simple architectural concept that can be comprehended and applied by a broad audience

Two examples

to the macro level (the WWW architecture)

- Architecture is totally separated from the code
- There is no single piece of code that implements the architecture
- There are multiple pieces of code that implement the various components of the architecture (e.g., different browsers)
- One of the most successful applications is only understood adequately from an architectural point of view

Architectural styles (or patterns)

An architectural style consists of:

- a set of component types (e.g., process, procedure) that perform some function at runtime
- a topological layout of the components showing their runtime relationships
- a set of semantic constraints (e.g. a layer may only talk to its adjacent)
- a set of connectors (e.g., data streams, sockets) that mediate communication among components

Architectural styles (or patterns)

- classify families of software architectures
- act as types for configurations
- provide
  - domain-specific design vocabulary (eg, set of connector and component types admissible)
  - a set of constraints to single out which configurations are well-formed. Eg, a pipeline architecture might constraint valid configurations to be linear sequences of pipes and filters.
  - guidance for architectural design based on the problem domain and the deployment context

Examples

- Layers
- Client & Server
- Master & Slave
- Publish & Subscribe
- Peer2Peer
- Pipes and Filters
- Event-bus
- Repositories
  - triggering by transactions: databases
  - triggering by current state: blackboard
- Table-driven (virtual machines)
- ...

Pattern: Layers

- helps to structure applications that can be decomposed into groups of subtasks at different levels of abstraction
- Layer n provides services to layer $n+1$ implementing them through services of the layer $n+1$
- Typically, service requests resort to synchronous procedure calls

Examples:

virtual machines (eg, JVM)
APIs (eg, C standard library on top of Unix system calls)
operating systems (eg, Windows NT microkernel)
networking protocols (eg, ISO OSI 7-layer model; TCP/IP)

Pattern: Client-Server

- permanently active servers supporting multiple clients
- requests typically handled in separate threads
- stateless (session state maintained by the client) vs stateful servers
- interaction by some inter-process communication mechanism

Examples:

remote DB access
web-based applications
interactive shells

Pattern: Peer-2-Peer

- symmetric Client-Service pattern
- peers may change roles dynamically
- services can be implicit (eg, through the use of a data stream)

Examples:

multi-user applications
P2P file sharing

Pattern: Publish-Subscribe

- used to structure distributed systems whose components interact through remote service invocations
- servers publish their capabilities (services + characteristics) to a broker component, which accepts client requests and coordinate communication
- allows dynamic reconfiguration
- requires standardisation of service descriptions through IDL (eg CORBA IDL, .Net, WSDL) or a binary standard (eg, Microsoft OLE — methods are called indirectly using pointers)

Examples:

web services
CORBA (for cooperation among heterogeneous OO systems)

Pattern: Master-Slave

- a master component distributes work load to similar slave components and computes a final result from the results these slaves return
- isolated slaves; no sharing of data
- supports fault-tolerance and parallel computation

Examples:

dependable systems

Pattern: Event-Bus

- event sources publish messages to particular channels on an event bus
- event listeners subscribe to particular channels and are notified of message availability
- asynchronous interaction
- channels can be implicit (eg, using event patterns)
- allows dynamic reconfiguration
- variant of so-called event-driven architectures

Examples:

process monitoring
trading systems

Pattern: Pipe & Filter

- suitable for data stream processing
- each processing step is encapsulated into a filter component
- uniform data format
- no shared state
- concurrent processing is natural

Examples:

compilers
Unix shell commands

Pattern: Blackboard

- suitable for problems with non deterministic solution strategy known
- all components have access to a shared data store
- components feed the blackboard and inspect it for new partial data
- extending the data space is easy, but changing its structure may be hard

Examples:

complex IA problems (eg, planning, machine learning)
complex applications in computing science (eg, speech recognition; computational chemistry)

Software Architecture as a discipline

- Until the 90's, SA was largely an ad hoc affair
  (but see [Dijkstra,69], [Parnas79], ...)
- Descriptions relied on informal box-and-line diagrams, rarely maintained once the system was built

Challenges

- recognition of a shared repertoire of methods, techniques and patterns for structuring complex systems
- quest for reusable frameworks for the development of product families

The last 15 years

- Formal notations for representing and analysing SA: ADL
- Examples: Wright, Rapide, SADL, Darwin, C2, Aesop, Piccola, AADL

ADLs provide:

- conceptual framework + concrete syntax
- tools for parsing, displaying, analysing or simulating architectural descriptions

