University of Oviedo

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Architectural styles at Runtime

SOFTWARE ARCHITECTURE

2025-26

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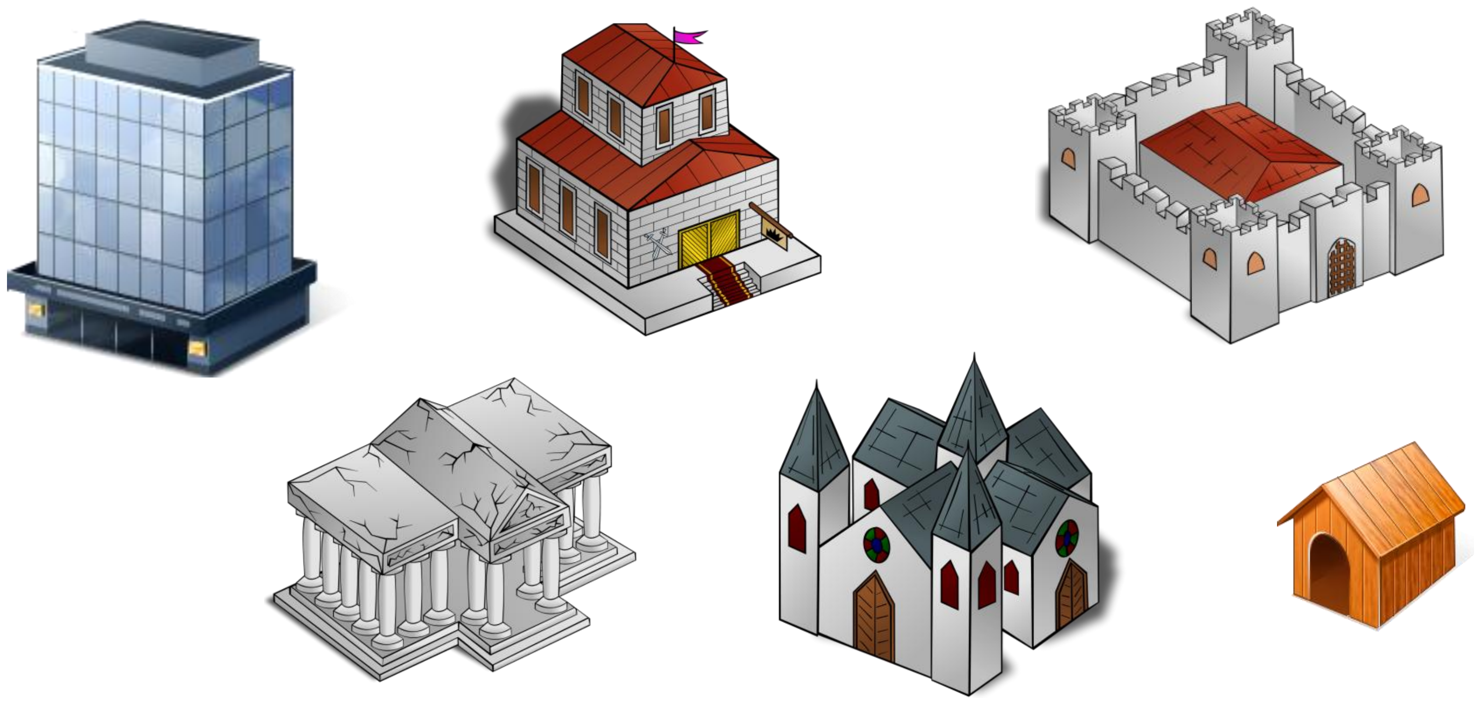
Runtime - Behaviour

Also called: Components and connectors



1st part.
Basic and monolith styles

Data flow

Batch

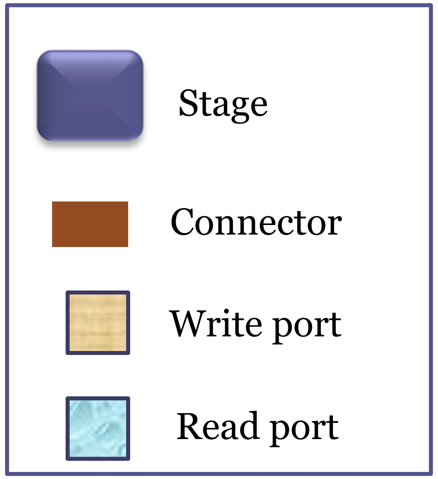
Pipes & Filters

- Pipes & Filters with uniform interface

Batch

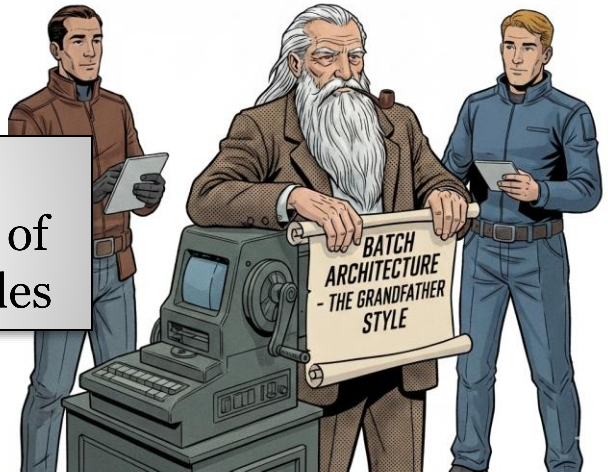
Independent programs are executed sequentially

Data is passed from one program to the next



Note

Batch style = grandfather of software architectural styles



Batch

Elements:

- Independent executable programs

Constraints

- Output of one stage is linked to input of the next
- A program usually waits for the previous one to finish its execution

Batch

Advantages

- Low coupling between components
- Re-configurability
- Debugging
  - It is possible to debug each input independently

Challenges

- It does not offer interactive interface
- Requires external intervention
- No support for concurrency
  - Low throughput
- High latency

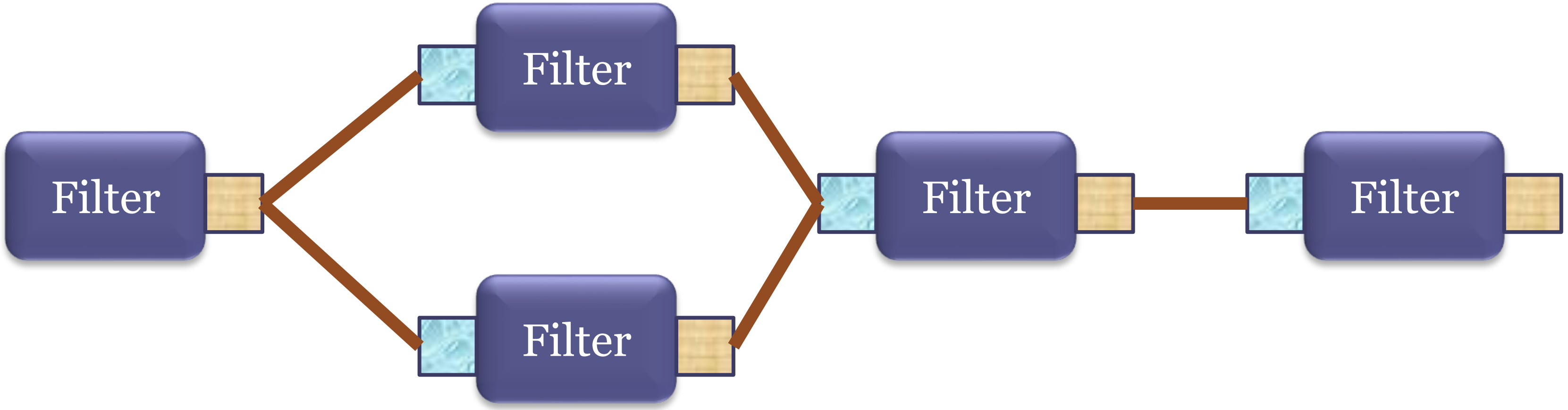
Definitions:

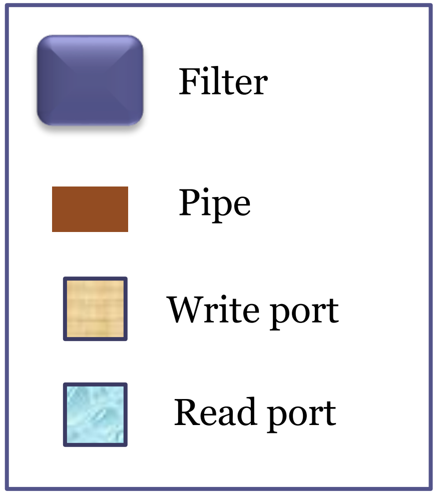
Throughput: rate at which something can be processed.
Example: number of jobs/second

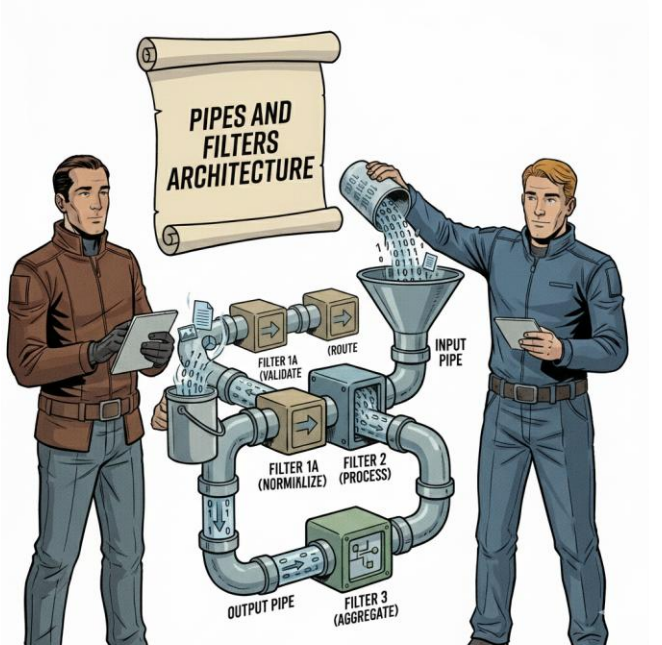
Latency: time delay experienced by a process
Example: 2 seconds

Pipes & Filters

Data flows through pipes and is processed by filters



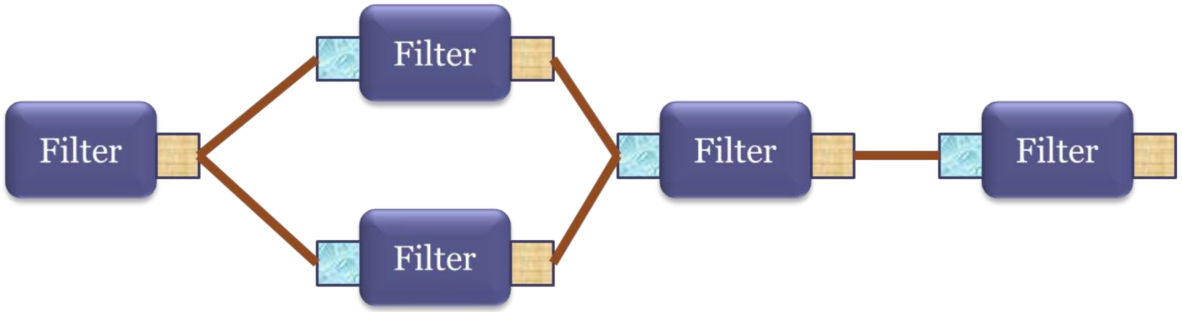




Pipes & Filters

Elements

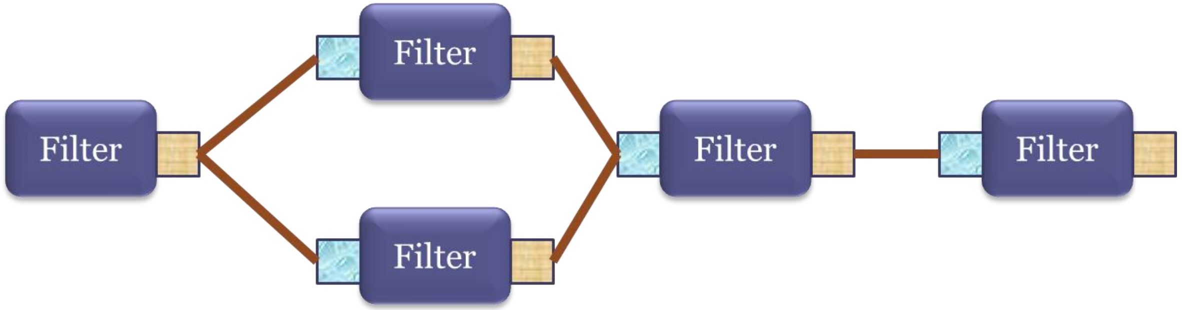
- Filter: component that transforms data
  - Filters can be executed concurrently
  - Types of filters:
    - Data sources (input to the system)
    - Flow
    - Sinks (output of the system)
- Pipe: Takes output data from one filter to the input of another filter
  - Properties to consider:
    - Buffer size
    - Data format
    - Interaction protocol



Pipes & Filters

Constraints

- Pipes connect outputs from one filter to inputs of other filters
- Filters must agree on the exchange format they admit



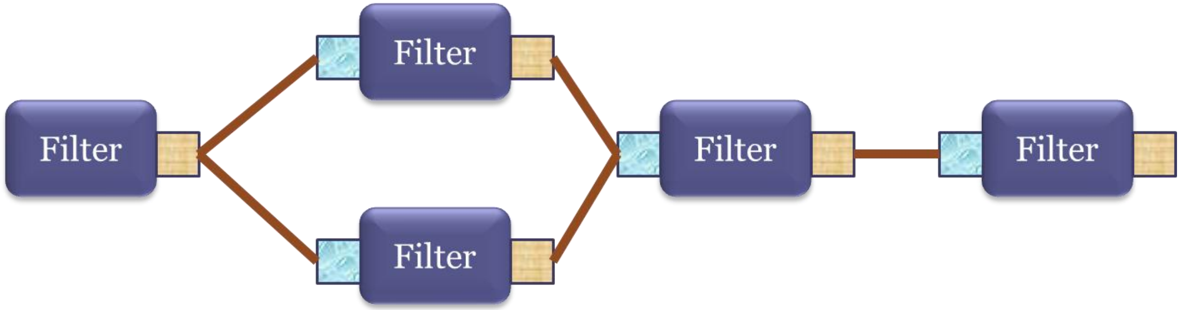
Pipes & Filters

Advantages

- Better understanding of global system
  - Total behavior = sum of each filter behavior
- Reusability:
  - Filters can be recombined
- Evolution and extensibility:
  - It is possible to create/add new filters
  - It is possible to substitute old filters by new ones
- Testability
  - Independent verification of each filter
- Performance
  - It enables concurrent execution of filters

Challenges

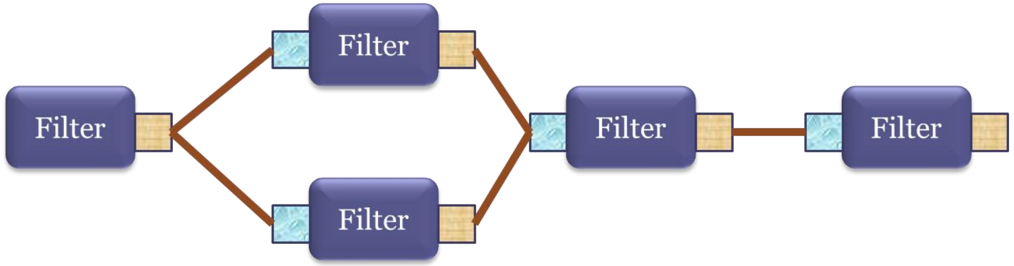
- Possible delays in case of long pipes
- It may be difficult to pass complex data structures
- Non interactivity
  - A filter can not interact with its environment
- Backpressure
  - When consumers receive more data than they can process



Pipes & Filters

Examples & Applications

- Unix
  - who | wc -l
- Yahoo Pipes
- Java Streams
- Flow based programming
  - https://en.wikipedia.org/wiki/Flow-based_programming
- Stream programming



Pipes & Filters - uniform interface

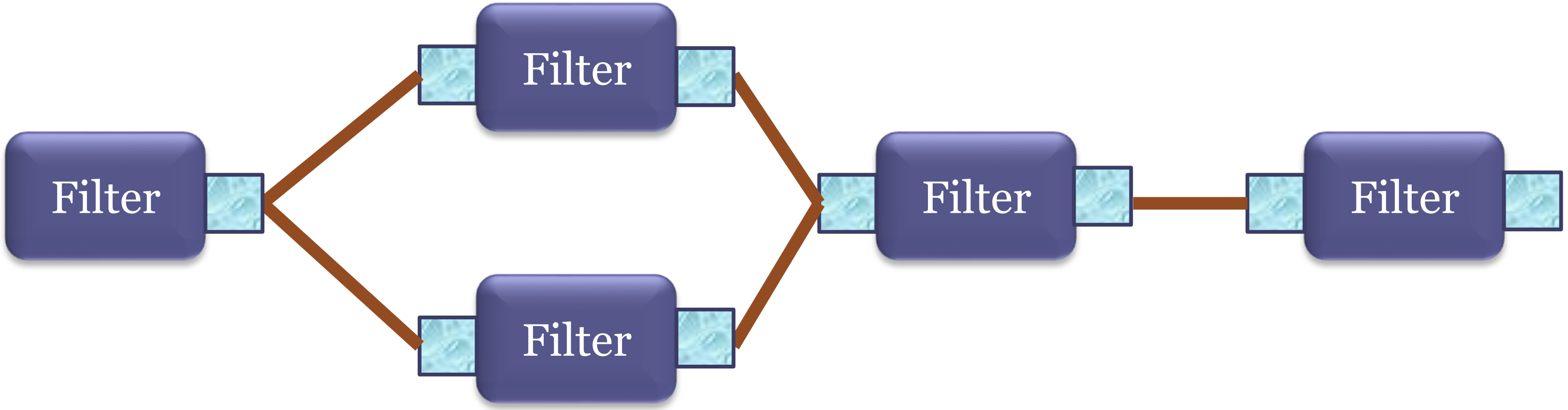
Variant of Pipes & Filters where filters have the same interface

Elements

- The same as in Pipes & Filters

Constraints

- Filters must have a uniform interface



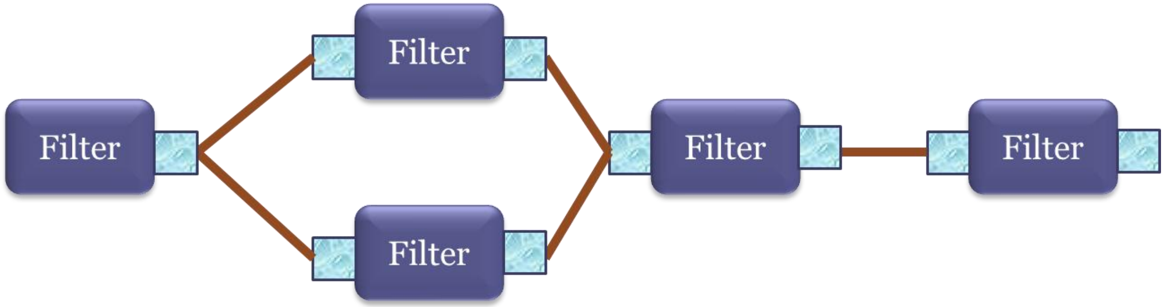
Pipes & Filters - uniform interface

Advantages:

- Independent development of filters
- Re-configurability
- Facilitates system understanding

Challenges:

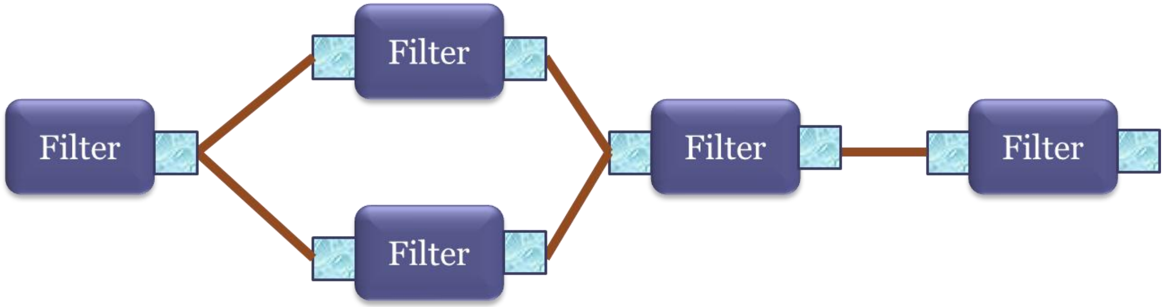
- Performance can be affected if data have to be converted to the uniform interface
  - Marshalling



Pipes & Filters - uniform interface

Examples:

- Unix operating system
  - Programs with a text input (*stdin*) and 2 text outputs (*stdout* y *stderr*)
- Web architecture: REST



