ETH Zürich
Chair of Software Engineering

Robotics Programming Laboratory

Bertrand Meyer
Jiwon Shin

Lecture 9: Software Architecture in Robotics

Some design patterns

Creational

- Abstract Factory
- Builder
- Factory Method
- Prototype
- Singleton

Structural

- Adapter
- Bridge
- Composite
- Decorator
- Façade
- Flyweight
- Proxy

Behavioral

- Chain of Responsibility
- Command (undo/redo)
- Interpreter
- Iterator
- Mediator
- Memento
- Observer
- State
- Strategy
- Template Method
- Visitor

Erich Gamma, Ralph Johnson, Richard Helms, John Vlissides: *Design Patterns*, Addison-Wesley, 1994

Benefits of design patterns

- Capture the knowledge of experienced developers
- Publicly available repository
- Common pattern language
- Newcomers can learn & apply patterns
- Yield better software structure
- Facilitate discussions: programmers, managers

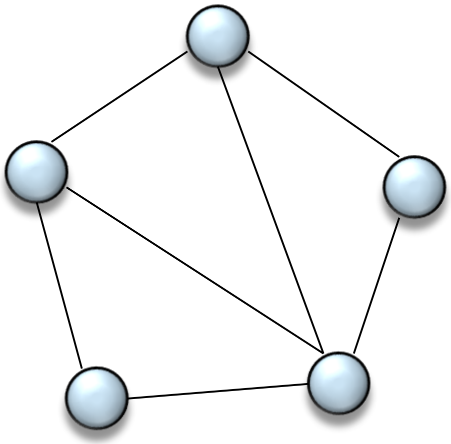
Architectural styles
(based in part on material by Peter Müller)

Software architecture styles

An architectural style is defined by

- Type of basic architectural components
  (e.g. classes, filters, databases, layers)

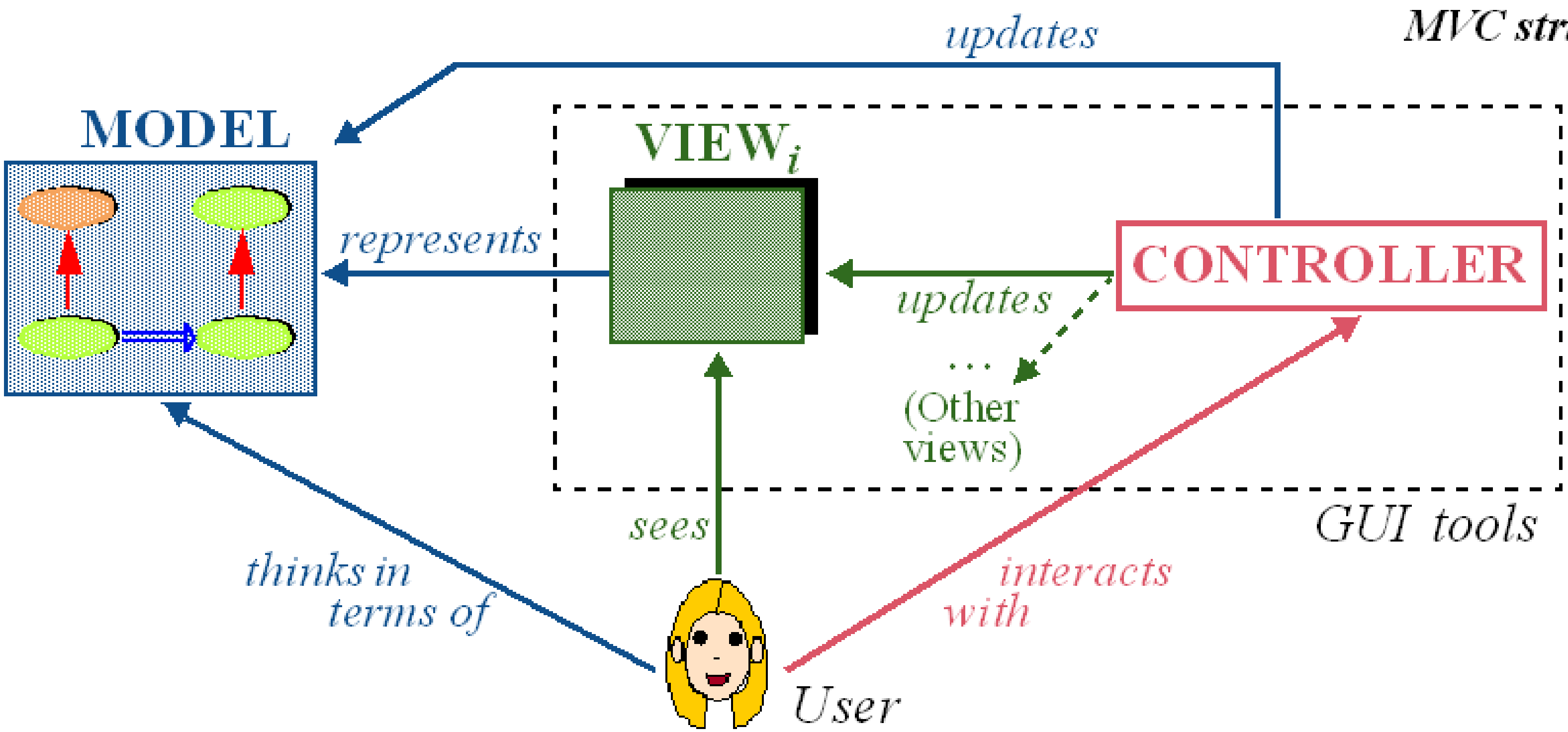
- Type of connectors
  (e.g. calls, pipes, inheritance,
  event broadcast)