- Acme [Garlan et al, 97] as an architectural interchange language (a sort of XML for architectural description)
- Use of model-based prototyping tools (eg Z, VDM) or model-checkers (eg Alloy) to analyse architectural descriptions

The last 15 years

- Classification of architectural styles characterising families of SA and acting as types for configurations
- Standardisation efforts: ANSI/IEEE Std 1471-2000, but also 'local' standards (eg, Sun's Enterprise JavaBeans architecture)
- Impact of the emergence of a general purpose (object-oriented) design notation — UML — closer to practitioners and with a direct link to OO implementations
- SA becomes a mature discipline in Software Engineering; new fields include documentation and architectural recovery from legacy code

Current trends

Everyware everywhere

- Everyware products
- vs everywhere development:
  many companies look at themselves more as system integrators rather than as software developers:

> the code they write is glue code ...
> which entails the need for common frameworks to reduce architectural mismatchs

Current trends

From object-oriented to component-based

- In OO the architecture is implicit: source code exposes class hierarchies but not the run-time interaction
- Objects are wired at a very low level and the description of the wiring patterns is distributed among them
- CBD retains the basic encapsulation of data and code principle to increase modularity but shifts the emphasis from class inheritance to object composition
- ... to avoid interference between inheritance and encapsulation and pave the way to a development methodology based on third-party assembly of components

Current trends

From programming-in-the-large to programming-in-the-world

> 'not only the complexity of building a large application that one needs to deliver, in time and budget, to a client, but of managing an open-ended structure of autonomous components, possibly distributed and highly heterogeneous.
> This means developing software components that are autonomous and can be interconnected with other components, software or otherwise, and managing the interconnections themselves as new components may be required to join in and others to be removed.'
>
> [Fiadeiro, 05]

Challenges

Such trends entails a number of challenges to the way we think about SA

- new target: need for an architectural discipline for reactive systems
  (often complex, time critical, mobile, cyber-physical, etc ...)
- from composition to coordination (orchestration)
- relevance of wrappers and component adapters: integration *vs* incompatible assumptions about component interaction
- reconfigurability
- continued interaction as a first-class citizen and the main form of software composition

Reactive systems

Reactive system

system that computes by reacting to stimuli from its environment along its overall computation

- in contrast to sequential systems whose meaning is defined by the results of finite computations, the behaviour of reactive systems is mainly determined by interaction and mobility of non-terminating processes, evolving concurrently.
- observation $\equiv$ interaction
- behaviour $\equiv$ a structured record of interactions

Reactive systems

Concurrency vs interaction

$$x := 0;$$
$$x := x + 1 \mid x := x + 2$$

- both statements in parallel could read x before it is written
- which values can x take?
- which is the program outcome if exclusive access to memory and atomic execution of assignments is guaranteed?

Our approach

There is no general-purpose, universally tailored, approach to architectural design of complex and reactive systems