Job organization

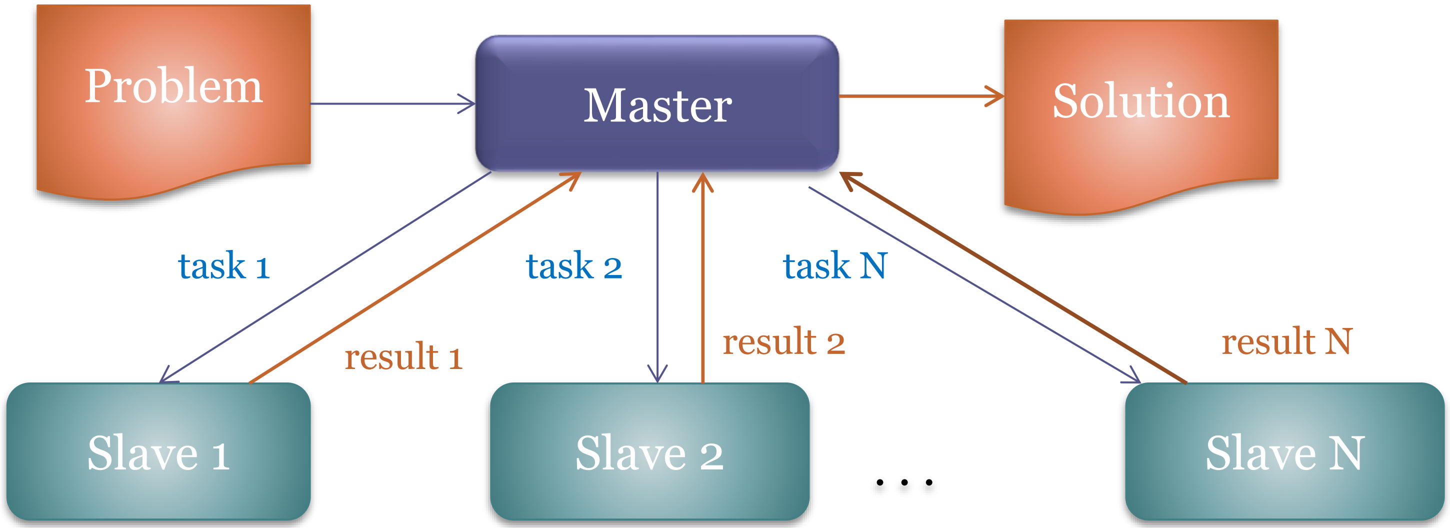
Master-Slave

Master-Slave

Master divides work in sub-tasks

Assigns each sub-task to different nodes

The computational result is obtained as the combination of the slaves results results



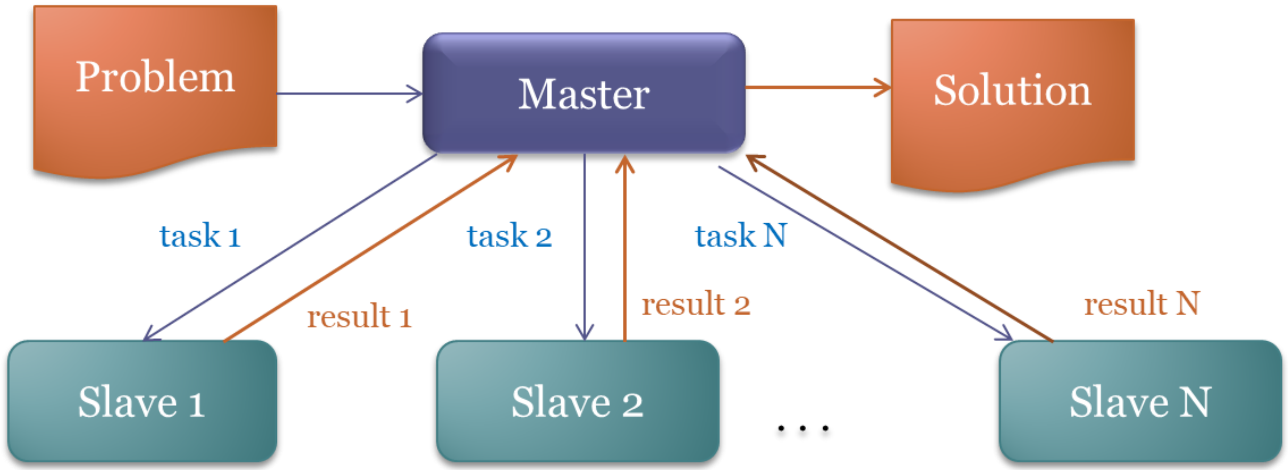
Master-Slave

Elements

- Master: Coordinates execution
- Slave: does a task and returns the result

Constraints

- Slave nodes are only in charge of the computation
- Control is done by the Master node



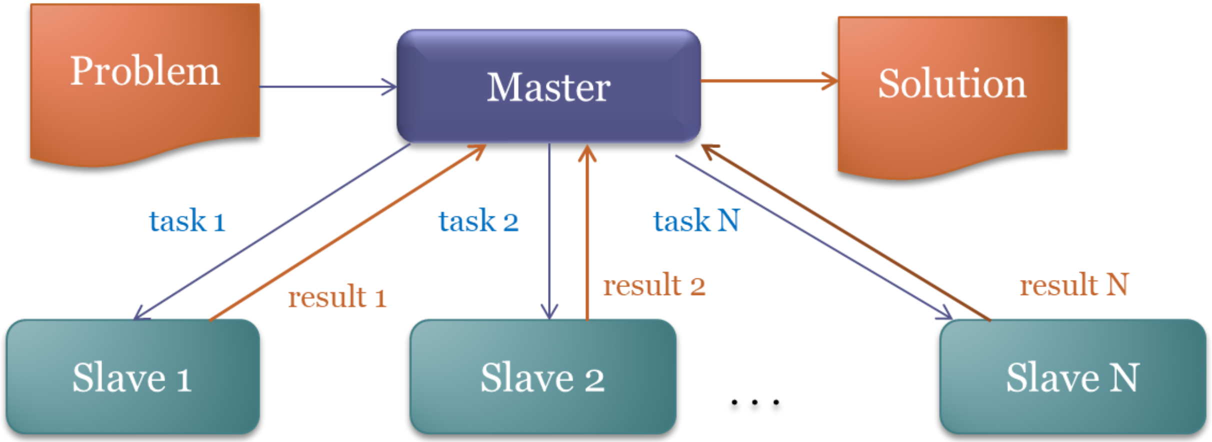
Master-Slave

Advantages

- Parallel computation
- Fault tolerance

Challenges

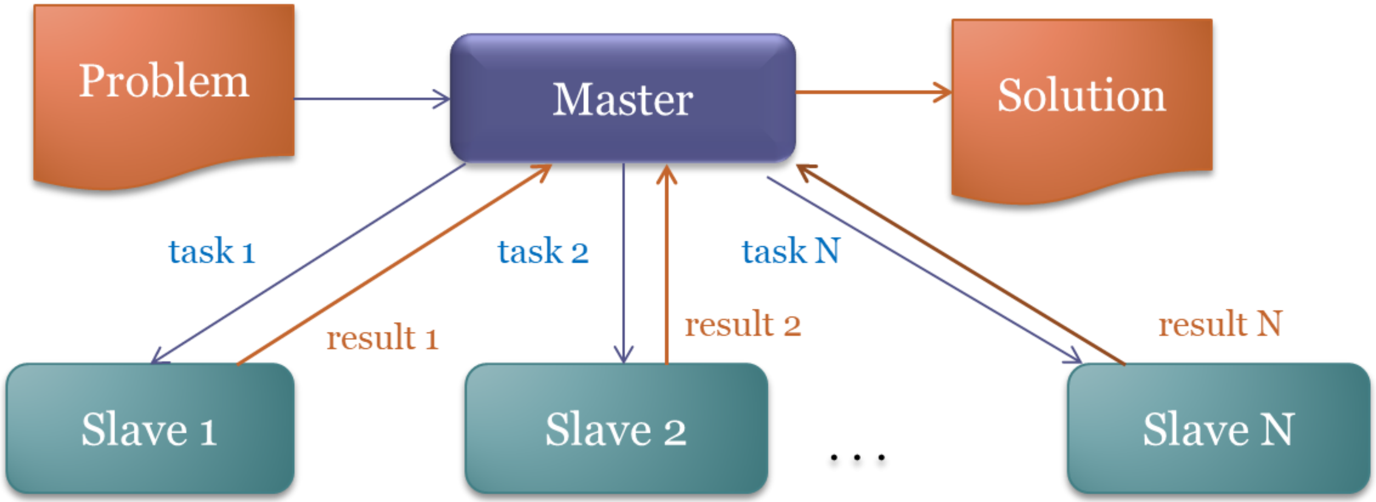
- Difficult to coordinate work between *slaves*
- Dependency on Master node
- Dependency on physical configuration



Master-Slave

Applications:

- Process control systems
- Embedded systems
- Fault tolerant systems
- Search systems



Interactive systems

MVC: Model - view - controller

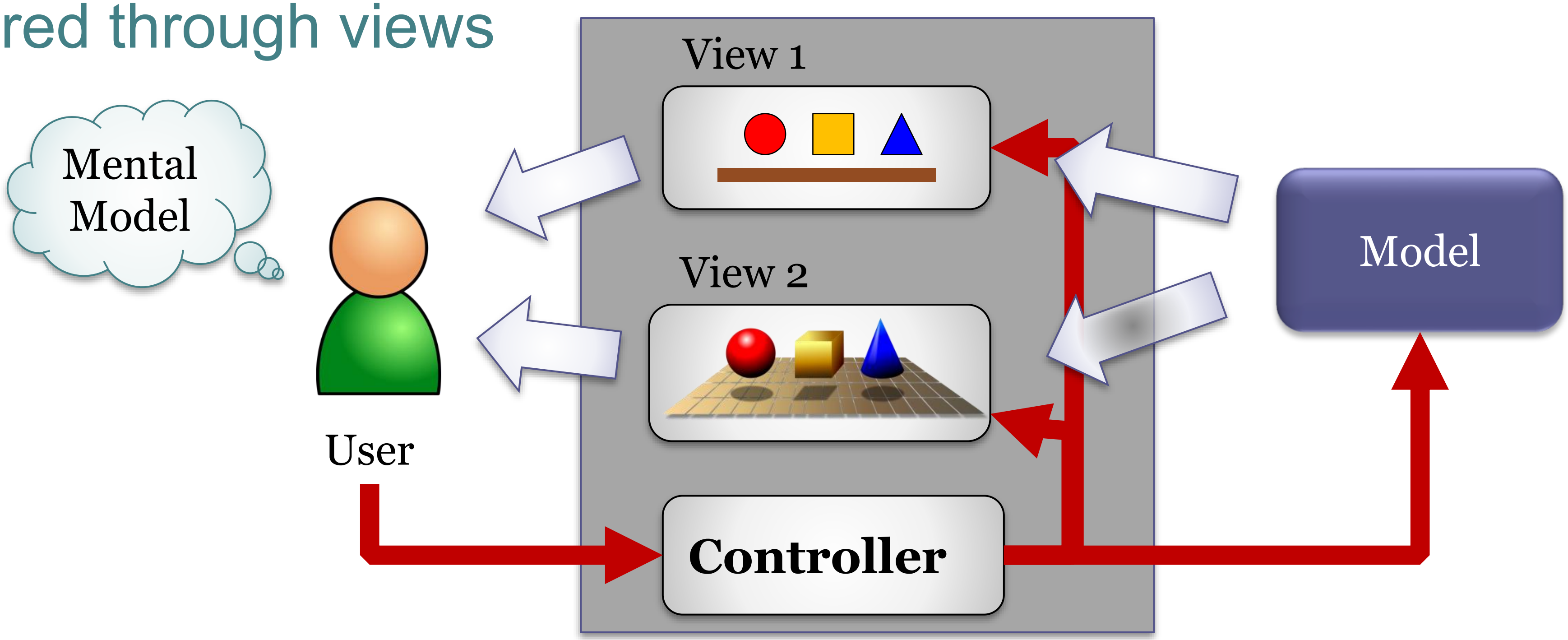
MVC variants

- PAC: Presentation - Abstraction - Control

MVC

MVC: Model - View - Controller

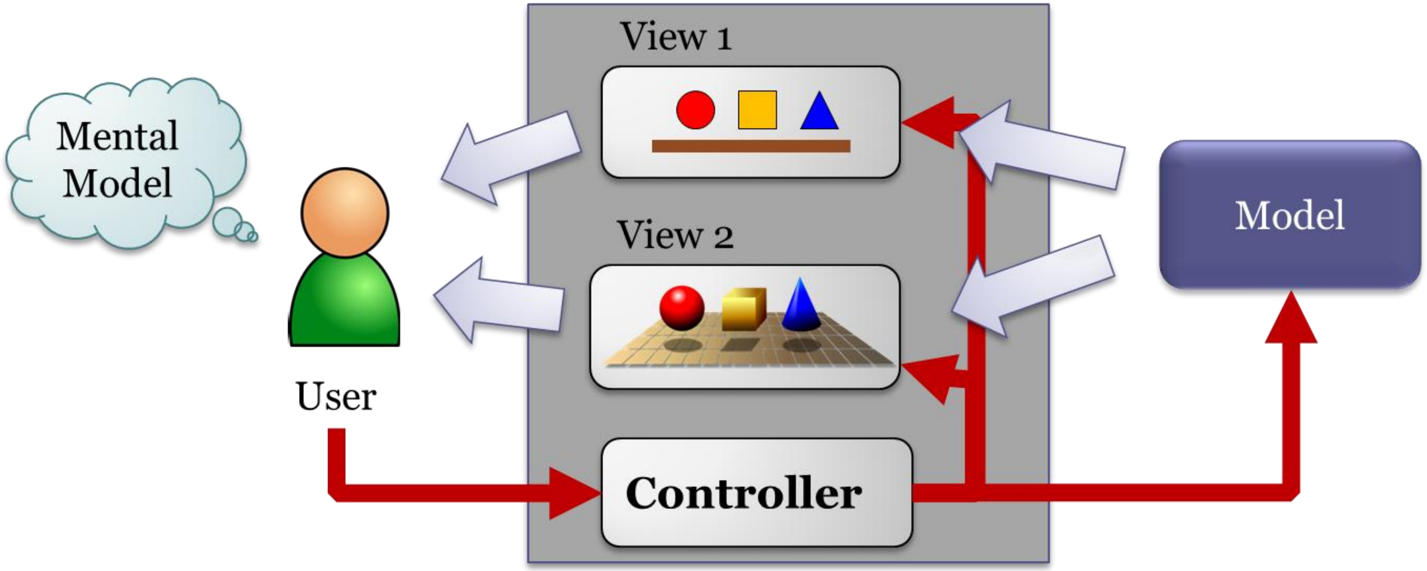
- Proposed by Trygve Reenskaug (end of 70's)
- Popular solution for GUIs
- Controller separates model from view
- *"Mental model"* offered through views



MVC

Elements

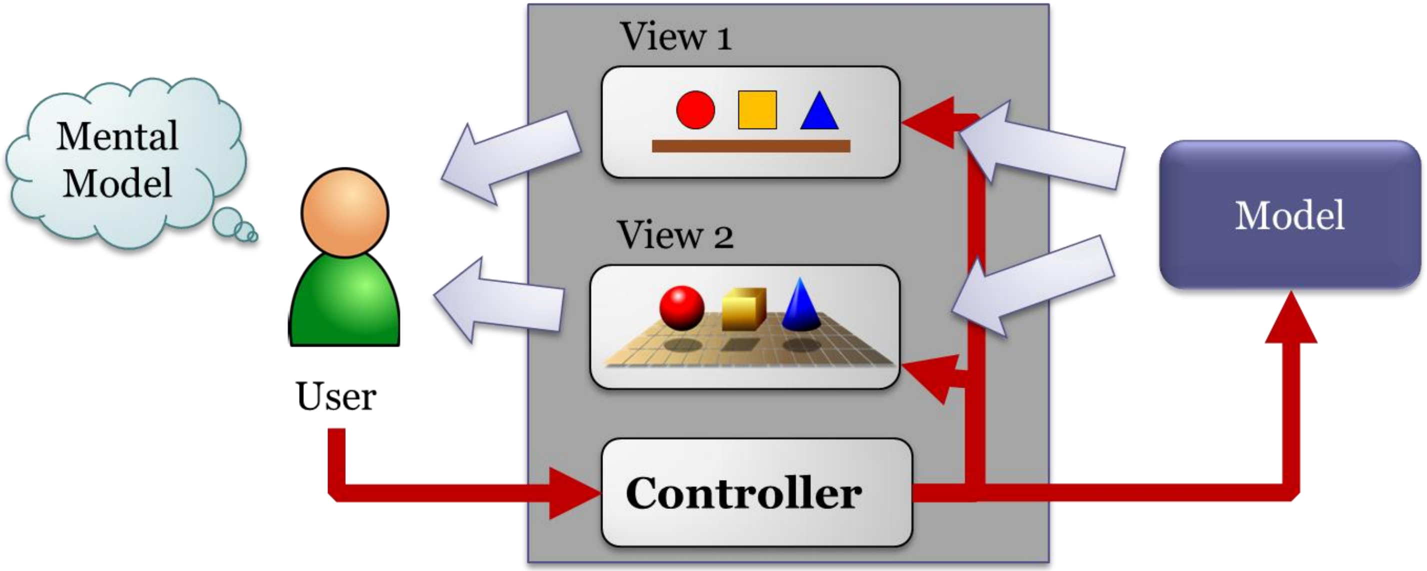
- Model: represents business logic and state
- View: Offers state representation to the user
- Controller: Coordinates interaction, views and model



MVC

Constraints

- Controller processes user events
  - Creates/removes views
  - Handles interaction
- Views only show values
- Models are independent of controllers/views



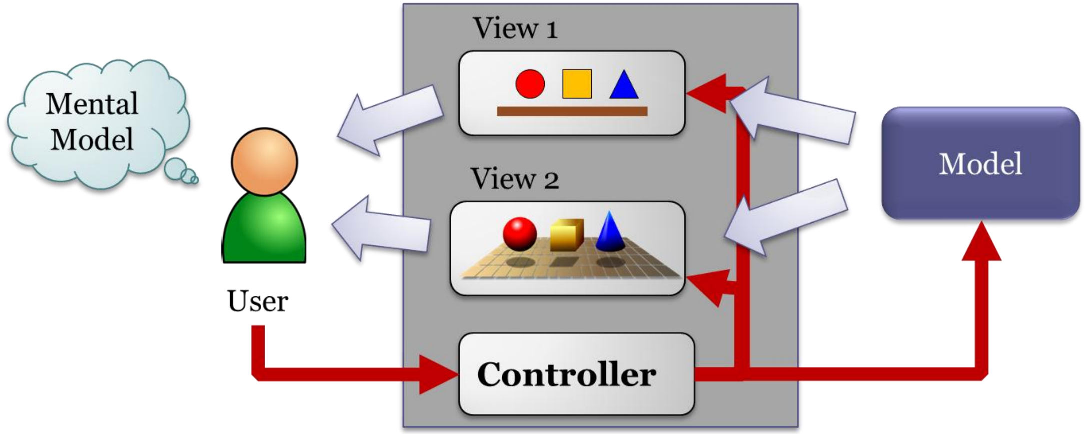
MVC

Advantages

- Supports multiple views of the same model
- Views synchronization
- Separation of concerns
  - Interaction (controller), state (model)
- It is easy to create new views and controllers
- Easy to modify *look & feel*
- Creation of generic frameworks

Challenges

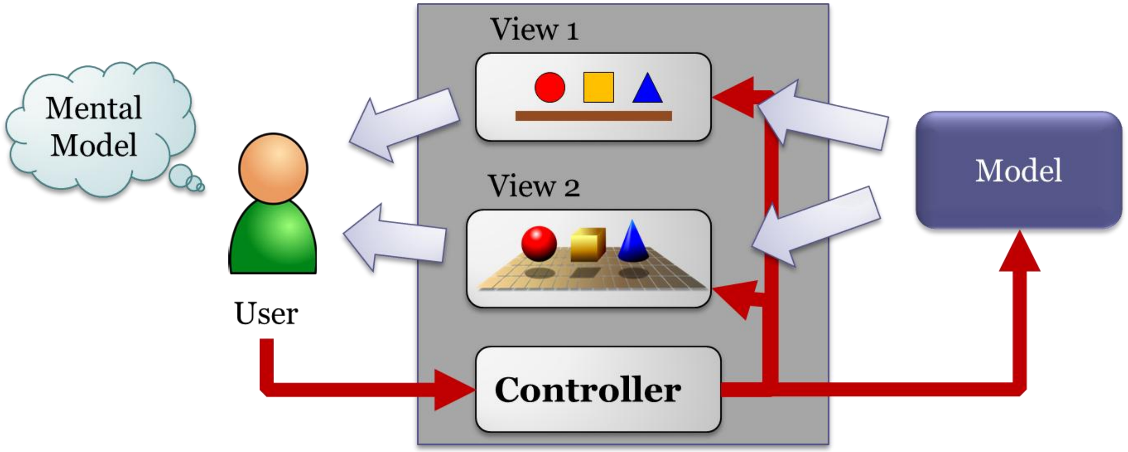
- Increases complexity of GUI development
- Coupling between controllers and views
- Controllers/Views should depend on a model interface
- Some difficulties for GUI tools