Model-View Controller

(Trygve Reenskaug, 1979)

MVC structure



Architecture styles

Overall system organization:

- Hierarchical
- Client-server
- Cloud-based
- Peer-to-peer

Individual program structuring:

- Control-based
  - Call-and-return (Subroutine-based)
  - Coroutine-based
- Dataflow:
  - Pipes and filters
  - Blackboard
  - Event-driven
- REST
- Object-oriented

Hierarchical

Each layer provides **services to the layer above** it and acts as a client of the layer below

Each layer collects services at a particular level of **abstraction**

A layer depends only on lower layers

- Has no knowledge of higher layers

Example

- Communication protocols
- Operating systems

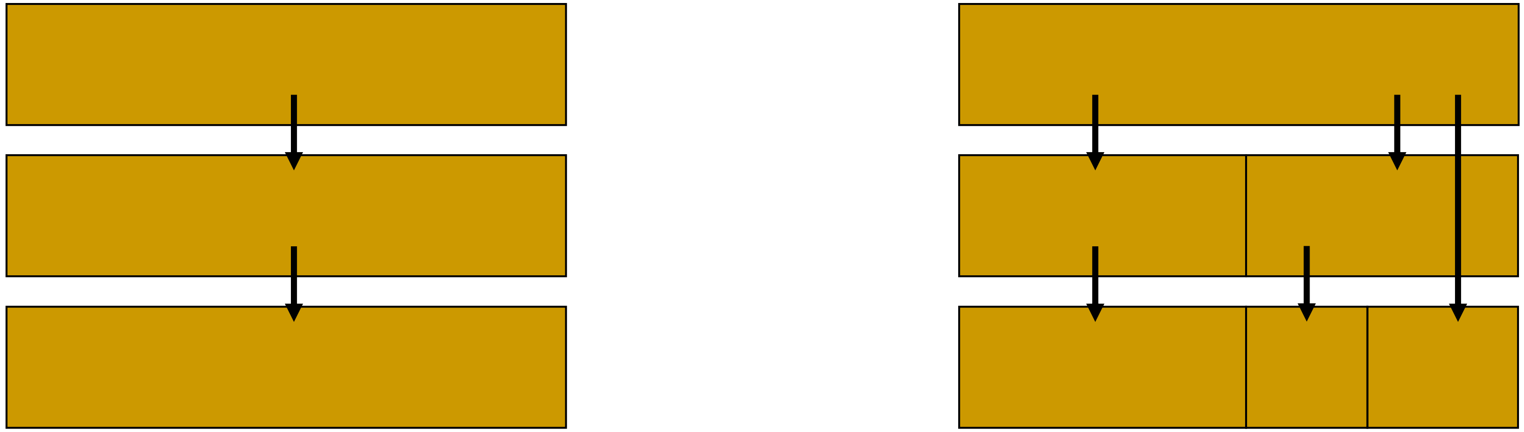
Hierarchical

Components

- Group of subtasks which implement an abstraction at some layer in the hierarchy

Connectors

- Protocols that define how the layers interact



Hierarchical: examples

THE operating system (Dijkstra)

The OSI Networking Model

- Each level supports communication at a level of abstraction
- Protocol specifies behavior at each level of abstraction
- Each layer deals with specific level of communication and uses services of the next lower level