Therefore, the course

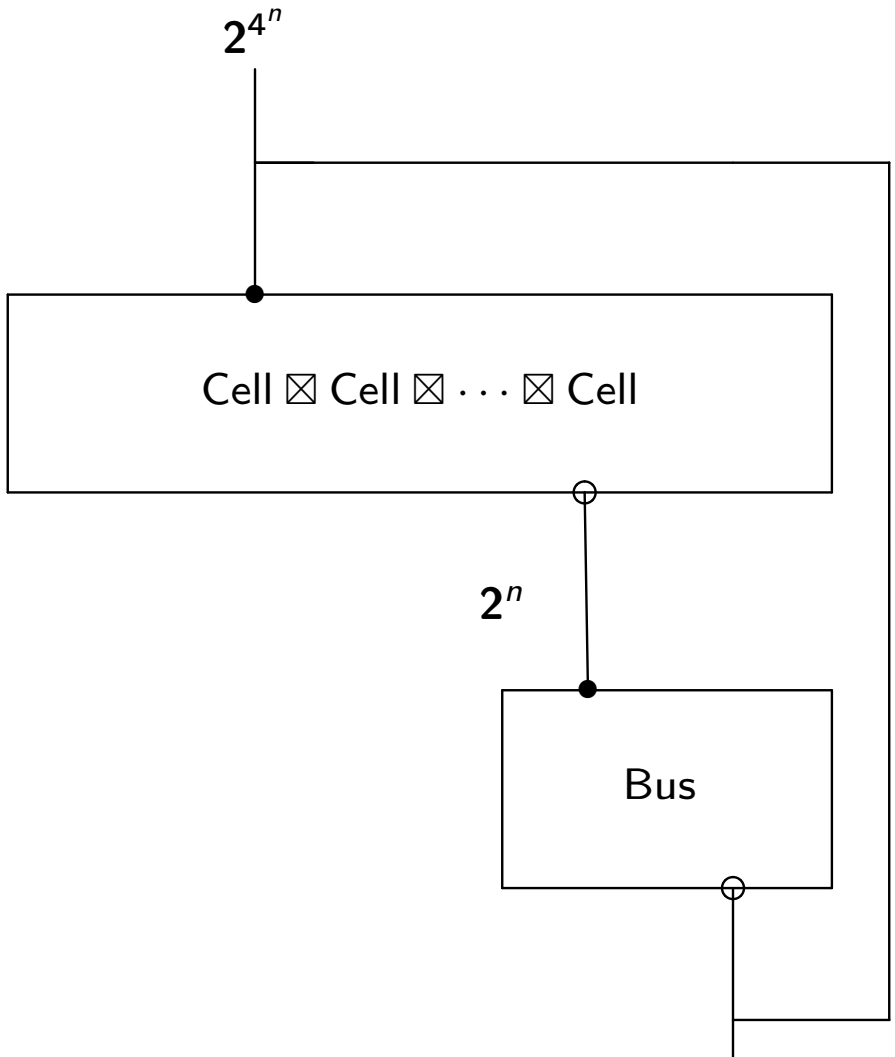
- introduces different models for reactive systems
- discusses their architectural design and analysis
- with (reasonable) tool support for modelling and analysis

Syllabus

- Introduction to software architecture
- Background
  - Introduction to transition systems (mCRL2)
  - Introduction to modal, hybrid and dynamic logic (mCRL2)
- Models and calculi of reactive systems
  - Timed (with real time constraints) (Uppaal)
  - Probabilistic (PRISM)
  - Cyber-physical (KeYmaera)
- Architecture for reactive systems
  - Component-oriented architectural design
    - Paradigm: Software components as monadic Mealy machines
    - Method: The mMm calculus; prototyping in Haskell
  - Coordination-oriented architectural design
    - Paradigm: The Reo exogenous coordination model
    - Method: Compositional specification of the glue layer

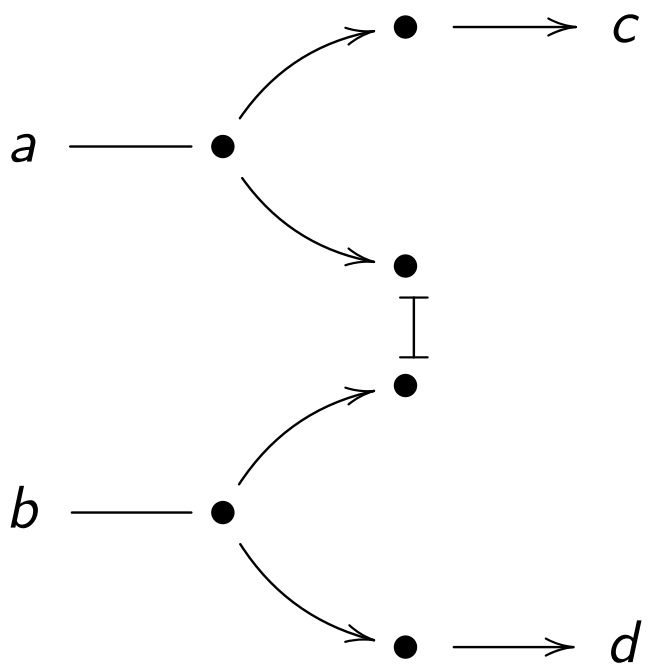
Component-oriented architectural design

new components from old in mMm



Coordination-oriented architectural design

a connector (synchronization barrier) in Reo



Pragmatics ...

- **Assessment:**
  - Test in June - 60 %
  - Group projects (3x) - 40 % (10+15+15)

http://ac1516.proenca.org

- **Research context:** Projects
  - Nasoni — 2012-15
    on heterogenous software coordination
    (continuous vs discrete systems)
  - Dali — 2016-18
    on Dynamic logics for cyber-physical systems

possible GRANTS available!
(with U. Nijmegen, U. Aveiro, CWI, INESC TEC)