MVC

Applications

- Lots of web frameworks follow MVC
  - Ruby on Rails, Spring MVC, Play, etc.
- Some variants
  - Push: controllers send orders to views
    - Ruby on Rails, Struts1
  - Pull: controllers receive orders from views
    - Play framework, Struts2



MVC variants

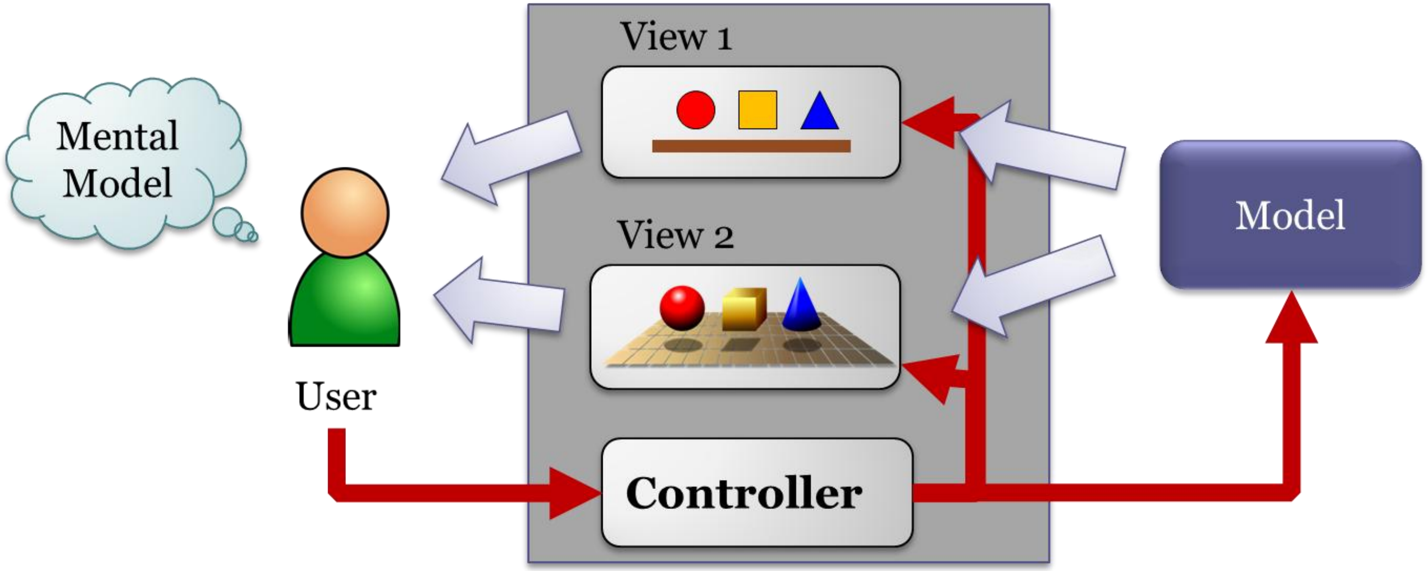
PAC

Model-View-Presenter

Model View ViewModel

Model View Update

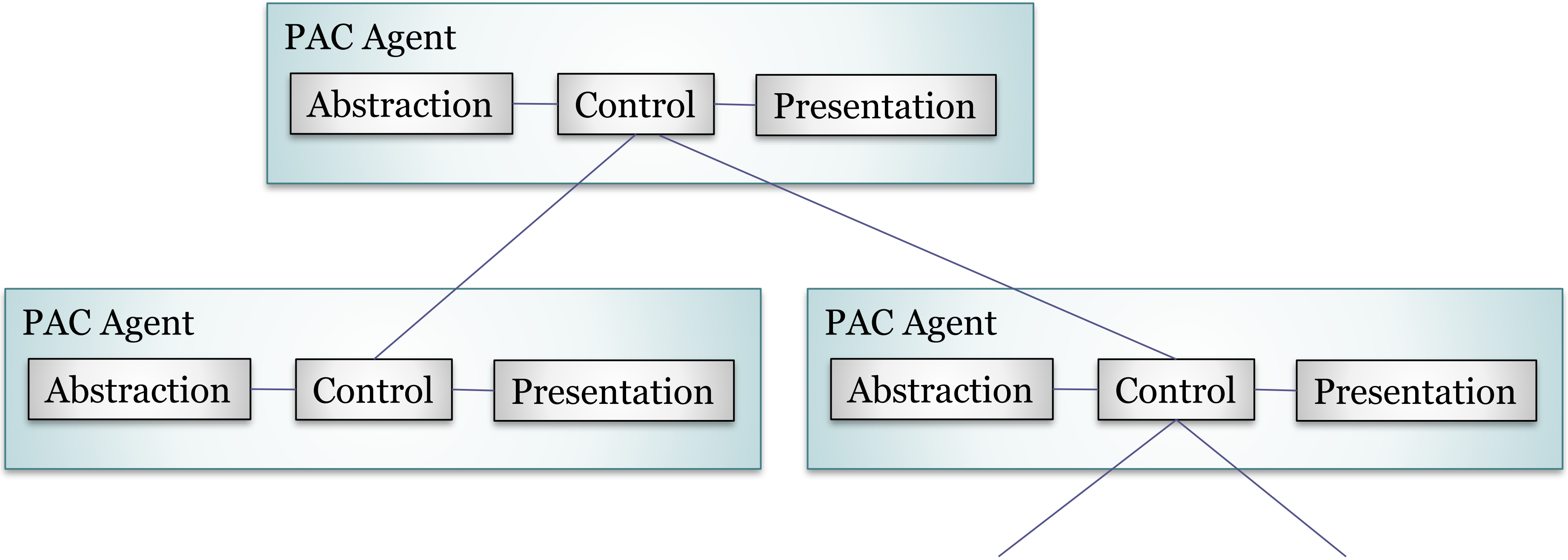
...

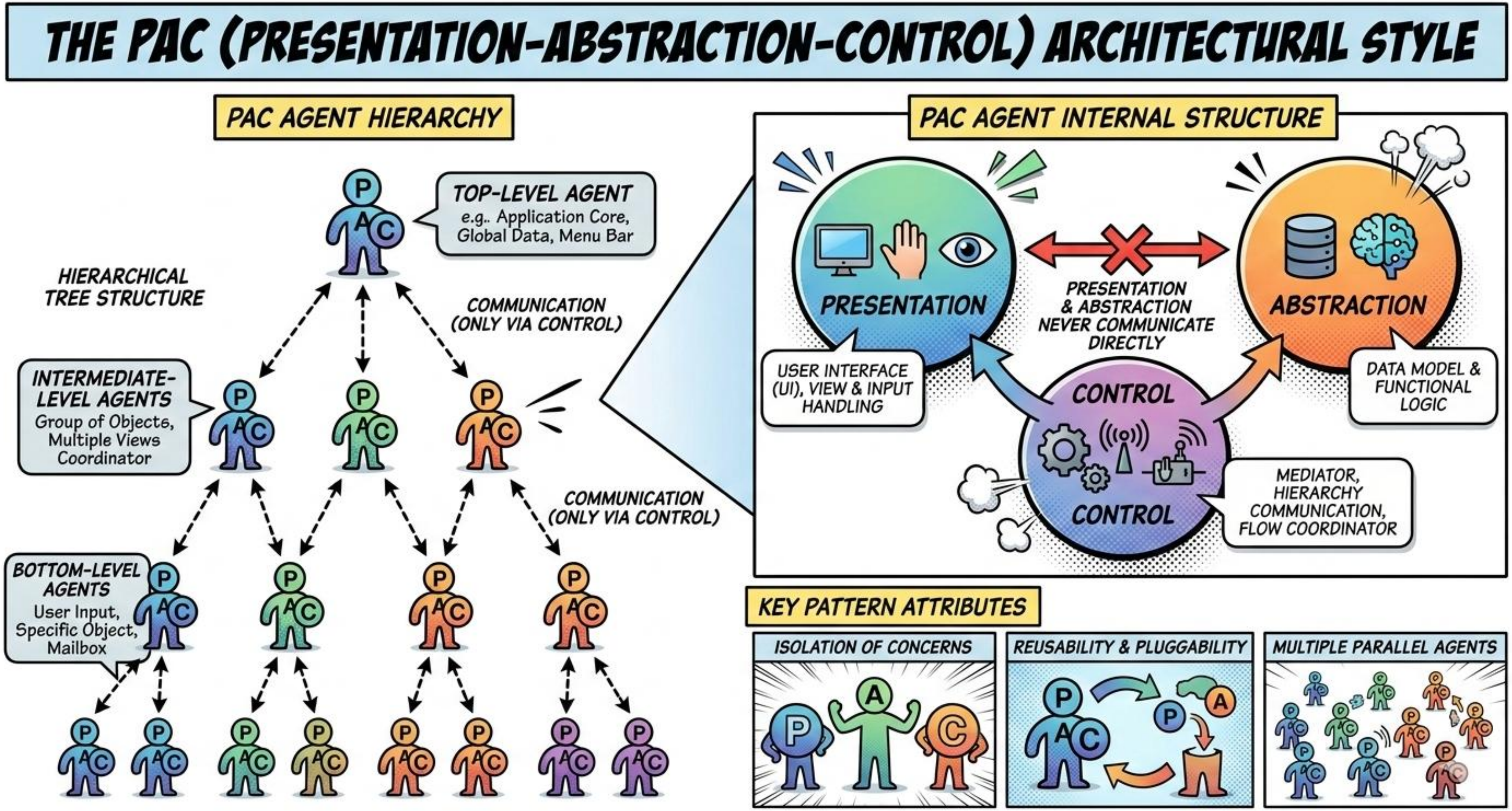


PAC

PAC: Presentation-Abstraction-Control

- Hierarchy of agents
- Each agent contains 3 components





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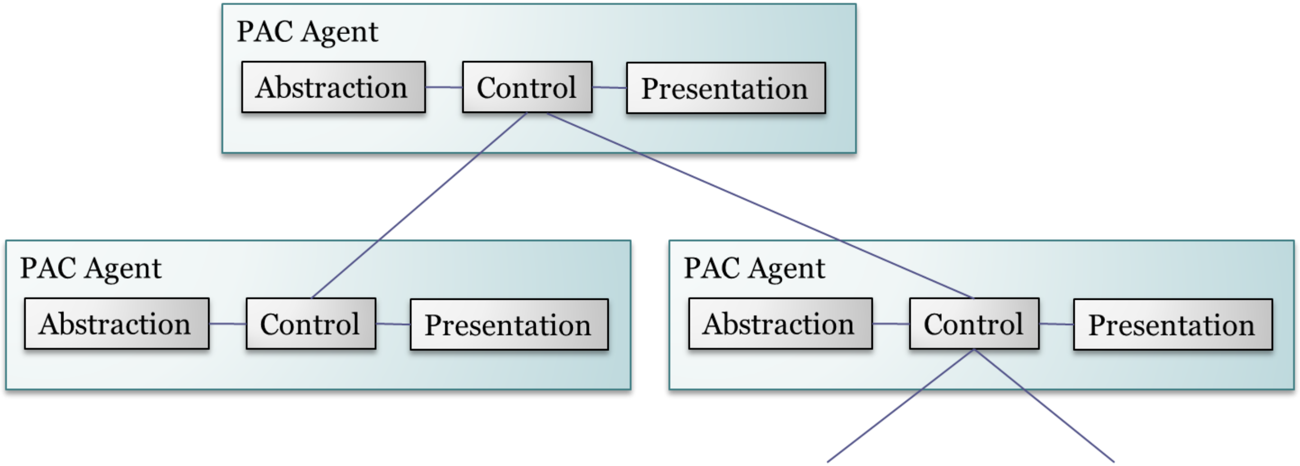
PAC



- Elements
  - Agents with
    - Presentation: visualization aspects
    - Abstraction: data model of an agent
    - Control: connects presentation and abstraction components and enables communication between agents
  - Hierarchical relationship between agents
- Constraints
  - Each agent is in charge of some functionality
  - No direct communication between abstraction and presentation in each agent
  - Communication through the control component

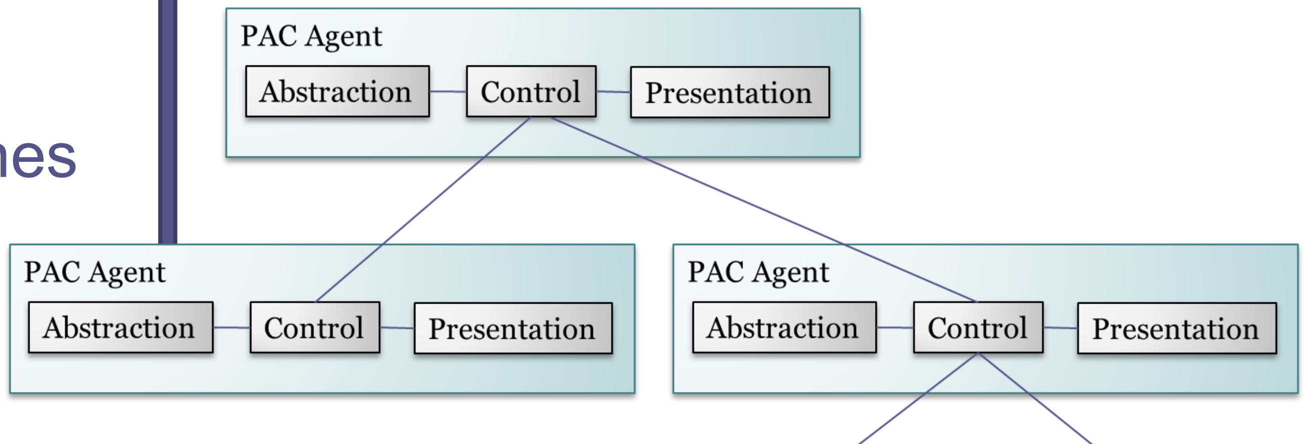
PAC

Advantages

- Separation of concerns
  - Identifies functionalities
- Support for changes and extensions
  - It is possible to modify an agent without affecting others
- Multitask
  - Agents can reside in different threads, processes or machines

Challenges

- Complexity of the system
  - Too many agents can generate a complex structure which can be difficult tom maintain
- Complexity of control components
  - Control components handle communication
  - Quality of control components is important for whole quality of the system
- Performance
  - Communication overload between agents



PAC

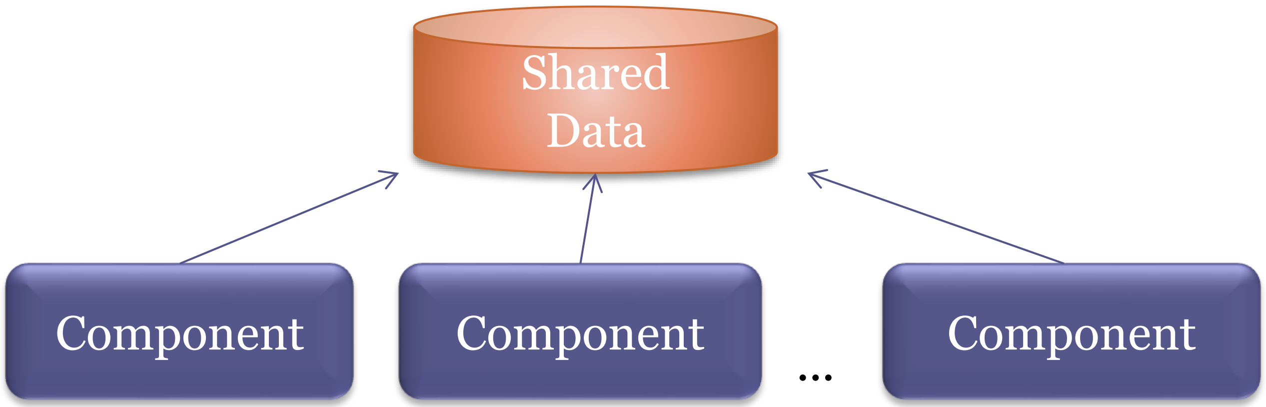
- Applications
  - Network monitoring systems
  - Mobile robots
  - Drupal is based on PAC
- Relationships
  - This patterns is related with MVC
    - MVC has no agent hierarchy
  - This pattern was re-discovered as Hierarchical MVC

Repository

Shared data
Blackboard
Rule based

Shared data

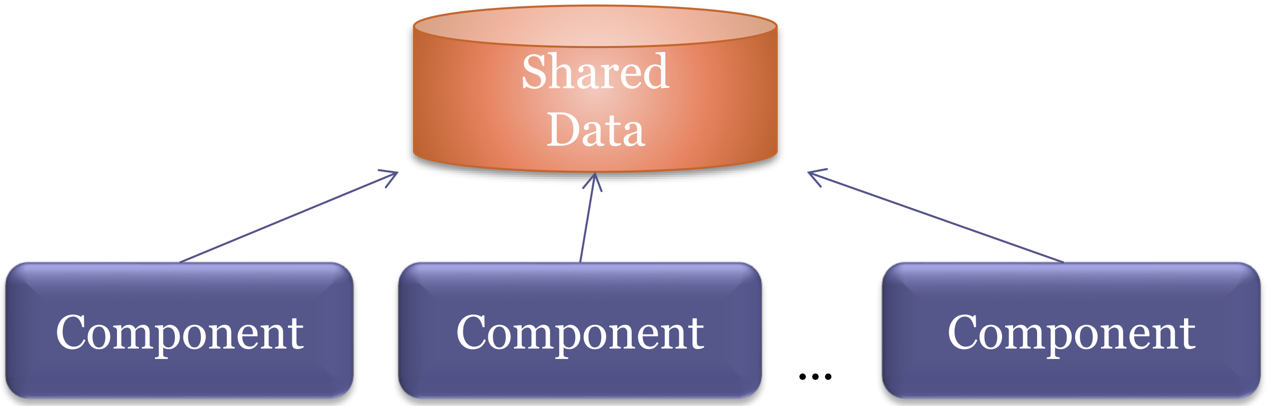
- Independent components access the same state
  - Applications based on centralized data repositories



Shared data

Elements

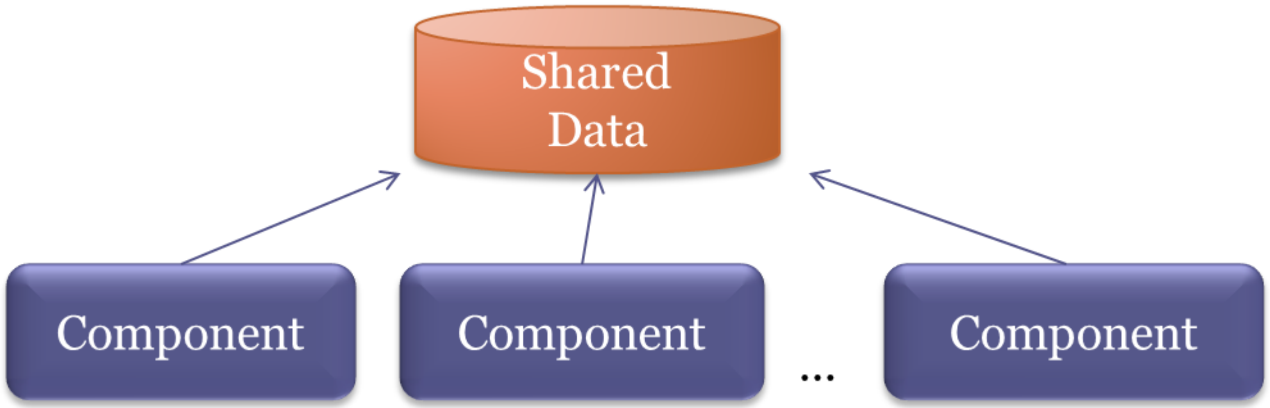
- Shared data
  - Database or centralized repository
- Components
  - Processors that interact with shared data



Shared data

Constraints

- Components interact with the global state
- Components don't communicate between each other
  - Only through shared state
- Shared data repository handles data stability and consistency



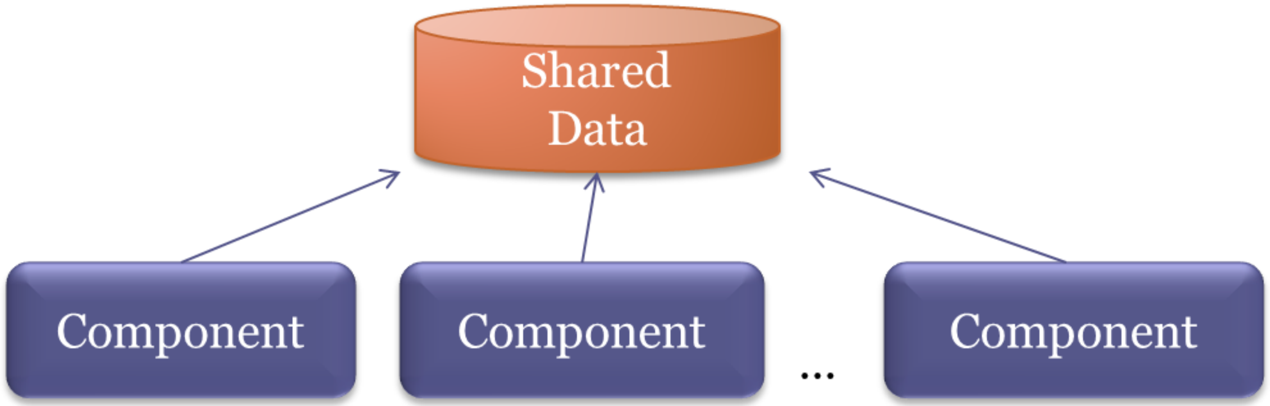
Shared data

Advantages

- Independent components
  - They don't need to be aware of the existence of other components
- Data consistency
  - Centralized global state
  - Unique *Backup* of all the system state