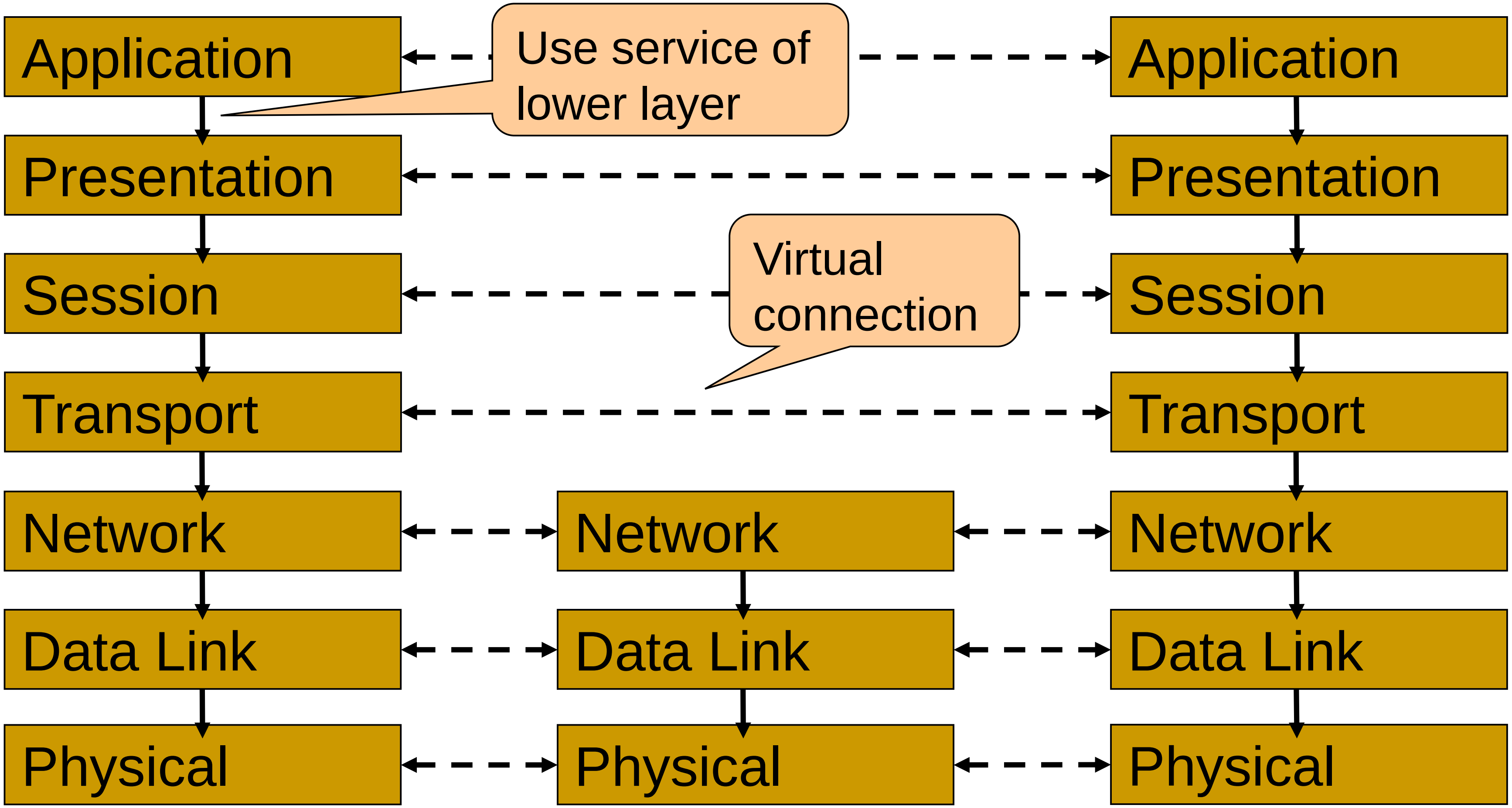
Layers can be exchanged

- Example: Token Ring for Ethernet on Data Link Layer

OSI model layers

Application	The system you are designing
Presentation	Data transformation services, such as byte swapping and encryption
Session	Initializes a connection, including authentication
Transport	Reliably transmits messages
Network	Transmits & routes data within network
Data Link	Sends & receives frames without error
Physical	Sends and receives bits over a channel

Hierarchical style example



Hierarchical: discussion

Strengths:

- Separation into levels of abstraction; helps partition complex problems
- Low coupling: each layer is (in principle) permitted to interact only with layer immediately above and under
- Extendibility: changes can be limited to one layer
- Reusability: implementation of a layer can be reused

Weaknesses:

- Performance overhead from going through layers
- Strict discipline often bypassed in practice

Call-and-return

Components: Objects

Connectors: Messages (routine invocations)

Key aspects

- Object preserves integrity of representation (encapsulation)
- Representation is hidden from client objects

Variations

- Objects as concurrent tasks

Call-and-return

Strengths:

- Change implementation without affecting clients
- Can break problems into interacting agents
- Can distribute across multiple machines or networks

Weaknesses:

- Objects must know their interaction partners; when partner changes, clients must change
- Side effects: if *A* uses *B* and *C* uses *B*, then *C*'s effects on *B* can be unexpected to *A*

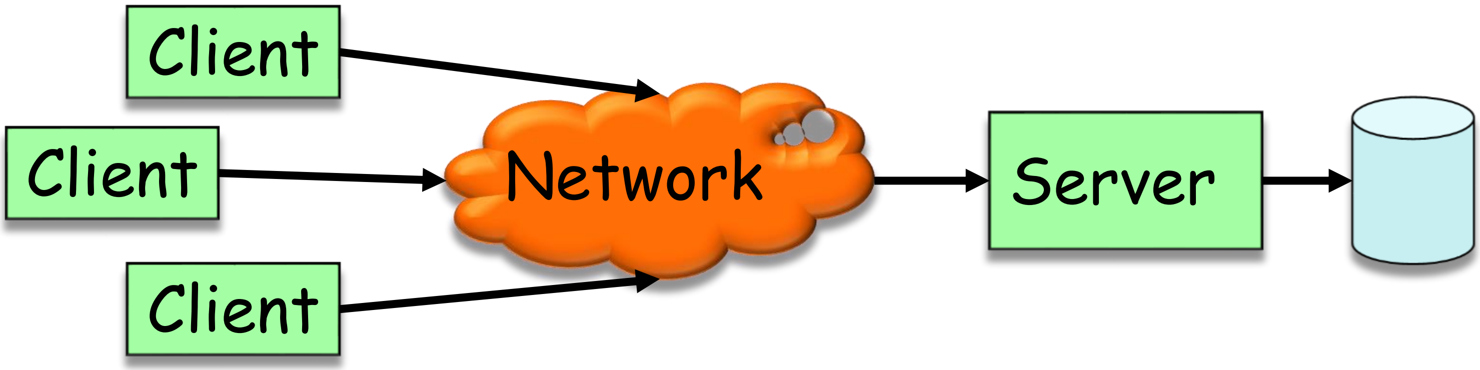
Client-server

Components

- Subsystems, designed as independent processes
- Each server provides specific services, e.g. printing, database access
- Clients use these services

Connectors

- Data streams, typically over a communication network



Client -server example: databases

Clients: user applications

- Customized user interface
- Front-end processing of data
- Initiation of server remote procedure calls
- Access to database server across the network

Server: DBMS, provides:

- Centralized data management
- Data integrity and database consistency
- Data security
- Concurrent access
- Centralized processing

Client-server variants

Thick / fat client

- Does as much processing as possible
- Passes only data required for communications and archival storage to the server
- Advantage: less network bandwidth, fewer server requirements

Thin client

- Has little or no application logic
- Depends primarily on server for processing
- Advantage: lower IT admin costs, easier to secure, lower hardware costs.