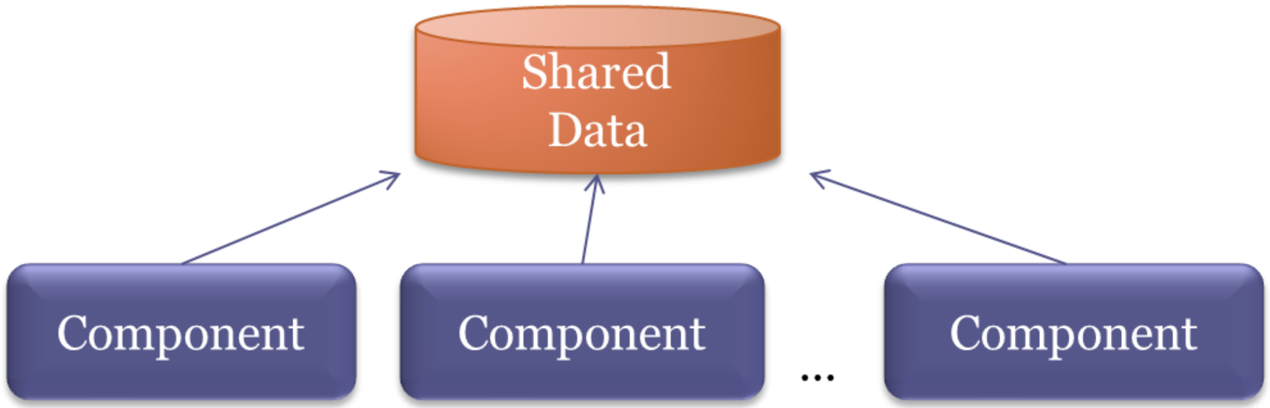
Challenges

- Unique point of failure
  - A failure in the central repository can affect the whole system
  - Distributing the central data can be difficult
- Possible bottleneck
  - Inefficient communication
  - Problems for scalability
- Synchronization to access shared data



Shared data

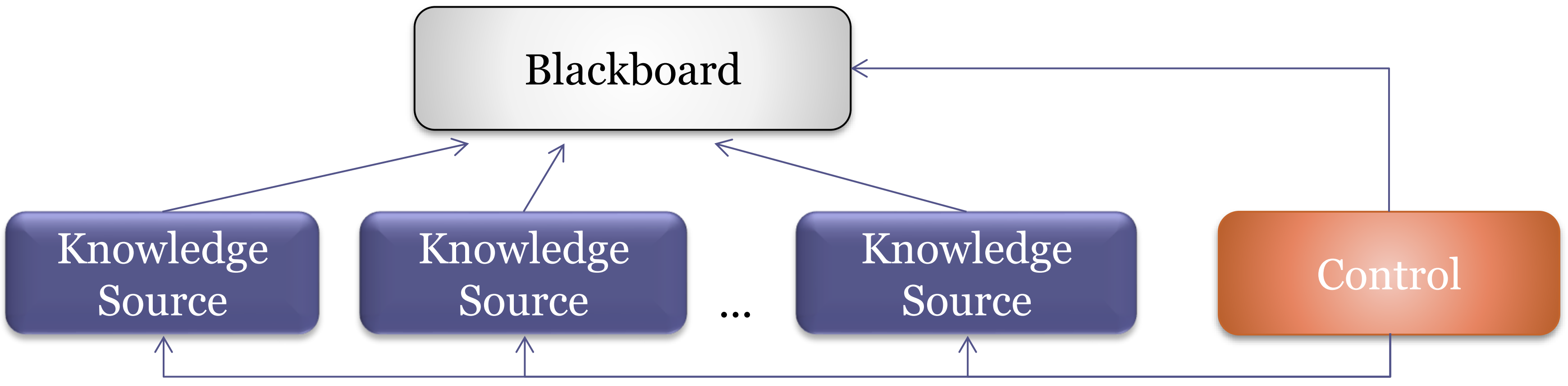
- Applications
  - Lots of systems use this approach
- Some variants
  - This style is also known as:
    - Shared Memory, Repository, Shared data, etc.
  - Blackboard
  - Rule based systems



Blackboard

Complex problems which are difficult to solve

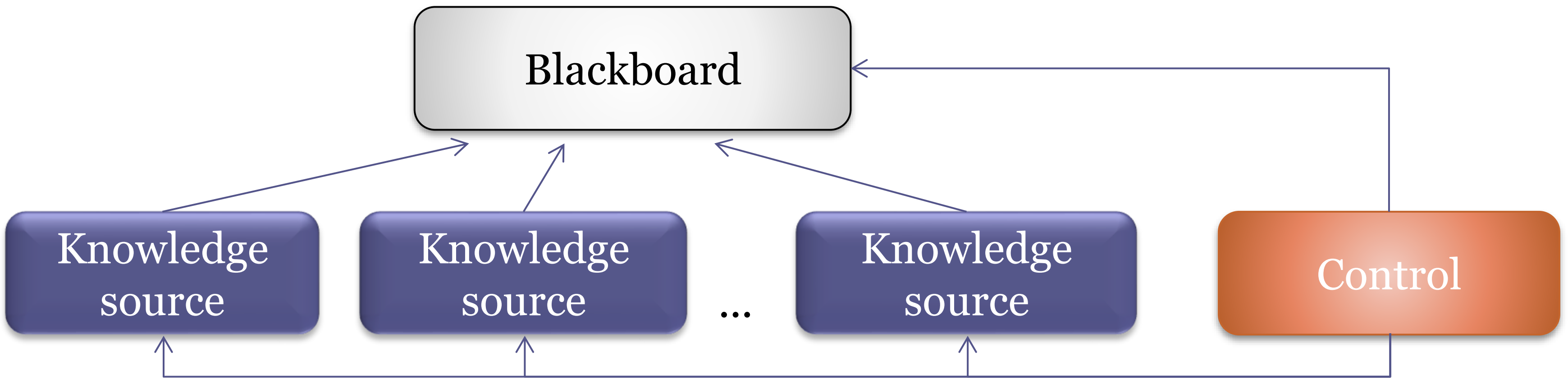
- Knowledge sources solve parts of the problem
- Each knowledge source aggregates partial solutions to the *blackboard*
- Also called *"Shared Knowledge Base"*



Blackboard

Elements

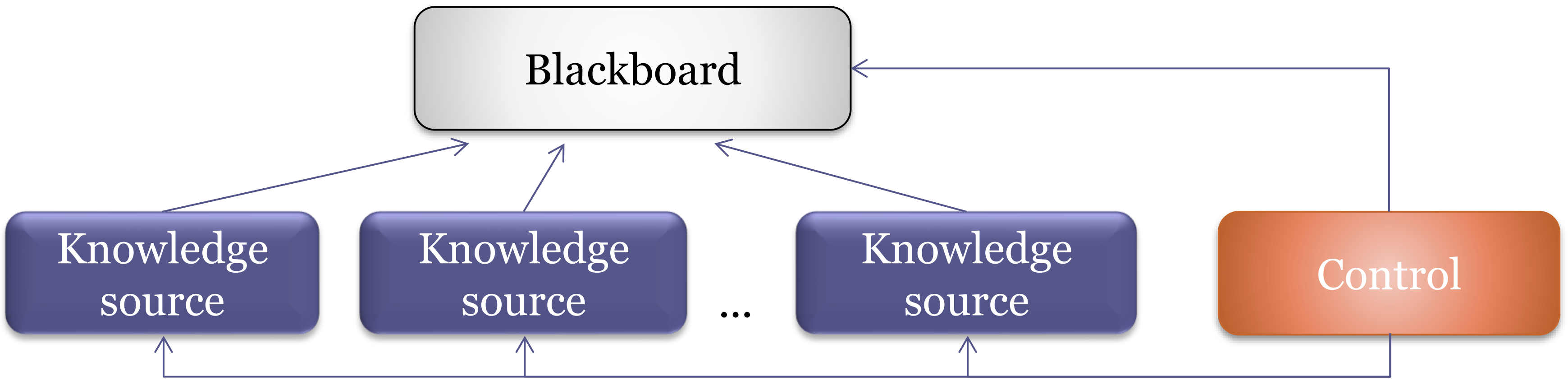
- *Blackboard*: Central data repository
- Knowledge source: solves part of the problem and aggregates partial results
- Control: Manages tasks and checks the work state



Blackboard

Constraints

- Problem can be divided in parts
- Each knowledge source solves a part of the problem
- *Blackboard* contains partial solutions that are improving



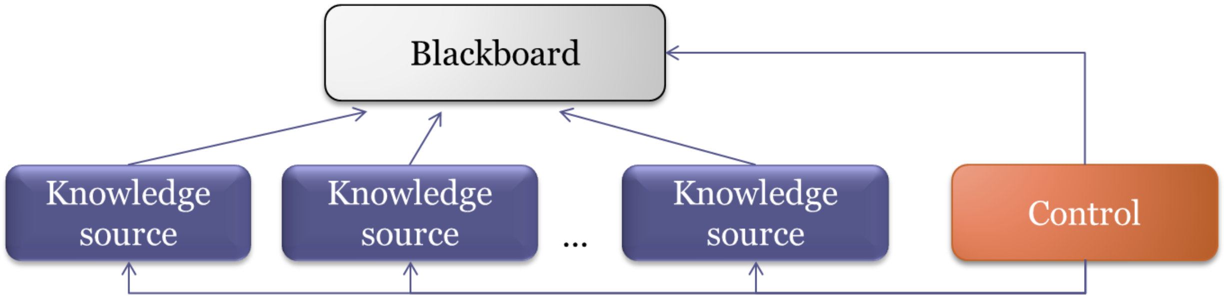
Blackboard

Advantages

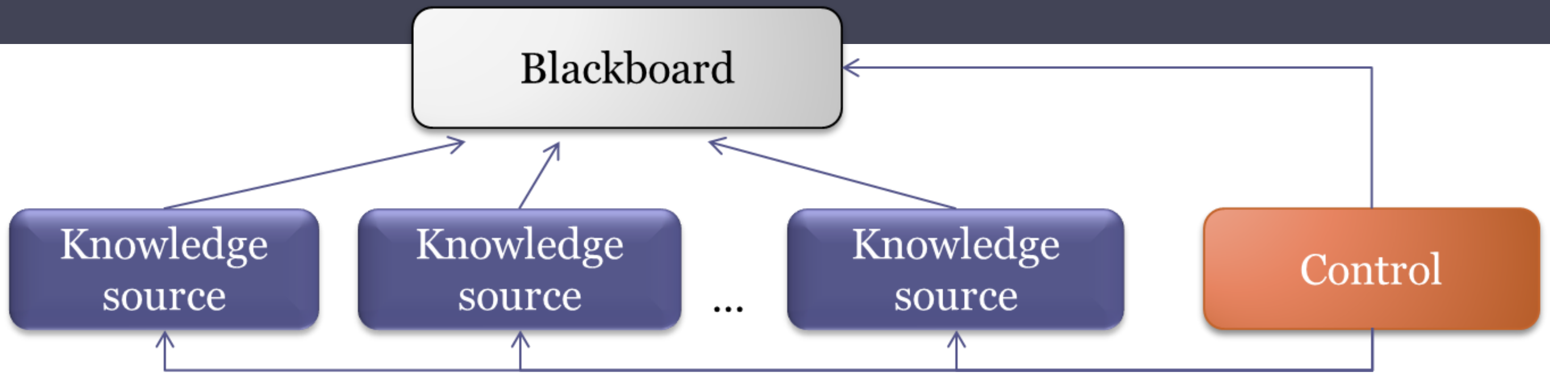
- Experimentability
  - Can be used for open problems
  - Facilitates strategy changes
- Reusability
  - Knowledge sources can be reused
- Fault tolerance

Challenges

- Debugging
  - No warranty that the right solution will be found
  - Difficult to establish control strategy
- Performance
  - It may need to review incorrect hypothesis
- High development cost
  - Parallelism implementation
  - It is necessary to synchronize blackboard access



Blackboard

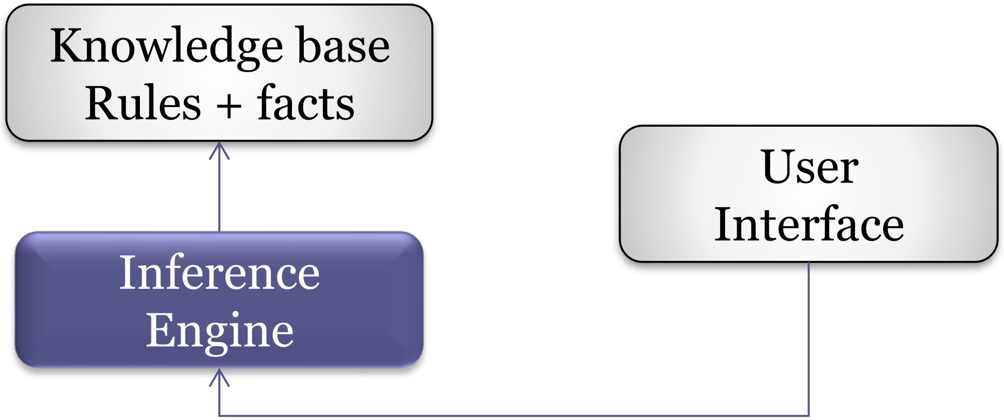


Applications

- Some speech recognition systems: HEARSAY-II
- Pattern recognition
- Weather forecasts
- Analysis of molecular structure: Crystalis
- It is reappearing in multi-agent systems

Rule based systems

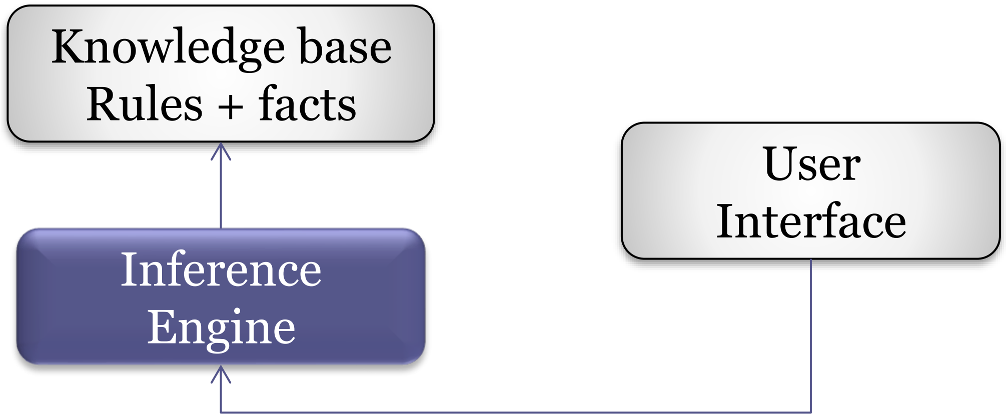
- Variant of shared data
  - Shared data = Knowledge base
    - Contains rules and facts



Rule based systems

Elements:

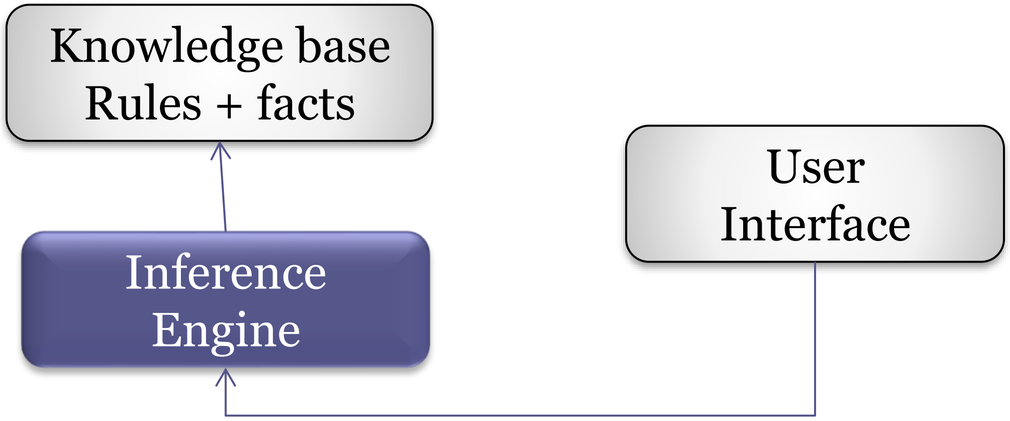
- Knowledge base: Rules and facts about some domain
- User interface: Queries/modifies knowledge base
- Inference engine: Answers queries from data and knowledge base



Rule based systems

Constraints:

- Domain knowledge captured in knowledge base
- Limit imperative access to knowledge base
  - It is based on rules like:
    - IF *antecedents* THEN *consequent*
  - Limits expressiveness with regards to imperative languages



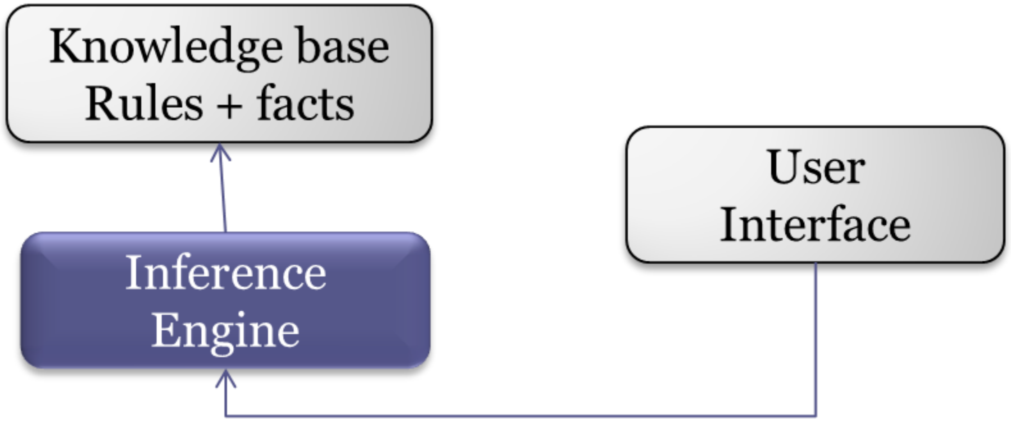
Rule based systems

Advantages

- Maintainability
  - It may be easy to modify the knowledge base
  - Specially tailored to be modified by domain experts
- Separation of concerns
  - Algorithm
  - Domain knowledge
- Reusability

Challenges

- Debugging
- Performance
- Rules creation and maintenance
  - Introspection
  - Automatic rule learning
  - Runtime update of rules



Rule based systems

Applications

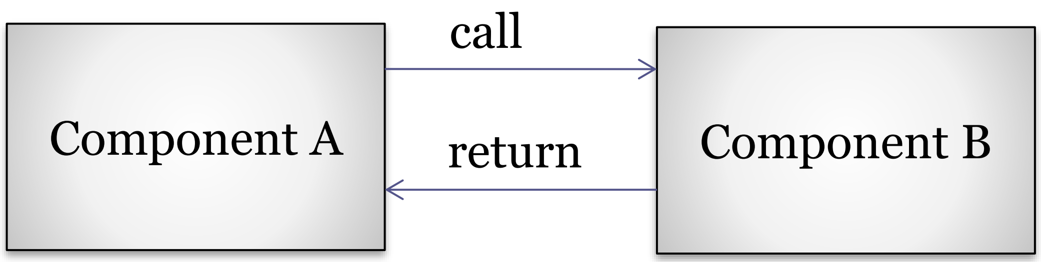
- Expert system
- Production systems
- Rules libraries in Java
  - JRules, Drools, JESS
- Declarative, rule based languages
  - Prolog (logic programming)
- BRMS (Business Rules Management Systems)

Invocation

- Call-return
- Client-Server
- Event based architectures
  - Publish-Subscribe
  - Actor models

Call-return

A component calls another component and waits for the answer



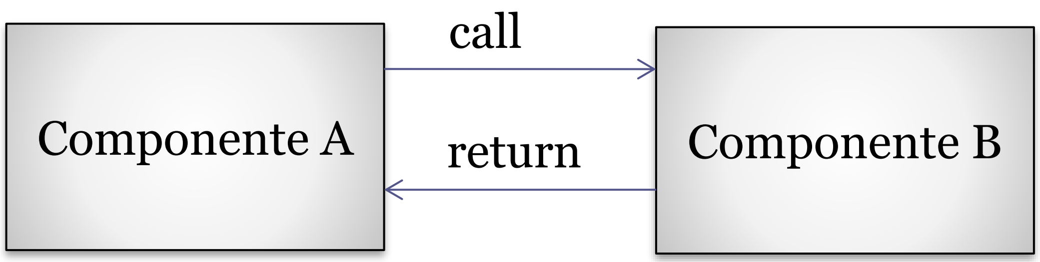
Call-return

Elements

- Component that does the call
- Component that sends the answer

Constraints

- Synchronous communication:
  - The caller waits for the answer

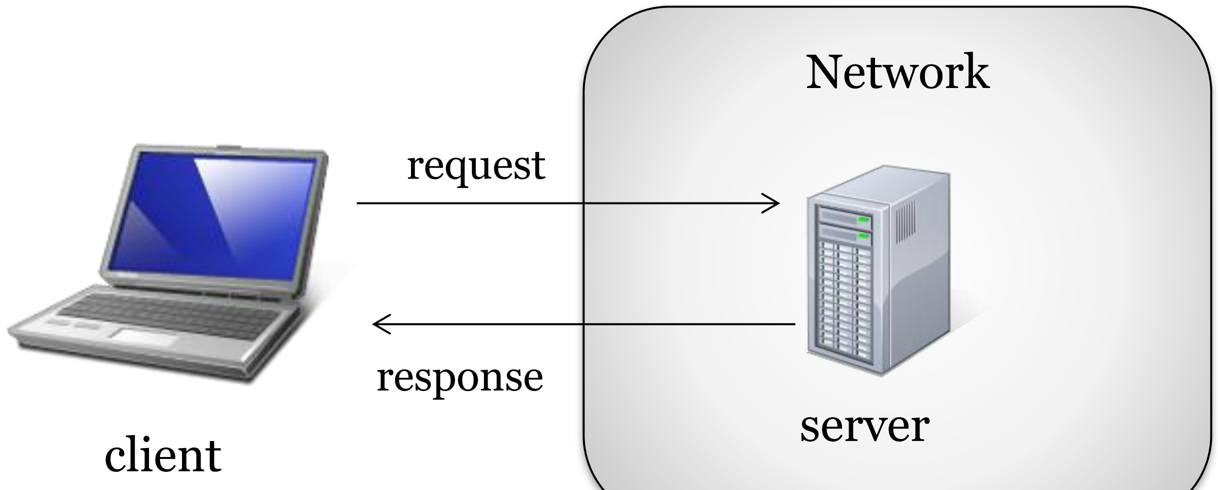


Call-return

- Advantages
  - Easy to implement
- Challenges
  - Problems for concurrent computation
    - If component is blocked waiting for the answer
      - It can be using unneeded resources
  - Distributed environments
    - Little utilization of computational capabilities

Client-Server

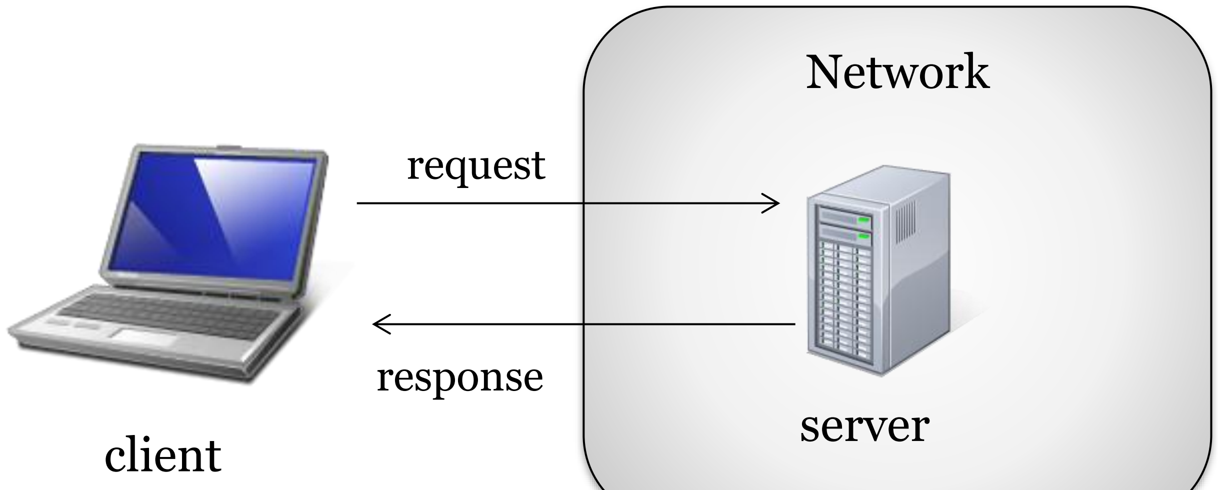
- Variant of layers
  - 2 layers physically separated (2-tier)
- Functionality is divided in several servers
- Clients connect to services
  - Interface request/response



Client-Server

Elements

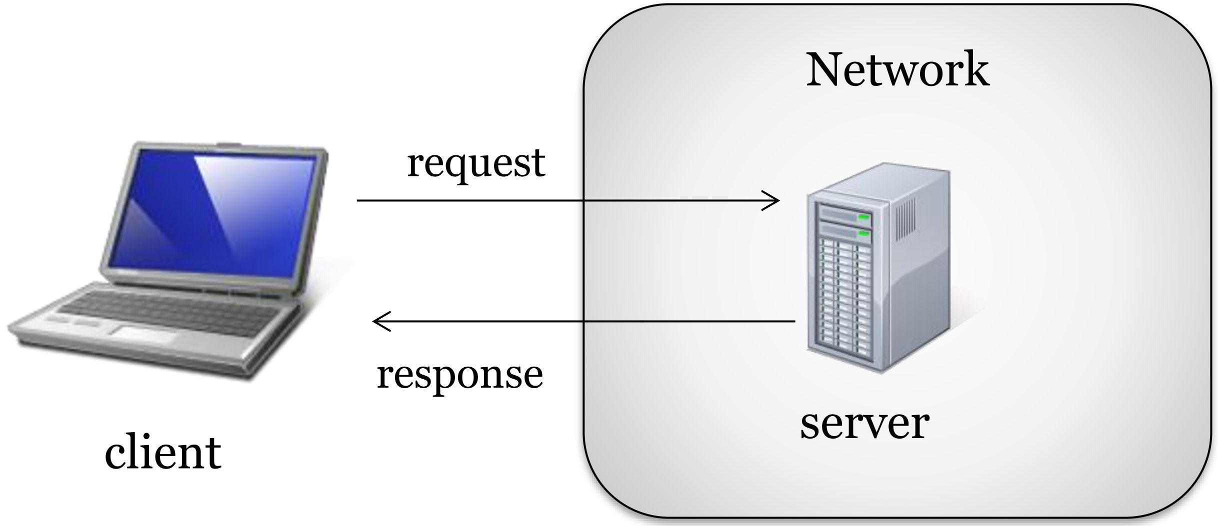
- Server: offers services through a query/answer protocol
- Client: does queries and process answers
- Network protocol: communication management between clients and servers



Client-Server

Constraints

- Clients communicate with servers
  - Not the other way
- Clients are independent from other clients
- Servers don't have knowledge about clients
- Network protocol establishes some communication warranties



Client-Server

Advantages

- Distribution
  - Servers can be distributed
- Low coupling
  - Separation of functionality between clients/servers
  - Independent development
- Scalability
- Availability
  - Functionality available to all clients
  - But not all the servers need to offer all functionality

Challenges

- Each server can be a single point of failure
  - Server attacks
- Unpredictable performance
  - Dependency on the system and the network
  - Problems when servers belong to other organizations
    - How can quality of service be warranted?

Client-Server

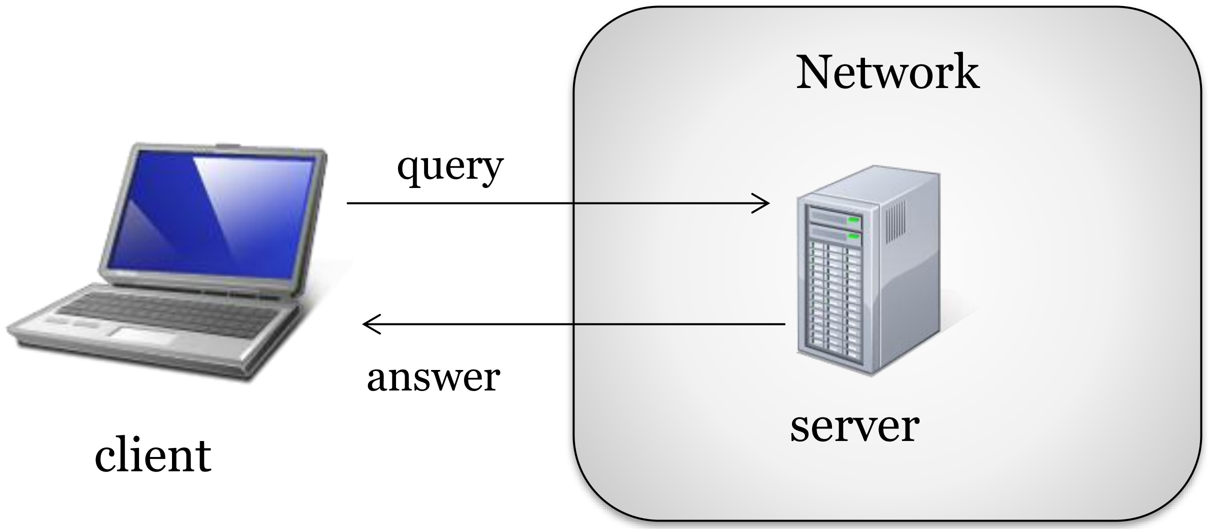
Variants

- Stateless
- Replicated server
- With cache

Client-Server stateless

Constraint

- Server does not store information about clients
- Same query implies same answer



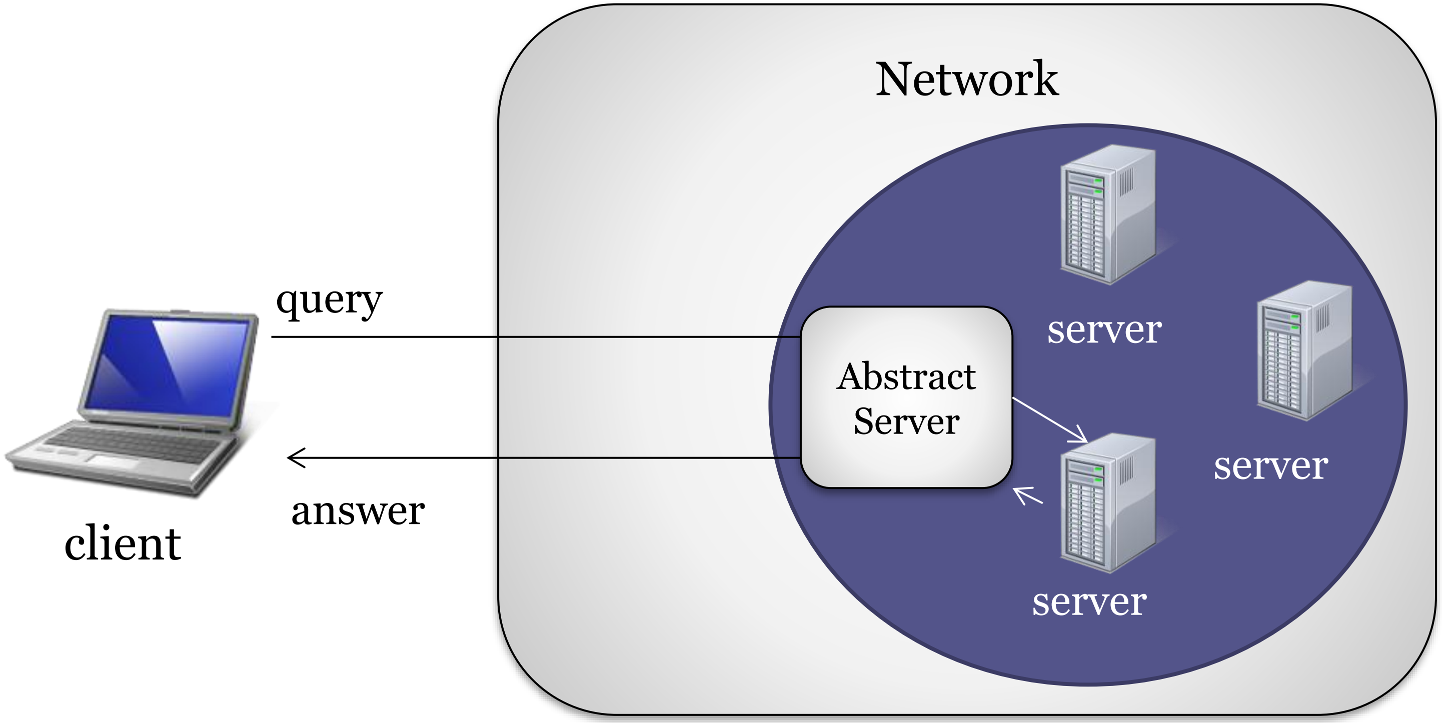
Client-Server stateless

- Advantages
  - Scalability
- Challenges
  - Application state management
    - Client must remember requests
    - Handle information between requests

Replicated server

Constraint

- Several servers offer the same service
  - Offer the client the appearance that there is only one server



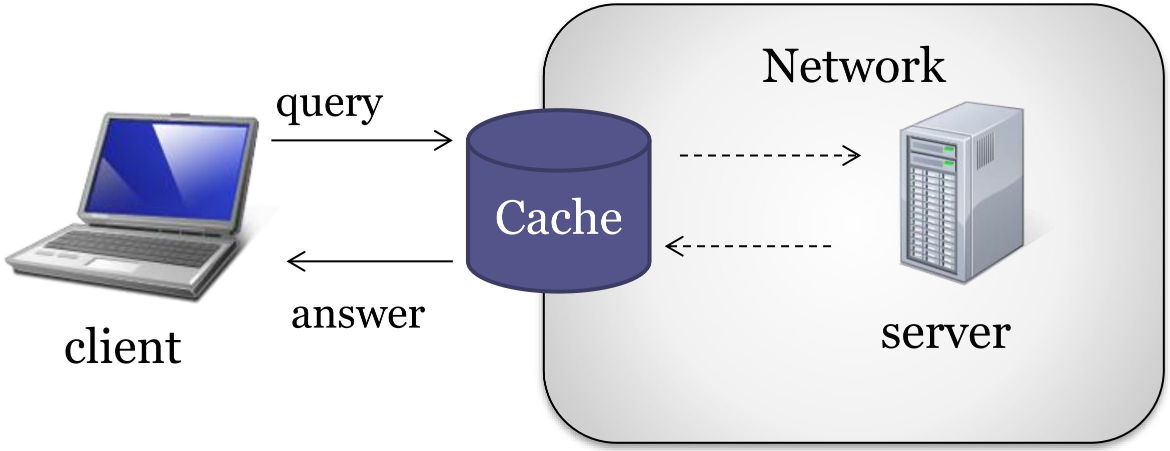
Replicated server

- Advantages
  - Better answer times
  - Less latency
  - Fault tolerance
- Challenges
  - Consistency management between replicated servers
  - Synchronization

Client-server with cache

Cache = mediator between client/server

- Stores copies of previous answers to the server
  - When a query is received it return the cached answer without asking the original server



Client-server with cache

- Elements:
  - Intermediate cache nodes
- Constraints
  - Some queries are directly answered by the cache node
  - Cache node has a policy for answer management
    - Expiration time

Client-server with cache

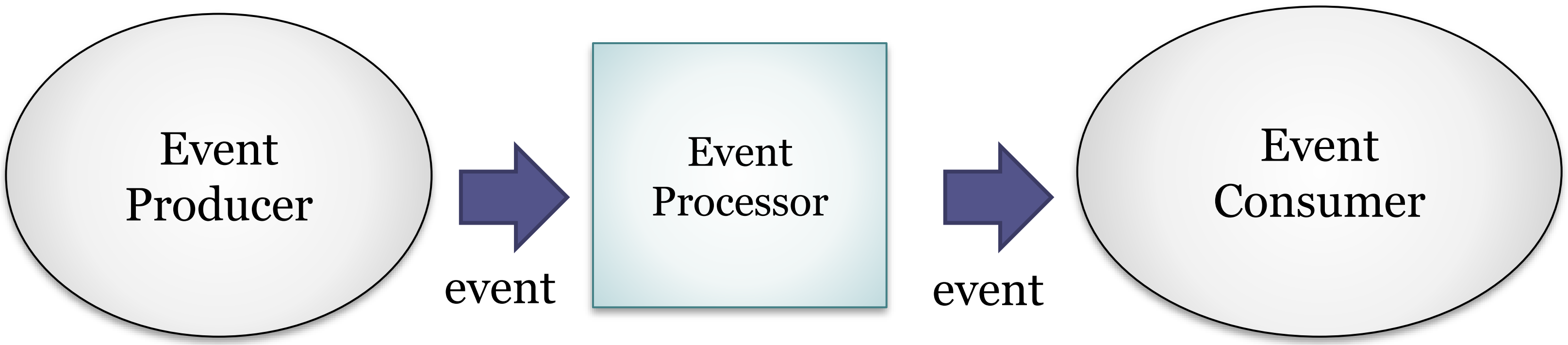
Advantages:

- Less network overload
  - Lots of repeated requests can be stored in the cache
- Less answer time
  - Cached answers arrive earlier

Challenges

- Complexity of configuration
- Expiration policy
- Not appropriate for certain domains
  - When high fidelity of answers is needed
  - Example: real time systems

Event driven architecture (EDA)



Event driven architecture

Elements:

- Event:
  - Something that has happened (≠ request)
- Event producer
  - Event generator (sensors, systems, ...)
- Event consumer
  - DB, applications, scorecards, ...
- Event processor
  - Transmission channel
  - Filters and transforms events

Event driven architecture

Constraints:

- Asynchronous communication
  - Producers generate events at any moment
  - Consumers can be notified of events at any moment
- Relationship one-to-many
  - An event can be sent to several consumers

Event driven architecture

Advantages

- Decoupling
  - Producer does not depend on consumer, nor vice versa.
- Timelessness
  - Events are published without any need to wait for the termination of any cycle
- Asynchronous
  - In order to publish an event there is no need to finish any process

Challenges

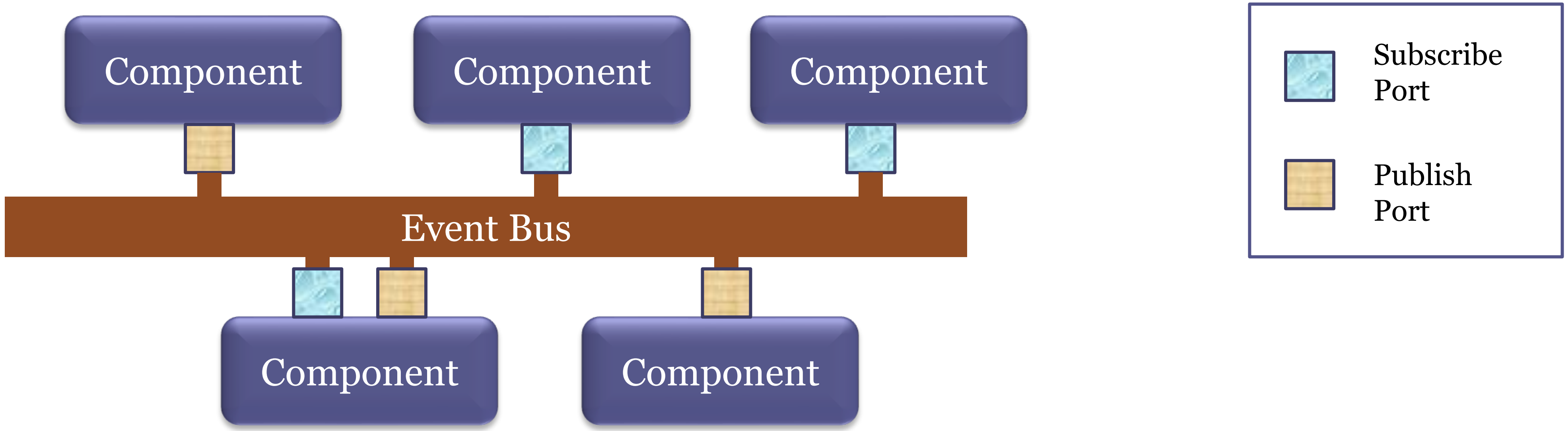
- Non sequential execution
  - Possible lack of control
- Consistency
- Difficult to debug