Client-server: discussion

Strengths:
- Makes effective use of networked systems
- May allow for cheaper hardware
- Easy to add new servers or upgrade existing servers
- Availability (redundancy) may be straightforward

Weaknesses:
- Data interchange can be hampered by different data layouts
- Communication may be expensive
- Data integrity functionality must be implemented for each server
- Single point of failure

Client-server variant: cloud computing

The server is no longer on a company's network, but hosted on the Internet, typically by a providing company

Example: cloud services by Google, Amazon, Microsoft

Advantages:

- Scalability
- Many issues such as security, availability, reliability are handled centrally

Disadvantages:

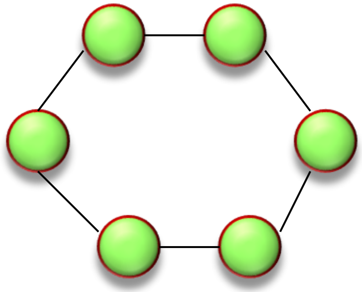
- Loss of control
- Dependency on Internet

Peer-to-peer

Similar to client-server style, but **each component is both client and server**

Pure peer-to-peer style

- No central server, no central router



Hybrid peer-to-peer style

- Central server keeps information on peers and responds to requests for that information

Examples

- File sharing applications, e.g., Napster
- Communication and collaboration, e.g., Skype

Peer-to-peer: discussion

Strengths:

- Efficiency: all clients provide resources
- Scalability: system capacity grows with number of clients
- Robustness
  - Data is replicated over peers
  - No single point of failure (in pure peer-to-peer style)

Weaknesses:

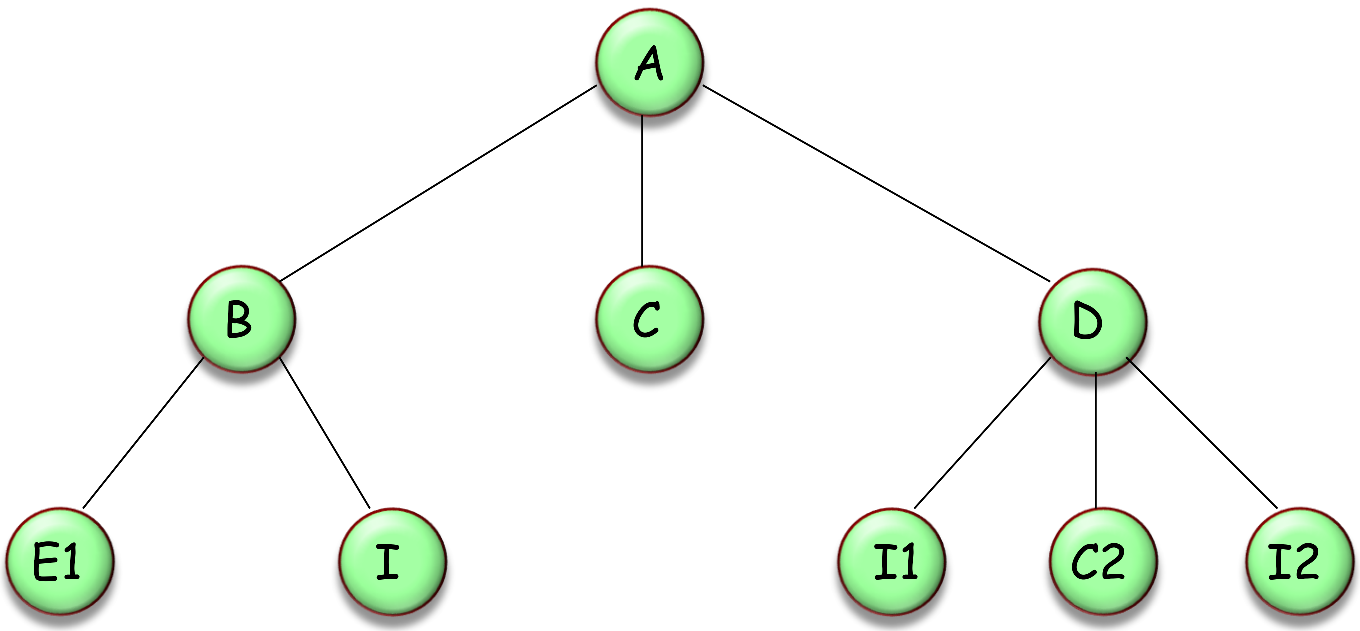
- Architectural complexity
- Resources are distributed and not always available
- More demanding of peers (compared to client-server)
- New technology not fully understood

Subroutines

Similar to hierarchical structuring at the program level

Functional decomposition

Topmost functional abstraction



Subroutines

Advantages:

- Clear, well-understood decomposition
- Based on analysis of system's function
- Supports top-down development

Disadvantages:

- Tends to focus on just one function
- Downplays the role of data
- Strict master-slave relationship; subroutine loses context each time it terminates
- Adapted to the design of individual functional pieces, not entire system

Coroutines

A more symmetric relationship than subroutines

Particularly applicable to simulation applications

A simulated form of concurrency

Dataflow systems

Availability of data controls the computation

The structure is determined by the orderly motion of data from component to component

Variations:

- Control: push versus pull
- Degree of concurrency
- Topology

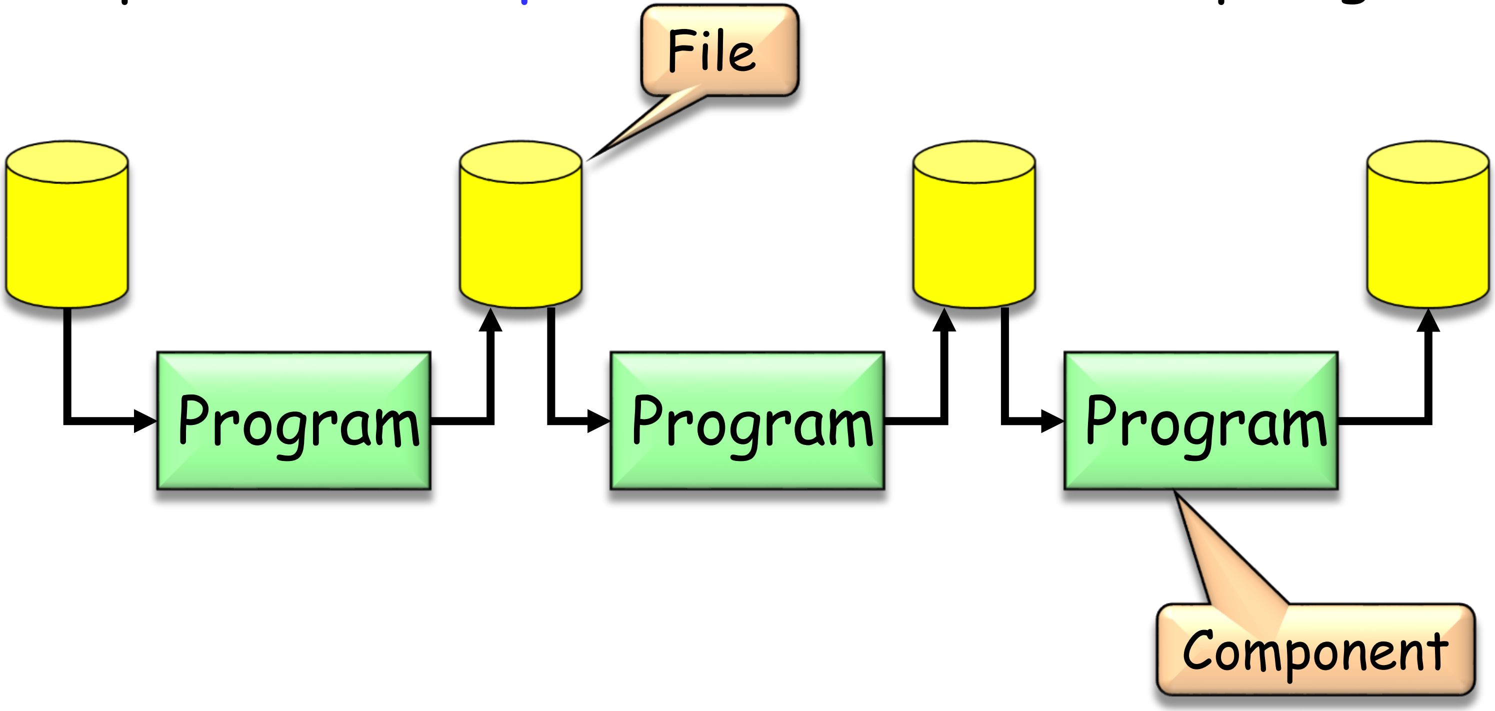
Dataflow: batch-sequential

Frequent architecture in scientific computing and business data processing

Components are independent programs

Connectors are media, typically files

Each step runs to completion before next step begins



Batch-sequential

History: mainframes and magnetic tape

Business data processing

- Discrete transactions of predetermined type and occurring at periodic intervals
- Creation of periodic reports based on periodic data updates

Examples

- Payroll computations
- Tax reports

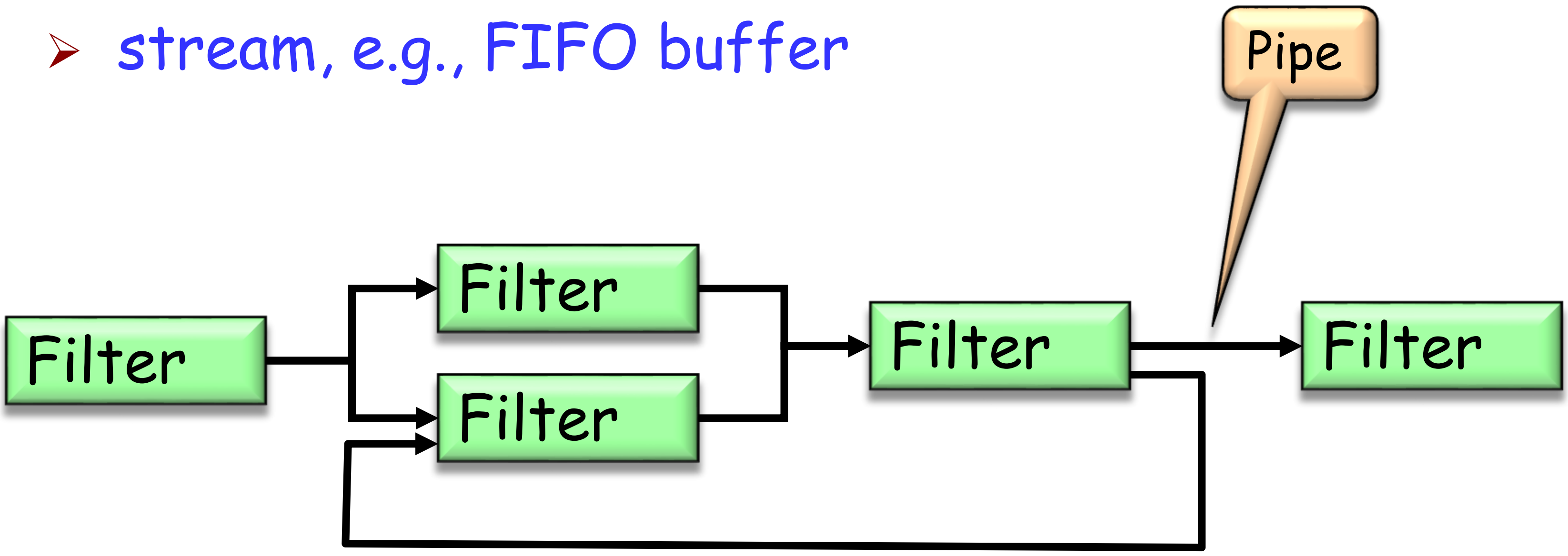
Dataflow: pipe-and-filter

Component: filter

- Reads input stream (or streams)
- Locally transforms data
- Produces output stream (s)