Event driven architecture

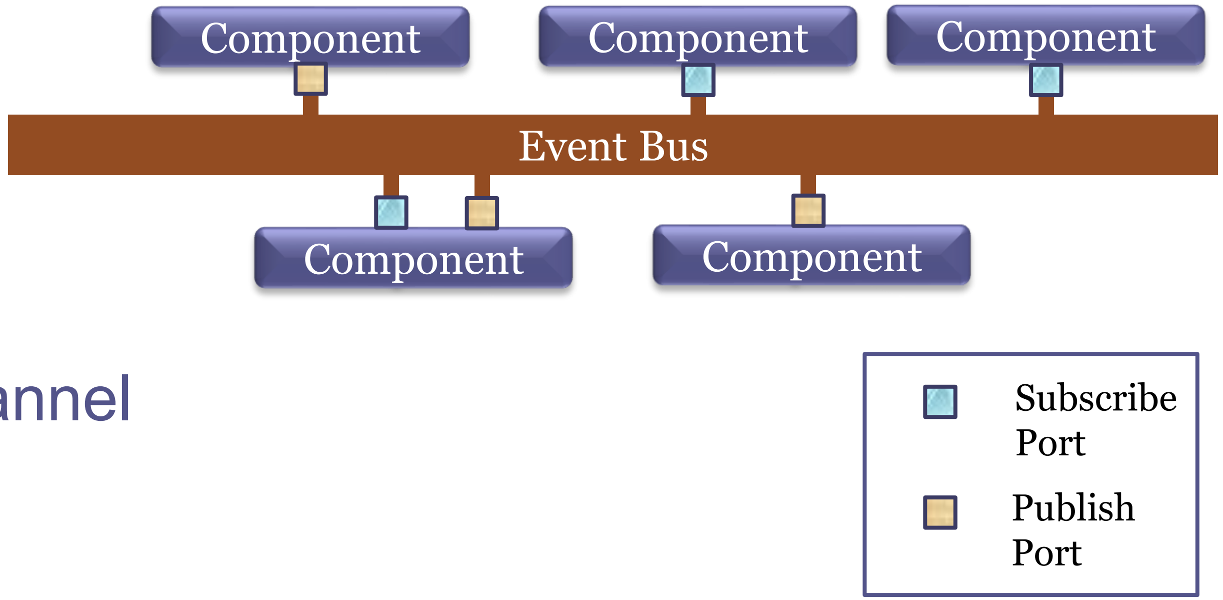
- Applications
  - Event processing networks
  - *Event-Stream-Processing (ESP)*
  - *Complex-event-processing*
- Variants
  - Publish-subscribe
  - Actor models
- Related patterns
  - CQRS, Event sourcing

Publish-subscribe

Components subscribe to a channel to receive messages from other components



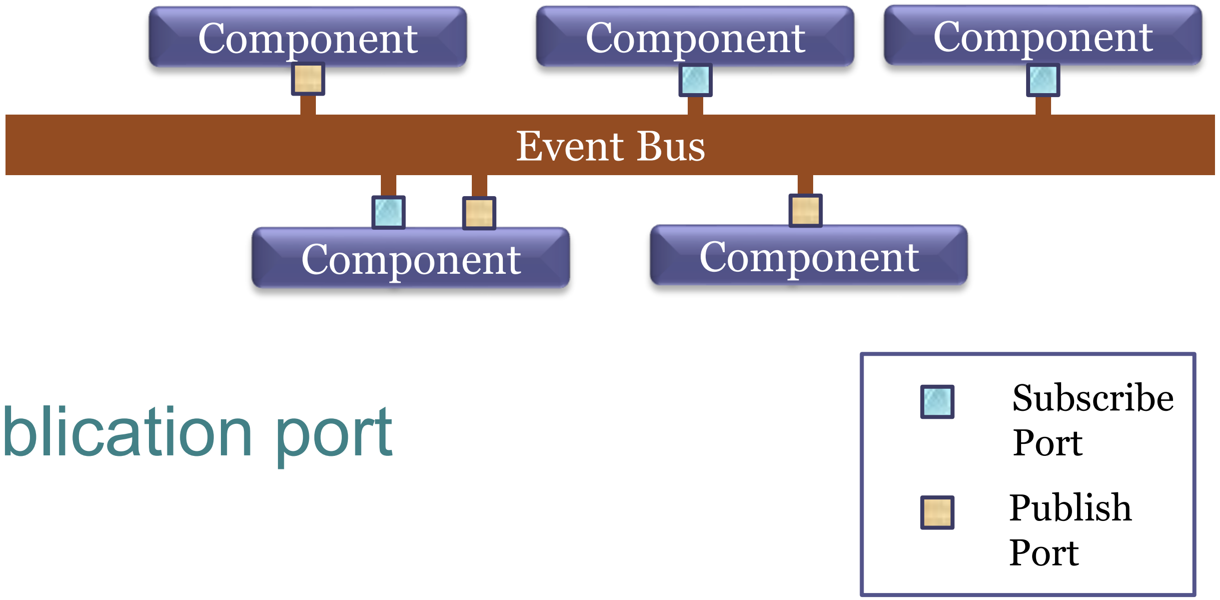
Publish-subscribe



Elements:

- Component:
  - Component that subscribes to a channel
- Publication port
  - It is registered to publish messages
- Subscription port
  - It is registered to receive some kind of messages
- Event bus (message channel):
  - Transmits messages to subscribers

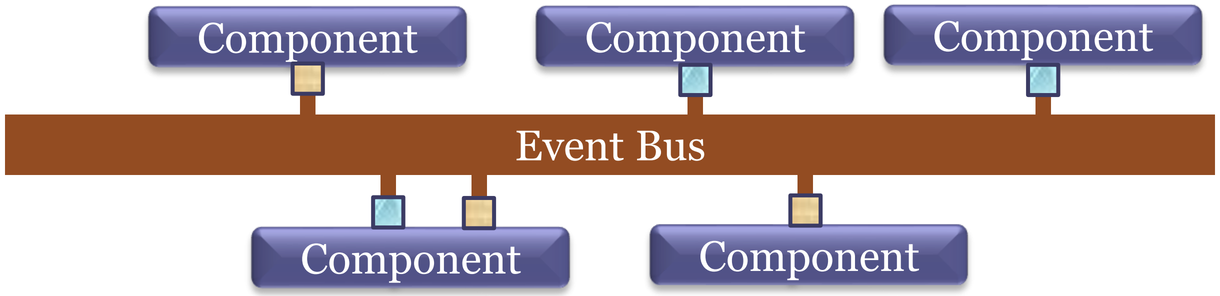
Publish-subscribe



Constraints:

- Separation between subscription/publication port
  - A component may have both ports
- Non-direct communication
  - Asynchronous communication in general
  - Components delegate communication responsibility to the channel

Publish-subscribe



Advantages

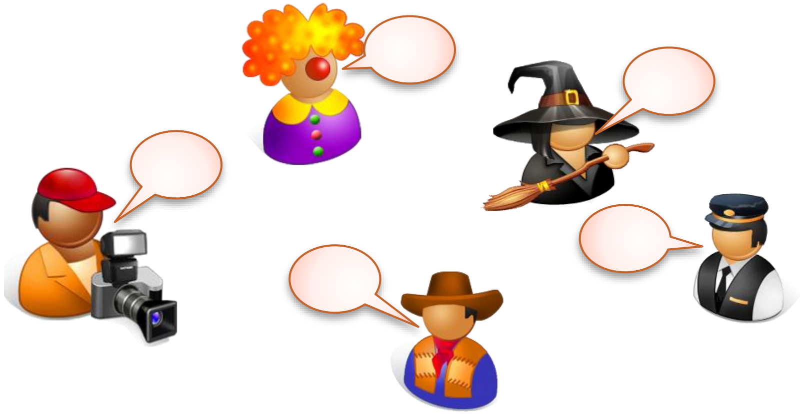
- Communication quality
  - Improves performance
  - Debugging
- Low coupling between components
  - Consumers do not depend on publishers
  - ...nor vice versa...

Challenges

- It adds a new indirection level
  - Direct communication may be more efficient in some domains
- Complex implementation
  - It may require COTS

Actor models

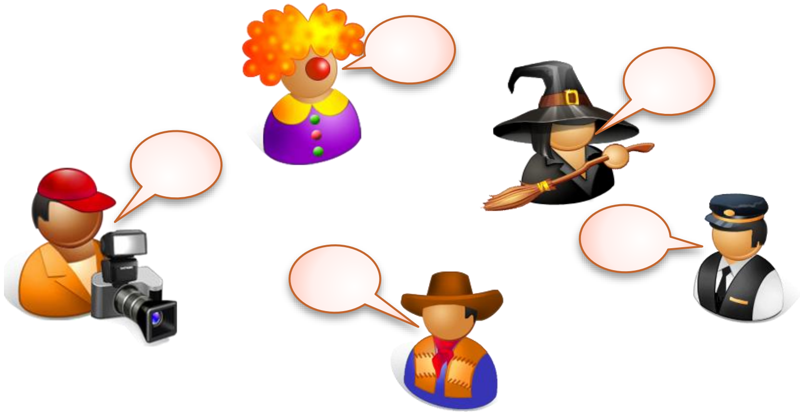
- Used for concurrent computation
  - Actors instead of objects
  - There is no shared state between actors
  - Asynchronous message passing
- Theoretical developments since 1973 (Carl Hewitt)



Actor models

Elements

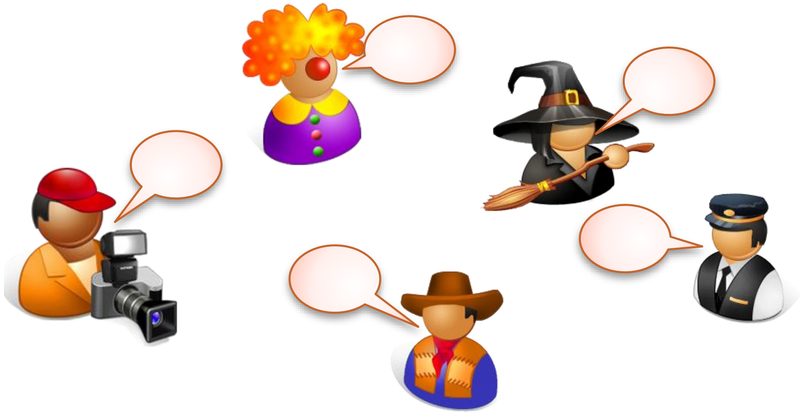
- Actor: computational entity with state
  - It communicates with other actors sending messages
  - It process messages one by one
- Messages
- Addresses: Identify actors (*mailing address*)



Actor models

Constraints

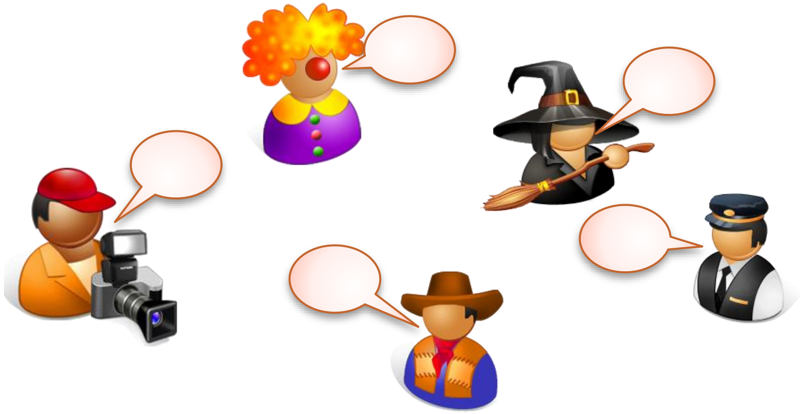
- An actor can only:
  - Send messages to other actors
    - Messages are immutable
  - Create new actors
  - Modify how it will process next message
- Actors are decoupled
  - Receiver does not depend on sender



Actor models

Constraints (2)

- Local addresses
  - An actor can only send messages to known addresses
  - Because they were given to it or because he created them
- Parallelism:
  - All actions are in parallel
  - No shared global state
  - Messages can arrive in any order



Actor models

Advantages

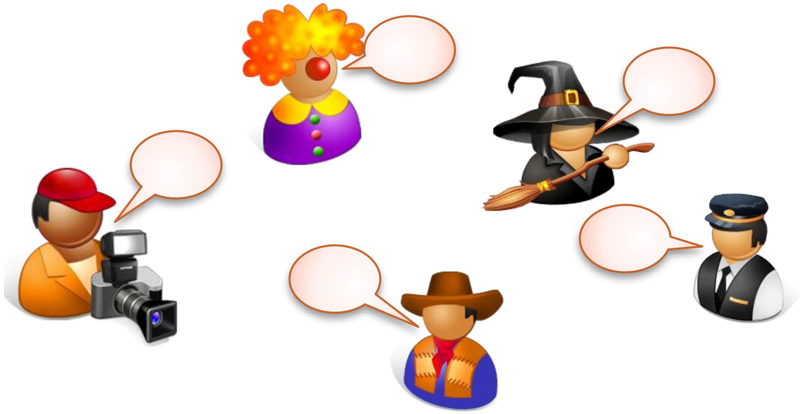
- Highly parallel
- Transparency and scalability
  - Internal vs external addresses
- Non-local actor models
  - Web Services
  - Multi-agent systems

Challenges

- Message sending
  - How to handle arriving messages
- Actor Coordination
- Non-consistent systems by definition

Actor models

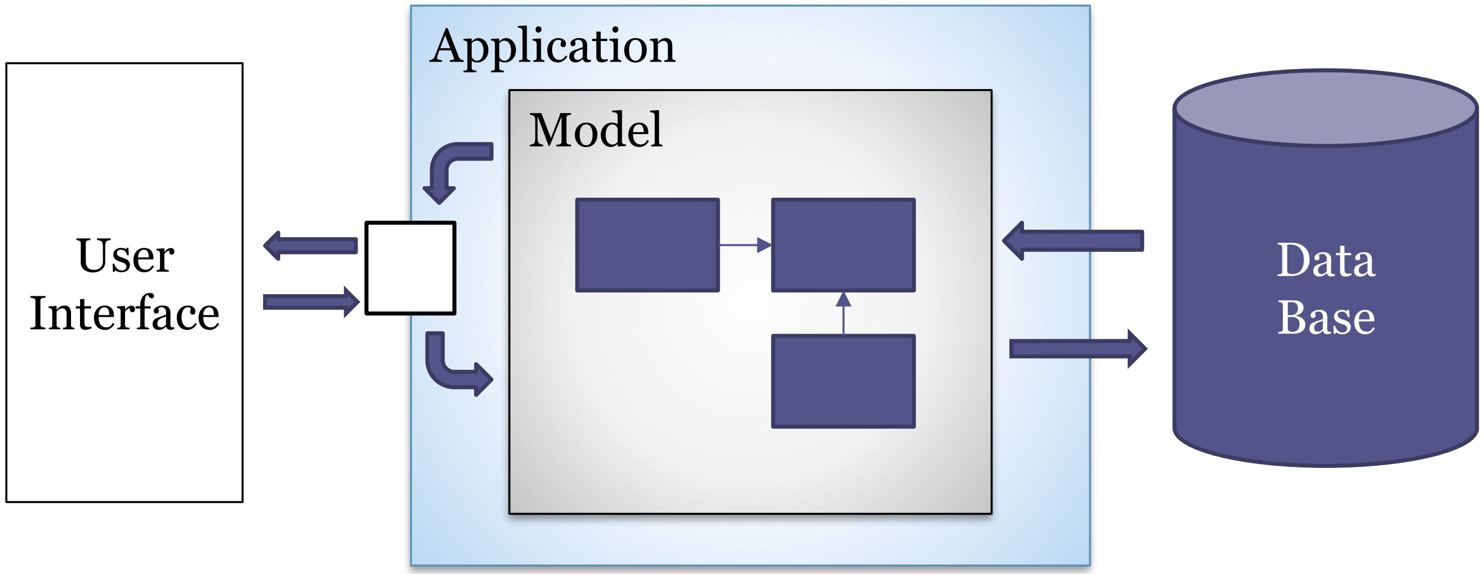
- Implementations
  - Erlang (programming language)
  - Akka (library)
- Applications
  - Reactive systems
  - Examples: Ericsson, Facebook, twitter



CQRS

Command Query Responsibility Segregation

- Separate models in 2 parts
  - Command: Does changes (updates information)
  - Query: Only queries (get information)



CQRS

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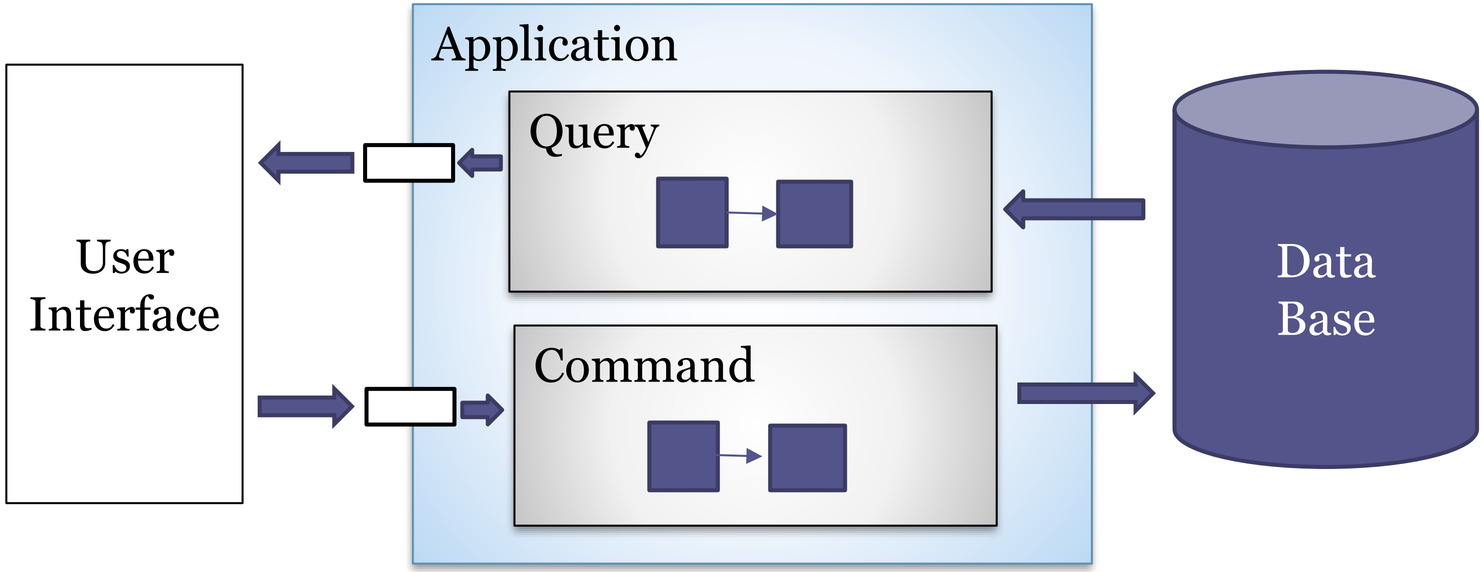


CQRS

Advantages

- Scalability
  - Optimize queries (read-only)
  - Asynchronous commands
- Facilitates team decomposition and organization
  - One team for read access (queries)
  - Another team for write/update access (command)

Applications
- Axon Framework

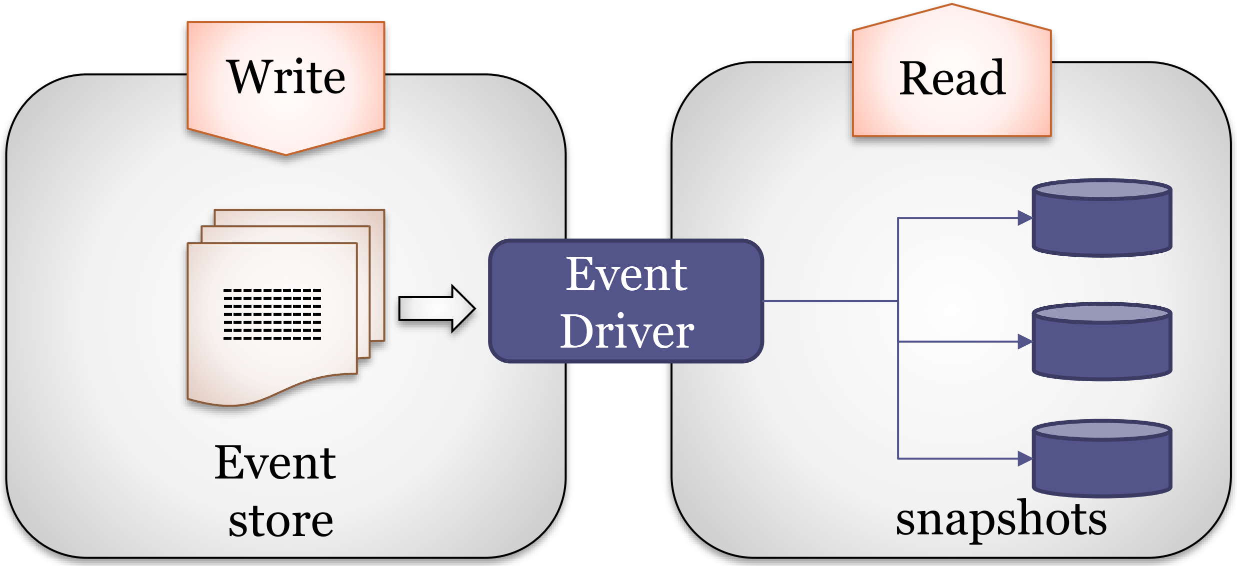
Challenges

- Hybrid operations
  - Both query and command
  - Example: *pop()* in a stack
- Complexity
  - For simple CRUD applications it can be too complex
- Synchronization
  - Possibility of queries over non-updated data

Event Sourcing

All changes to application state are stored as a sequence of events

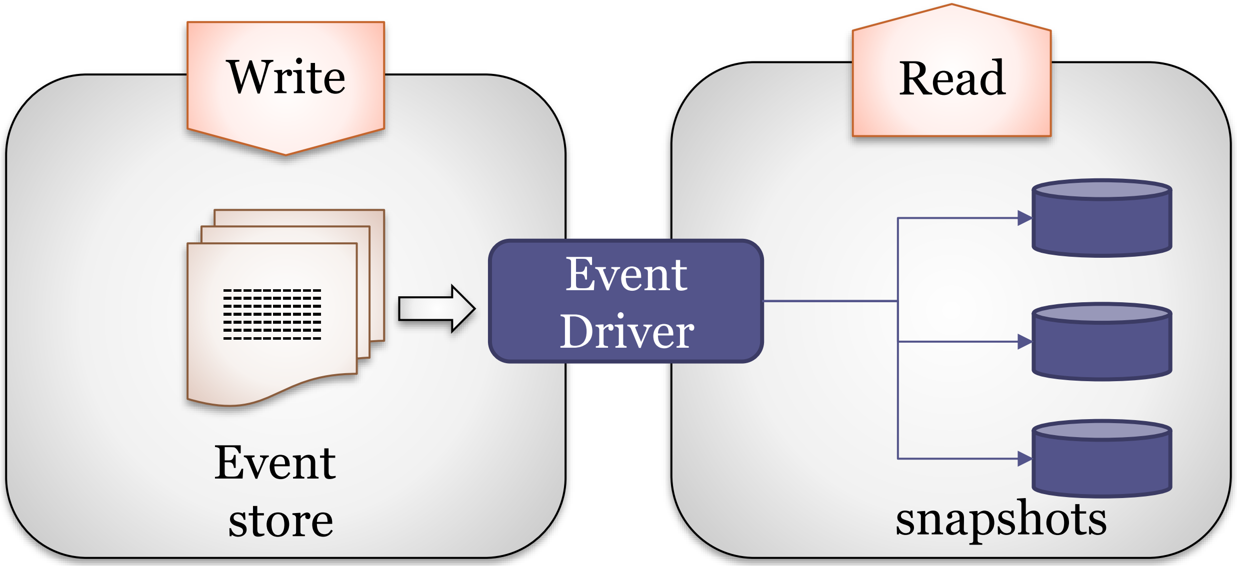
- Every change is captured in an event store
  - It is possible to trace and undo changes



Event Sourcing

Elements

- Events: something that has happened, in the past
- Event store: Events are always added (append-only)
- Event driver: handles the different events
- Snapshots of aggregated state (optional)



Event Sourcing

Advantages

- Fault tolerance
- Traceability
  - Determine the state of the application at any time
- Rebuild and event-replay
  - It is possible to discard an application state and re-run the events to rebuild a new state
- Scalability
  - Append-only DB can be optimized

Challenges

- Novelty of development
  - Different with traditional systems
- Eventual consistency
- Software updates
  - Different event versions together?
- Resource management
  - Granularity of events
  - Event storage grows with time
    - Snapshots can be used for optimization

Event Sourcing

Applications

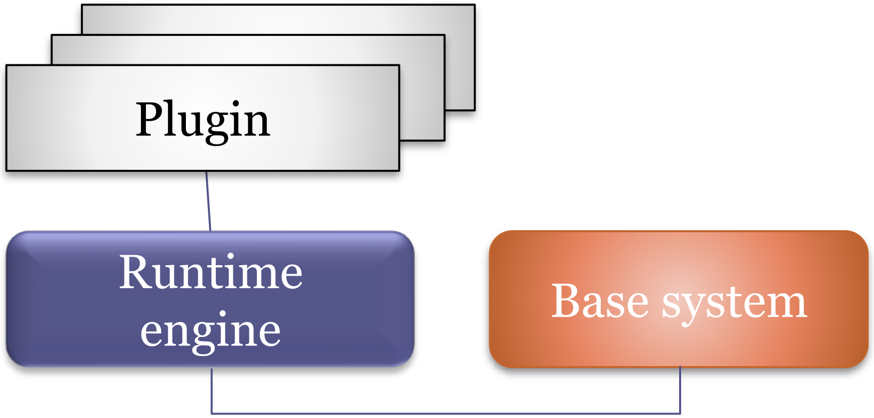
- Database systems
  - Datomic
  - EventStore

Adaptable Systems

Plugins
Microkernel
Reflection
Interpreters and DSL
Mobile code
- Code on demand
- Remote evaluation
- Mobile agents

Plugins

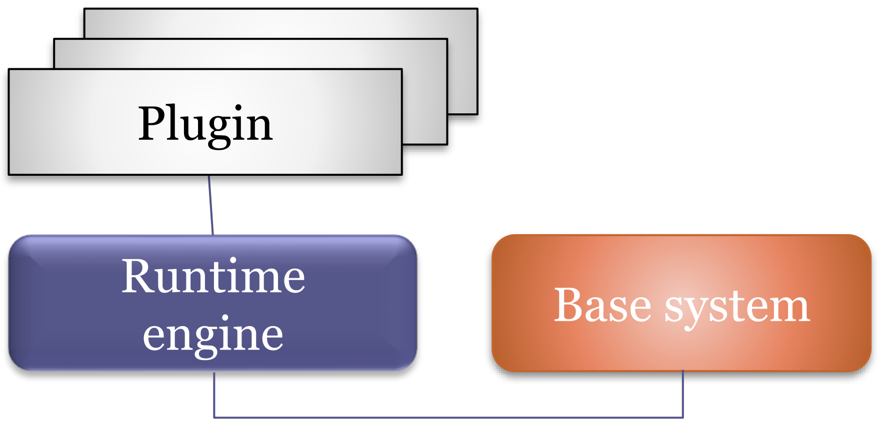
It allows to extend the system using plugins that add new functionality



Plugins

Elements

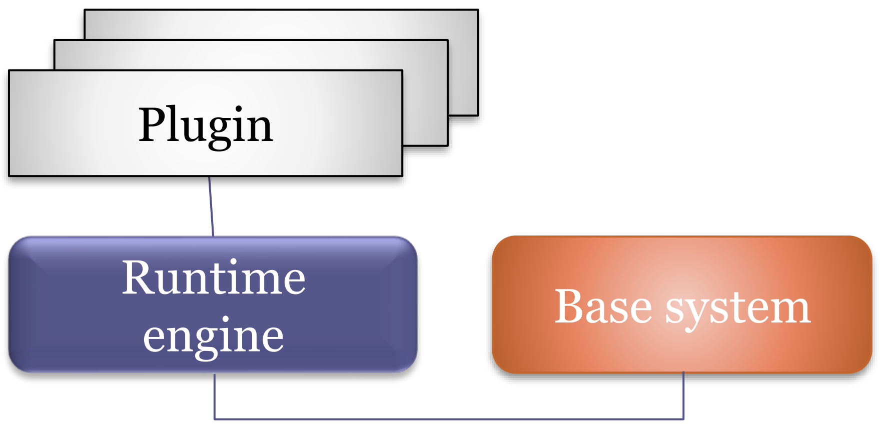
- Base system:
  - System that allows plugins
- *Plugins:* Components that can be added/removed dynamically
- Runtime engine:
  - Starts, localizes, initializes, executes, and stops plugins



Plugins

Constraints

- Runtime engine manages plugins
- System can add/remove plugins
- Some plugins can depend on other plugins
  - The plugin must declare dependencies and the exported API



Plugins

Advantages

- Extensibility
  - Application can get new functionalities in some ways that were not foreseen by the original developers
- Customization
  - Application can have a small kernel that is extended on demand

Challenges

- Consistency
  - Plugins must be added to the system in a sound way
- Performance
  - Delay searching/configuring plugins
- Security
  - Plugins made by third parties can compromise security
- Plugin management and dependencies

Plugins

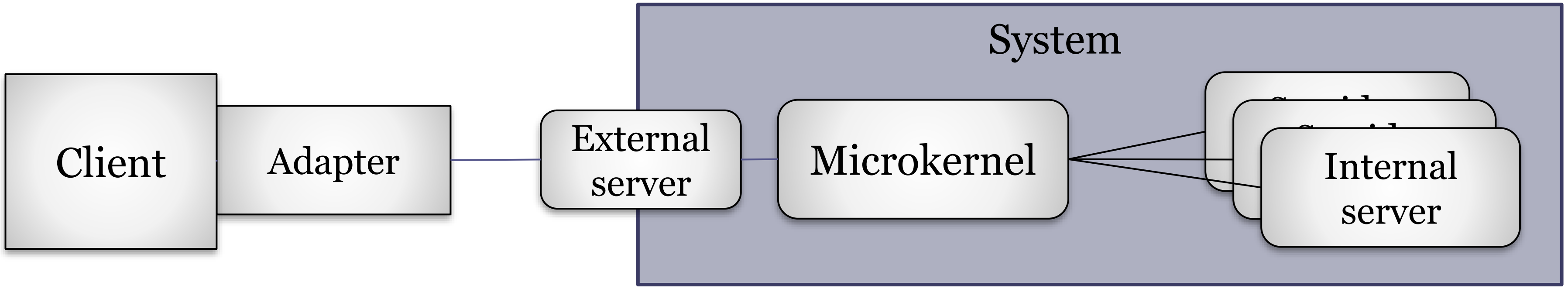
- Examples
  - Eclipse
  - Firefox
- Technologies
  - Component systems: OSGi

Microkernel

Identify minimal functionality in a microkernel

Extra functionality is added using internal servers

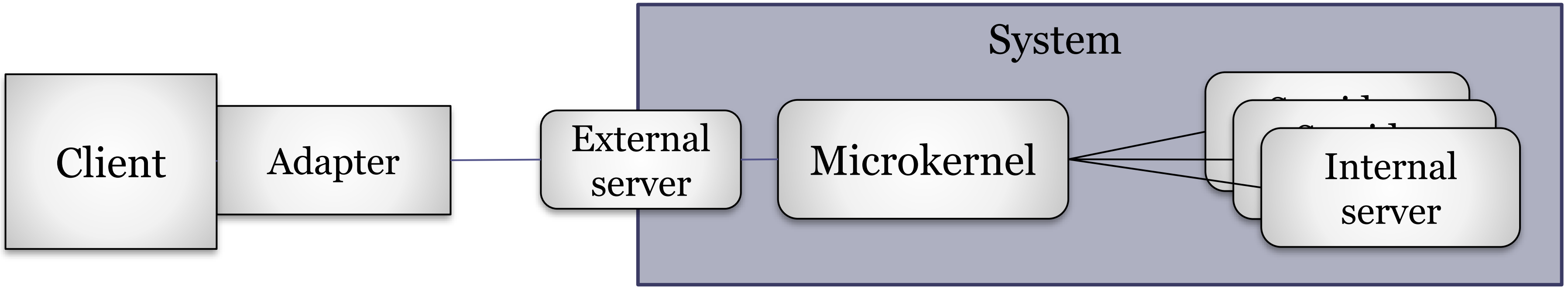
External server handles communication with other systems



Microkernel

Elements

- Microkernel: Minimal functionality
- Internal server: Extra functionality
- External server: Offers external API
- Client: External application
  - Adapter: Component that establish communication with external server

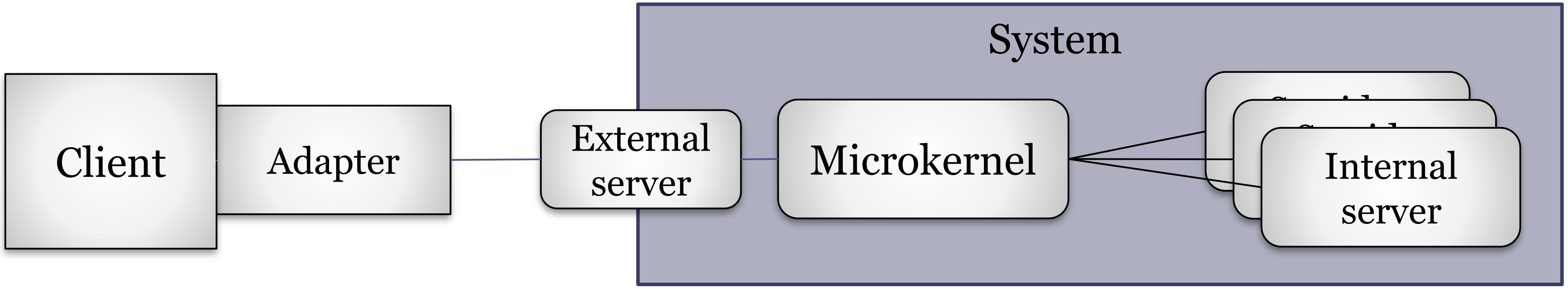


University of Oviedo

Microkernel

Constraints:

- *Microkernel* implements only minimal functionality
- The rest of the functionality is implemented using internal servers
- Communication with clients by external servers



School of Computer Science

Microkernel

Advantages

- Portability
  - It is only needed to port the kernel
- Flexibility and extensibility
  - Adding new functionality with new internal servers
- Security and reliability
  - Critical parts of the system are encapsulated
  - Errors in external parts don't affect the microkernel

Challenges

- Performance
  - A monolithic can be more efficient
- Design complexity
  - Identify components in the microkernel
    - It may be difficult to separate parts to internal servers
- Unique point of failure
  - If microkernel fails, the whole system may fail

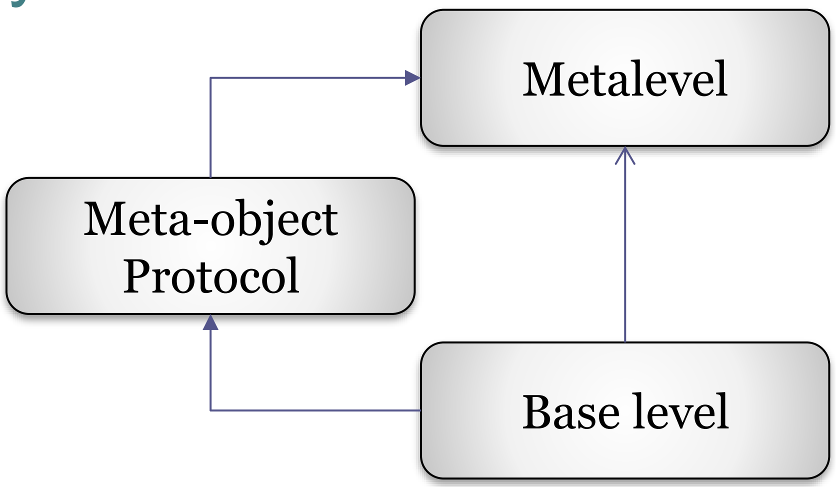
Microkernel

Applications

- Operating systems
- Games
- Editors

Reflection

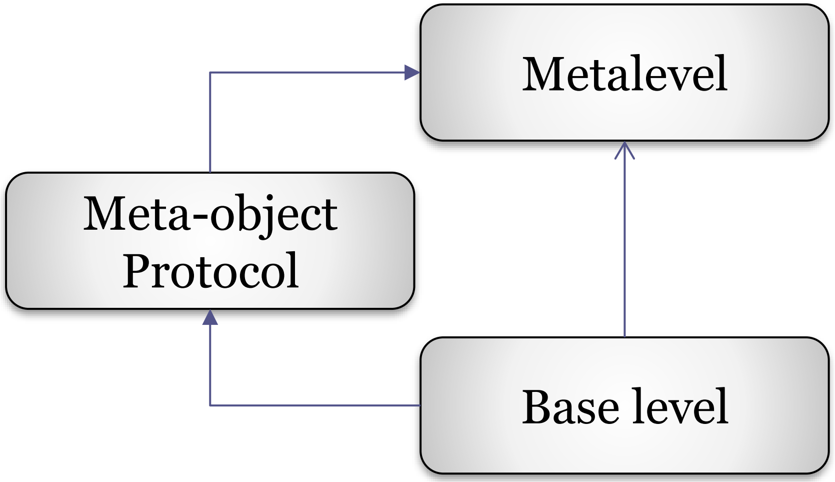
- Change the structure and behavior of an application dynamically
  - Systems that can modify themselves
- Elements
  - Base level: Implements application logic
  - Metalevel: Aspects that can be modified
  - Metaobject protocol: Interface that can modify the metalevel



Reflection

Constraints

- Base level uses metalevel aspects for its behavior
- At runtime, it is possible to modify the metalevel using the metaobject protocol



Reflection

Advantages

- Flexibility
  - Adapt to changing conditions
  - Change behavior of running system without changing source code or stopping execution

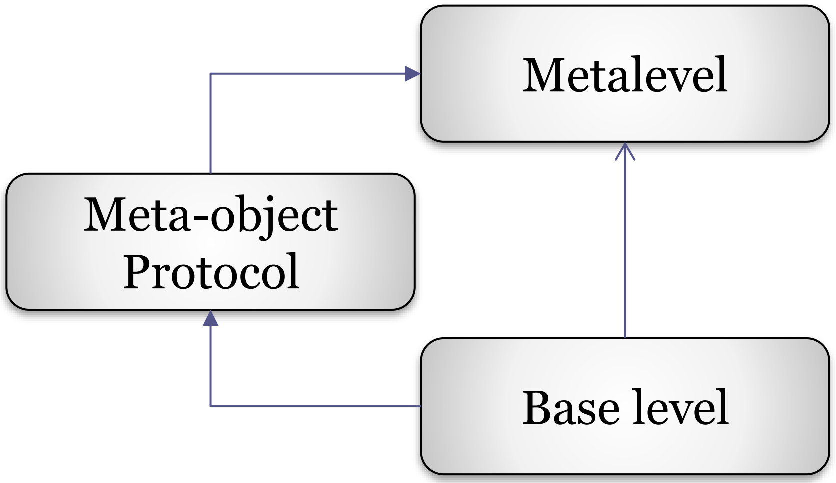
Challenges

- Implementation
  - Not all languages enable meta-programming
  - More difficult to combine with static type systems
- Performance
  - It may be necessary to do some optimizations to limit reflection
- Security:
  - Consistency maintenance

Reflection

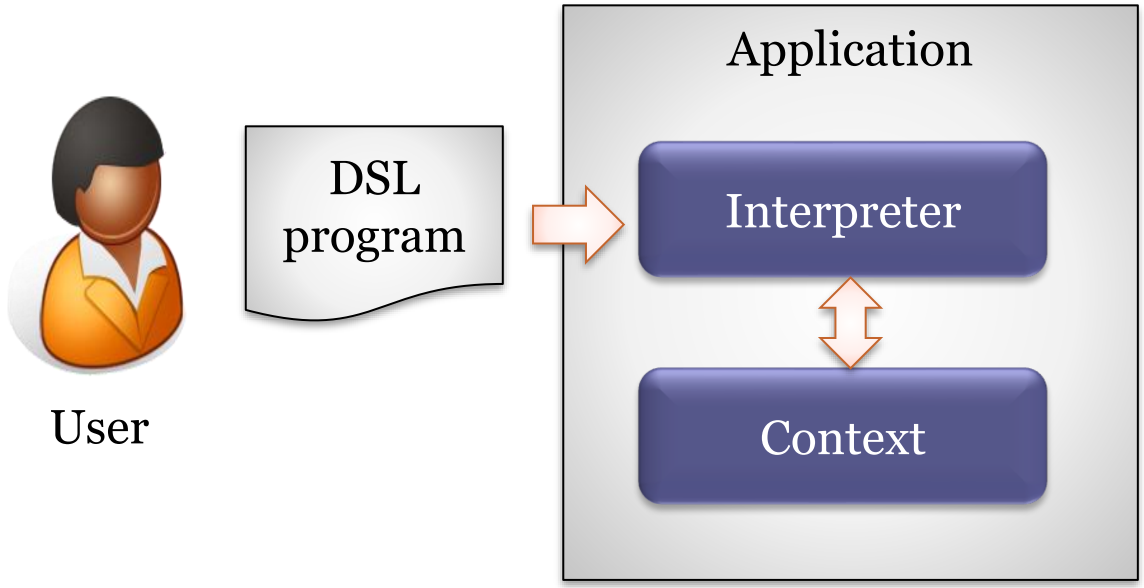
Applications

- Most dynamic languages support reflection
  - Scheme, CLOS, Ruby, Python, ...
- Intelligent systems
- Self-modifiable code



Interpreters and DSLs

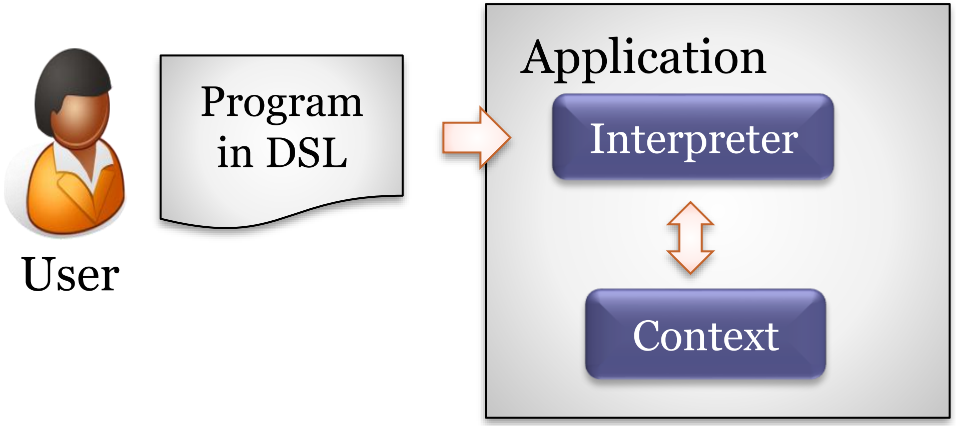
Include a domain specific language (DSL) that is interpreted by the system