Connector: pipe

- stream, e.g., FIFO buffer



Pipe-and-filter

Data processed incrementally as it arrives

Output can begin before input fully consumed

Filters must be independent: no shared state

Filters don't know upstream or downstream filters

Examples

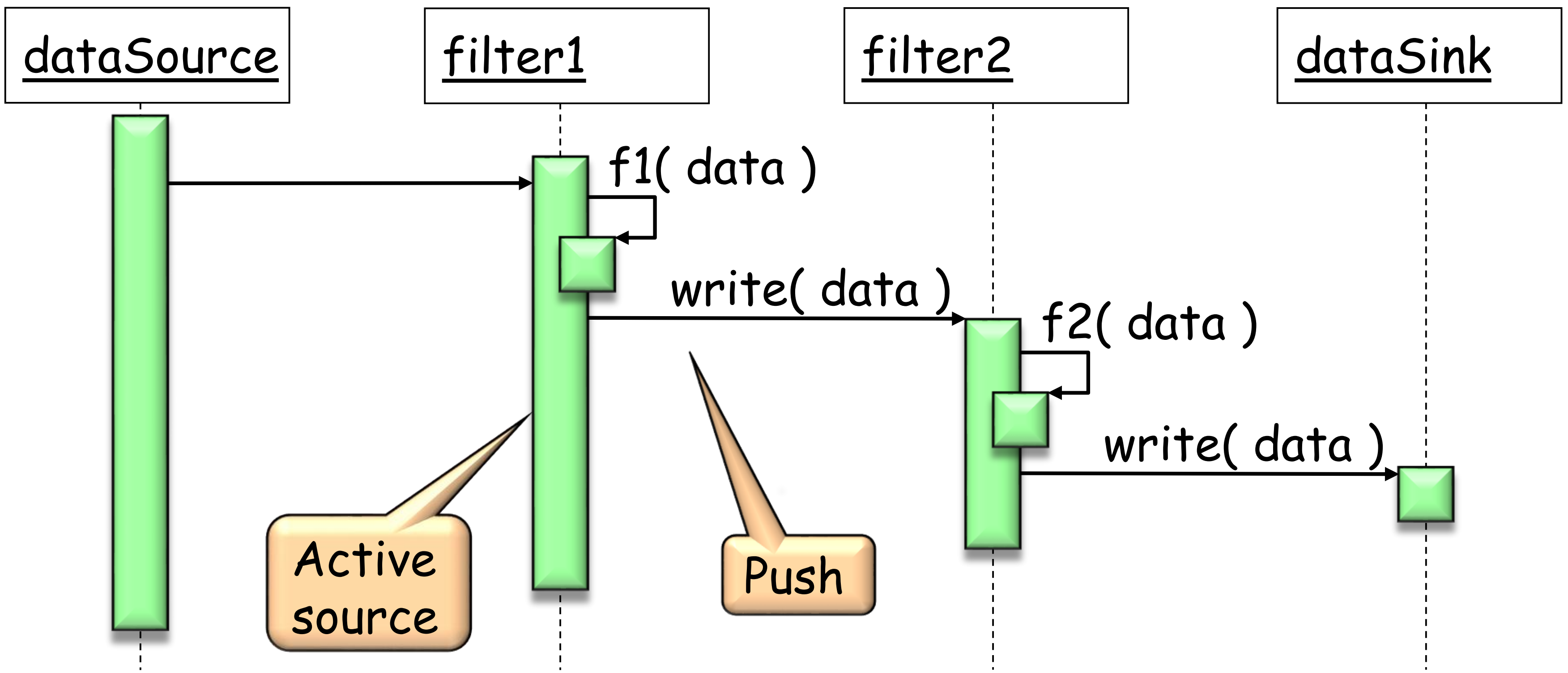
- lex/yacc-based compiler (scan, parse, generate…)
- Unix pipes
- Image / signal processing

Push pipeline with active source

Source of each pipe pushes data downstream

Example with Unix pipes:

grep p1 * | grep p2 | wc | tee my_file



Pipe-and-filter: discussion

Strengths:

- Reuse: any two filters can be connected if they agree on data format
- Ease of maintenance: filters can be added or replaced
- Potential for parallelism: filters implemented as separate tasks, consuming and producing data incrementally

Weaknesses:

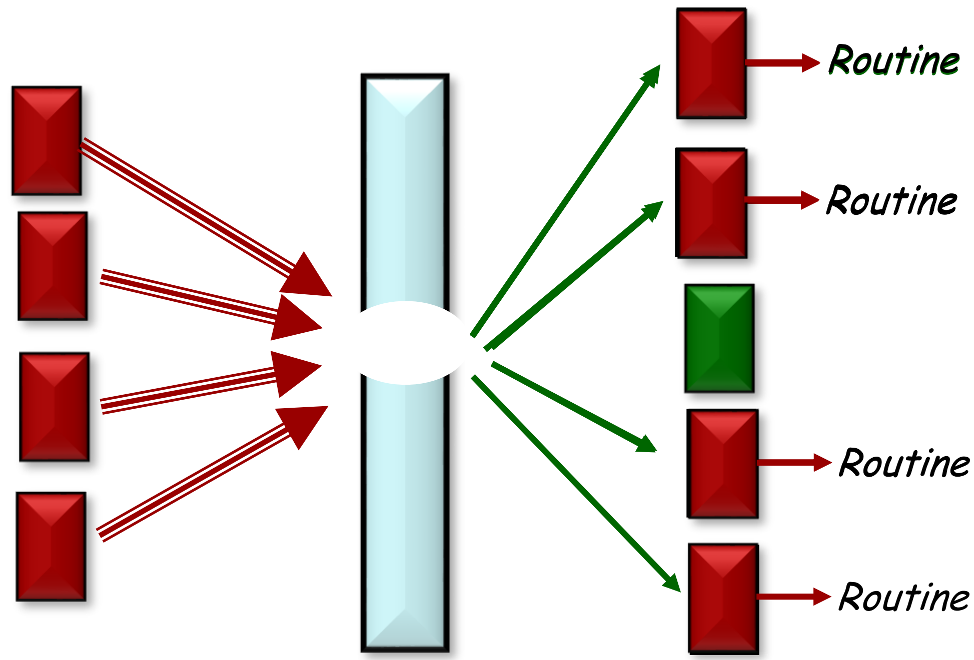
- Sharing global data expensive or limiting
- Scheme is highly dependent on order of filters
- Can be difficult to design incremental filters
- Not appropriate for interactive applications
- Error handling difficult: what if an intermediate filter crashes?
- Data type must be greatest common denominator, e.g. *ASCII*

Dataflow: event-based (publish-subscribe)

A component may:

- Announce events
- Register a callback for events of other components

Connectors are the bindings between event announcements and routine calls (callbacks)



Event-based style: properties

Publishers of events do not know which components (subscribers) will be affected by those events

Components cannot make assumptions about ordering of processing, or what processing will occur as a result of their events

Examples

- Programming environment tool integration
- User interfaces (Model-View-Controller)
- Syntax-directed editors to support incremental semantic checking

Event-based style: example

Integrating tools in a shared environment

Editor announces it has finished editing a module

- Compiler registers for such announcements and automatically re-compiles module
- Editor shows syntax errors reported by compiler

Debugger announces it has reached a breakpoint

- Editor registers for such announcements and automatically scrolls to relevant source line

Event-based: discussion

Strengths:

- Strong support for reuse: plug in new components by registering it for events
- Maintenance: add and replace components with minimum effect on other components in the system

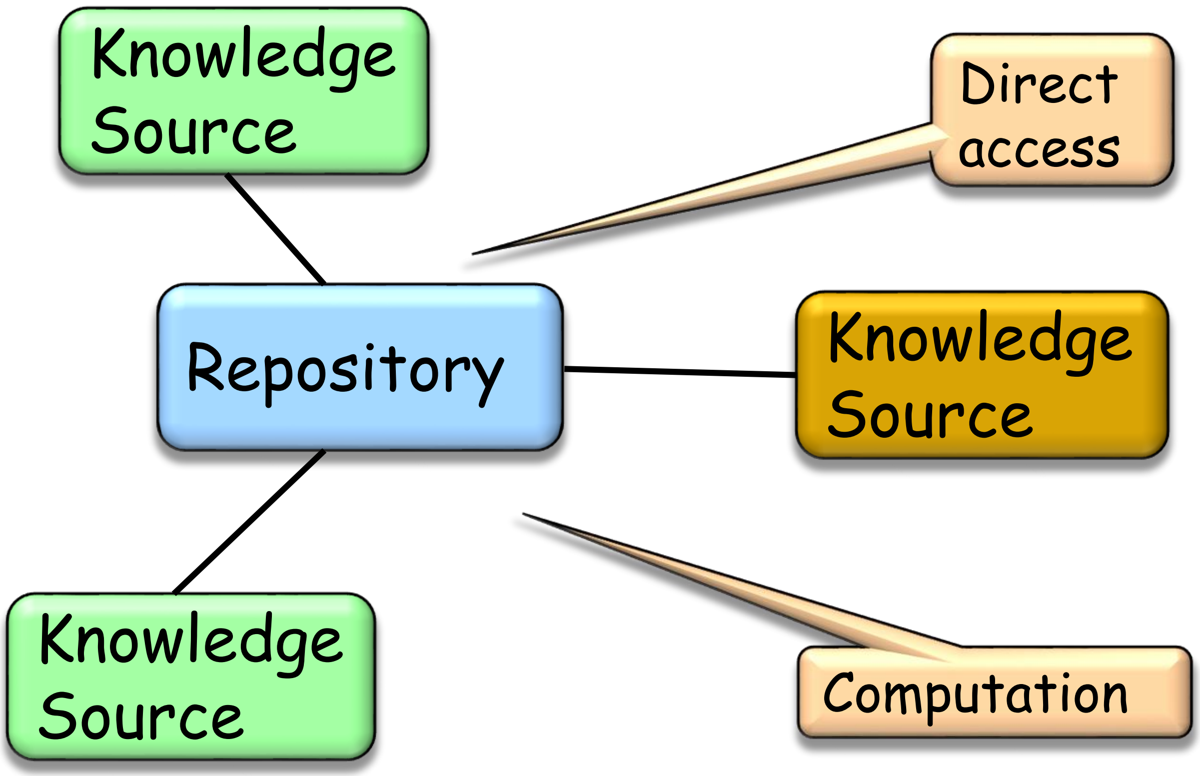
Weaknesses:

- Loss of control:
  - What components will respond to an event?
  - In which order will components be invoked?
  - Are invoked components finished?
- Correctness hard to ensure: depends on context and order of invocation

Data-centered (repository)

Components

- Central data store component represents state
- Independent components operate on data store



Data-Centered: discussion

Strengths:

- Efficient way to share large amounts of data
- Data integrity localized to repository module

Weaknesses:

- Subsystems must agree (i.e., compromise) on a repository data model
- Schema evolution is difficult and expensive
- Distribution can be a problem

Blackboard architecture

Interactions among knowledge sources **solely through repository**

Knowledge sources make changes to the shared data that lead incrementally to solution

Control is driven entirely by the state of the blackboard

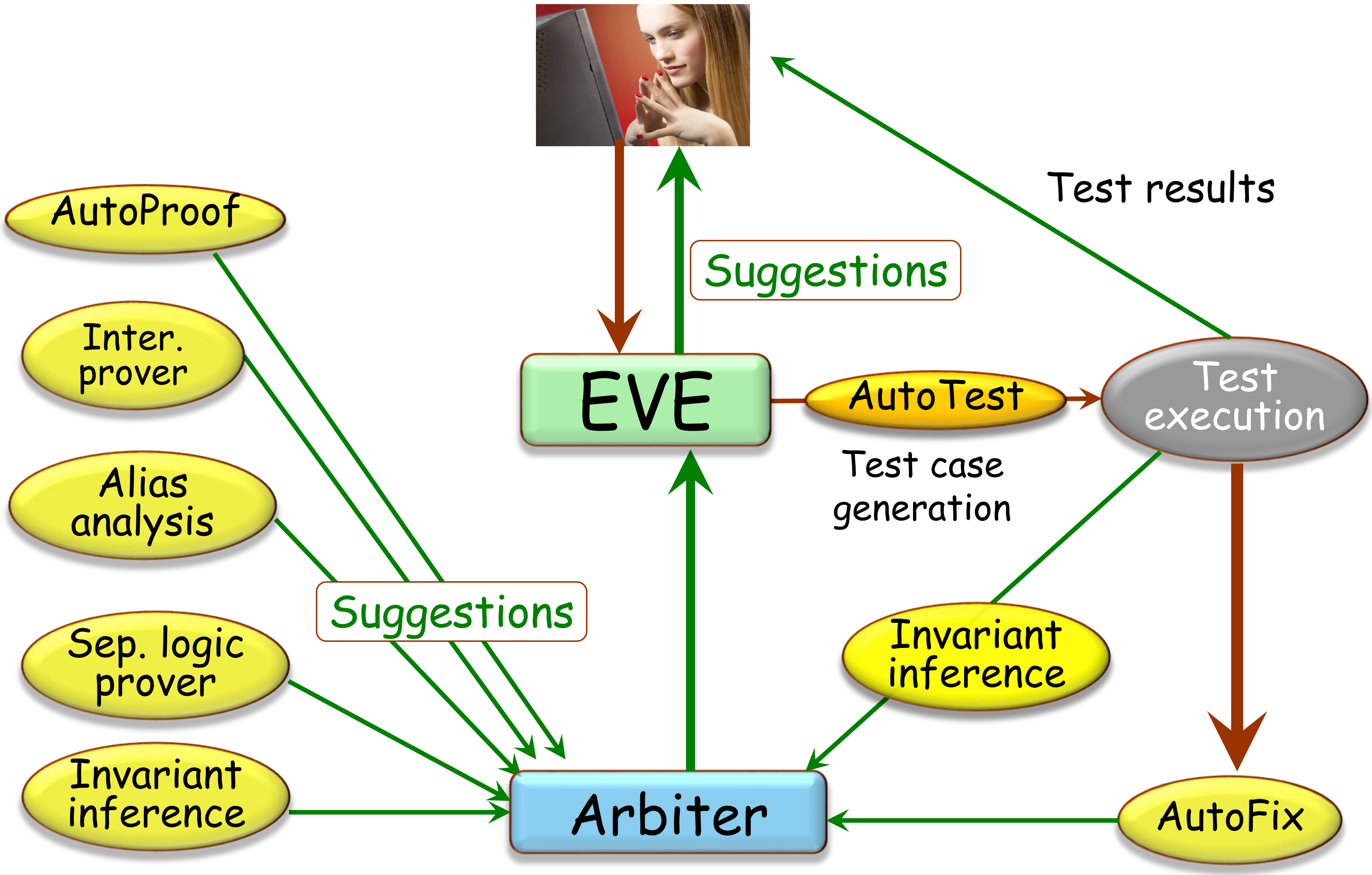
Example

- Repository: modern compilers act on shared data: symbol table, abstract syntax tree
- Blackboard: signal and speech processing

Blackboard architecture: example

The EVE architecture

The EVE architecture (ETH chair of SE)



Interpreters

Architecture is based on a **virtual machine** produced in software

Special kind of a **layered architecture** where a layer is implemented as a true language interpreter

Components

- "Program" being executed and its data
- Interpretation engine and its state

Example: Java Virtual Machine

- Java code translated to platform independent bytecode
- JVM is platform specific and interprets the bytecode

Object-oriented

Based on analyzing the types of objects in the system and deriving the architecture from them

Compendium of techniques meant to enhance extendibility and reusability: contracts, genericity, inheritance, polymorphism, dynamic binding…

Thanks to broad notion of what an "object" is (e.g. a command, an event producer, an interpreter…), allows many of the previously discussed styles