Interpreters and DSLs

Elements

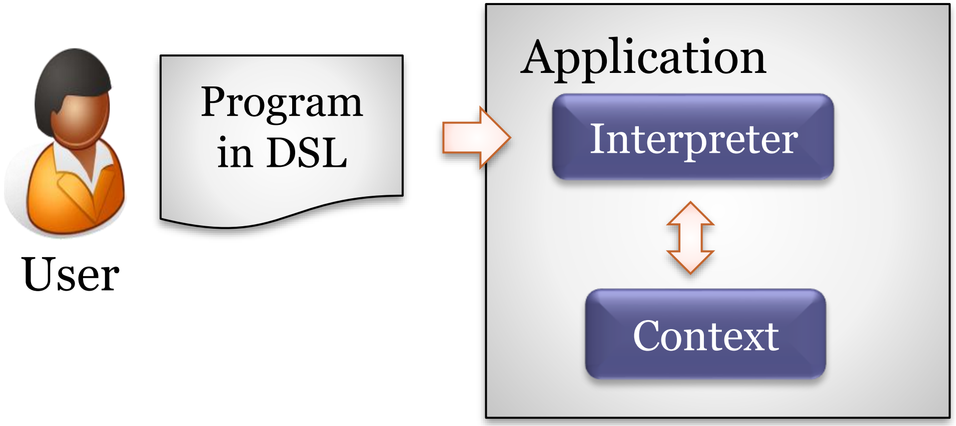
- Interpreter: Module that executes the program
- Program: Written in the DSL
  - DSL can be designed so the end user can write programs
- Context: Environment where the program is executed



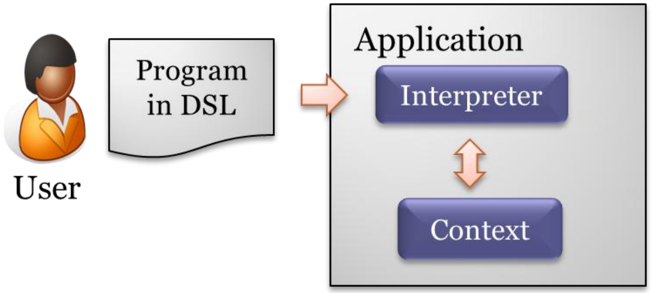
Interpreters and DSLs

Constraints

- Interpreter runs the program interacting with the context
- It is necessary to define a DSL
  - Syntax (grammar, parsing,...)
  - Semantics (behavior)



Interpreters and DSLs



Advantages

- Flexibility
  - Adapt application behavior to user needs
- Usability
  - End users can write their own programs
- Adaptability
  - Easy to adapt to unforeseen situations

Challenges

- Design of the DSL
- Complexity of implementation
  - Interpreter
  - Separation of context/interpreter
- Performance
  - Possible programs may be not optimal
- Security
  - Handle wrong programs

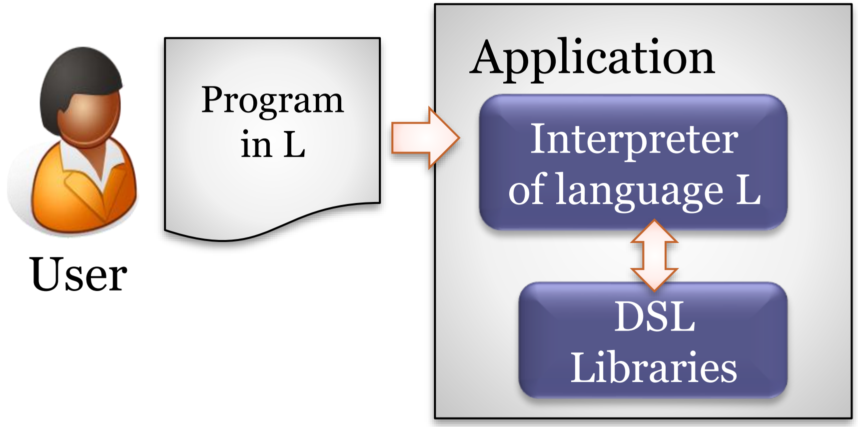
Interpreters and DSLs

Variants:

- Embedded DSLs

Embedded DSLs

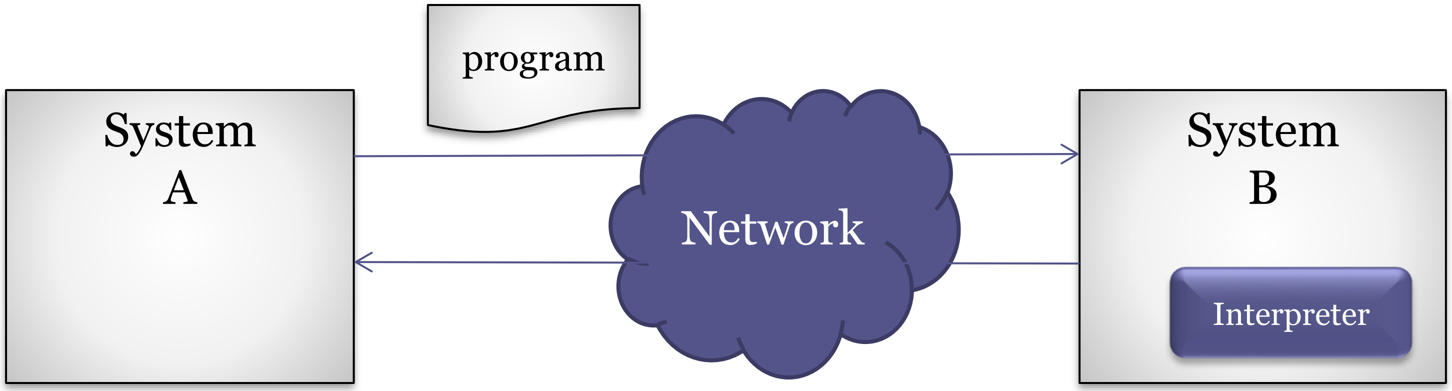
- Embedded DSLs
- Domain specific languages that are embedded in general purpose host languages
  - Popular approach in some languages like Haskell, Ruby, Scala, etc.
- Advantages:
  - Reuse of host language syntax
  - Access to libraries and IDEs of host language
- Challenges
  - Separation between DSL and host language
  - End users may have too many expressivity



Mobile code

Code that is transferred from one machine to another

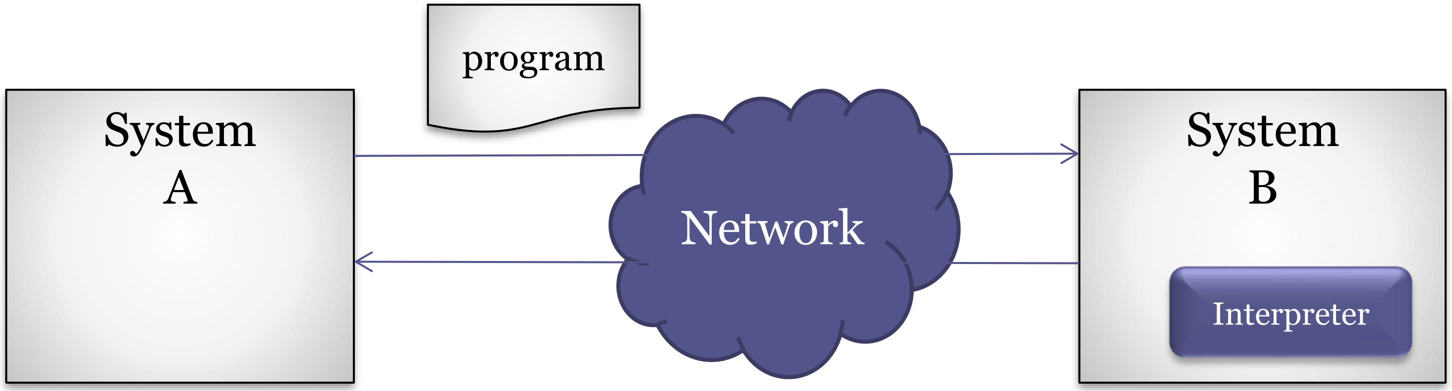
- System A sends a program to be run by system B
- System B must contain an interpreter for the language in which the program is written



Mobile code

Elements

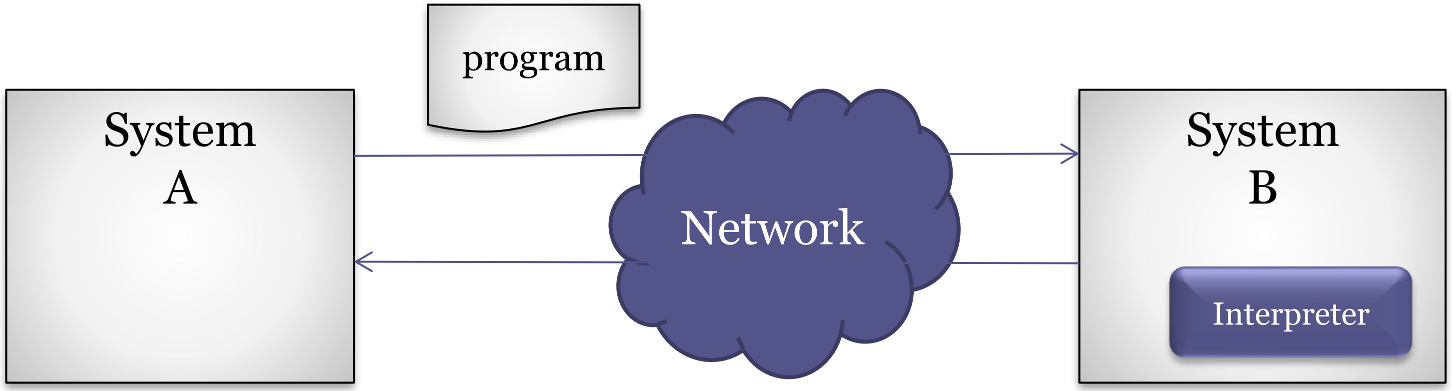
- Interpreter: Runs the code
- Program: Program that is transferred
- Network: Transfers the program



Mobile code

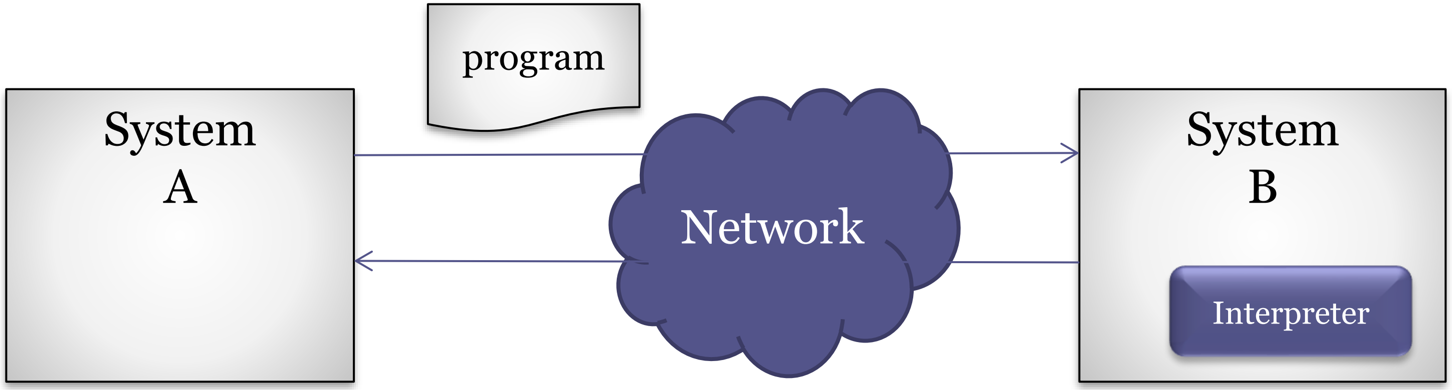
Constraints

- The program must be run in the receiver system
- The network protocol transfers the program



Mobile code

- Advantages
  - Flexibility and adaptability to new environments
  - Parallelism
- Challenges
  - Complexity of implementation
  - Security



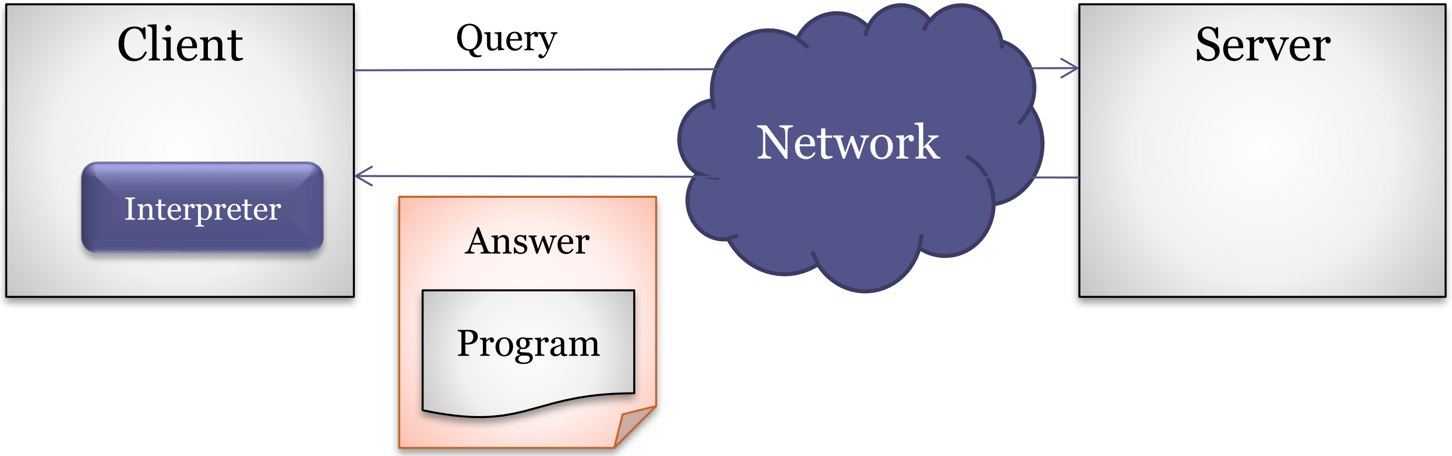
Mobile code

Variants

- Code on demand
- Remote evaluation
- Mobile Agents

Code on demand

- Code is downloaded and run by the client
- Combination between mobile code and client-server
- Example:
  - ECMAScript



Code on demand

- Elements
  - Client
  - Server
  - Code that is transferred from server to client
- Constraints
  - Code resides or is generated by the server
  - It is transferred to the client when it asks for it
  - It is run by the client
    - Client must have an interpreter for the corresponding language

Code on demand

Advantages

- Improves user experience
- Extensibility: Application can add new functionalities that were not foreseen
  - No need to install or download a whole application
  - Always *Beta*
- Adaptability to client environment

Challenges

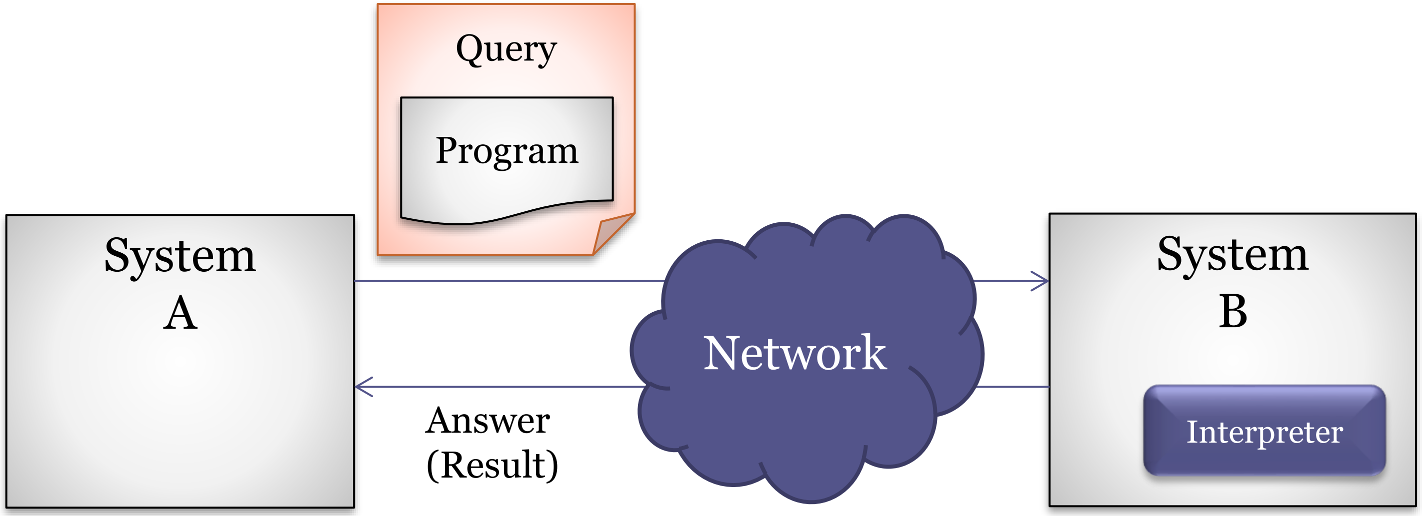
- Security
- Coherence
  - It may be difficult to ensure an homogeneous behavior in different types of clients
    - Client can even decide not to run the program
      - Reminder: Responsive design

Code on demand

- Applications:
  - RIA (Rich Internet Applications)
    - HTML5 standardizes a lot of APIs
    - Improves coherence between clients
- Variants
  - AJAX
    - Initially: *Asynchronous Javascript and XML*
    - The program that is running at the client side sends asynchronous requests to the server without stopping its running

Remote evaluation

System A sends program to system B to be run and obtain its results



Remote evaluation

- Elements
  - Sender: Does the query including the program
  - Receiver: Runs the program and returns the results
- Constraints
  - Receiver runs the program
    - It must contain some interpreter of the program language or the program could be in machine code
  - Network protocol transfers program and results

Remote evaluation

- Advantages
  - Exploits capabilities of third parties
    - Computational capabilities, memory, resources, etc.
- Challenges
  - Security
    - Untrusted code
    - Virus = variant of this style
  - Configuration

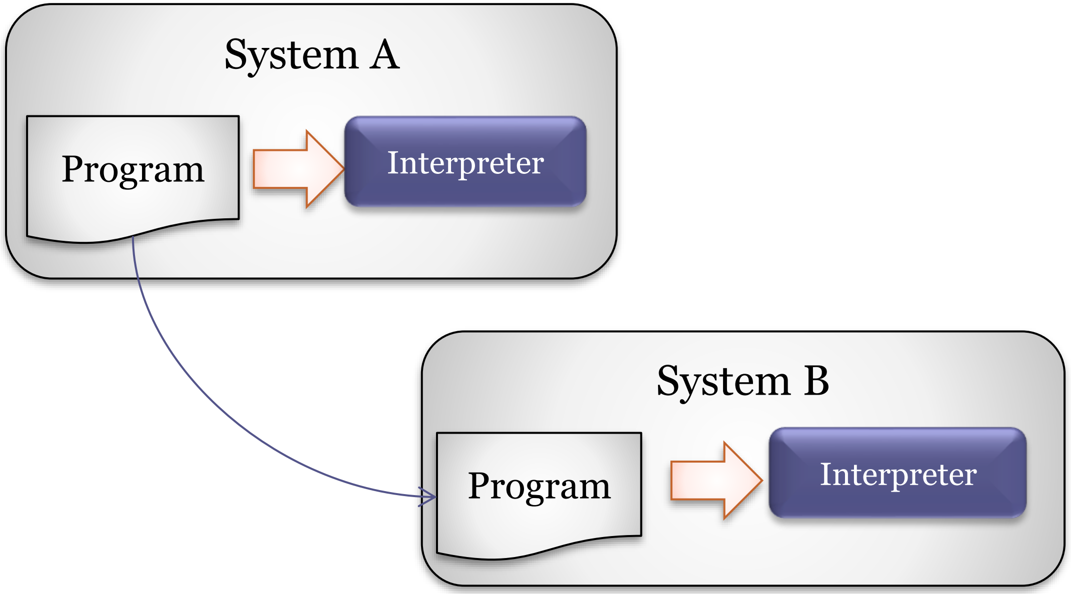
Remote evaluation

- Example:
  - Volunteer computation
    - SETI@HOME
      - It was the basis for the BOINC system
        - Berkeley Open Infrastructure for Network Computing
    - Other projects: Folding@HOME, Predictor@Home, AQUA@HOME, etc.

Mobile agents

Code and data can move from one machine to another to be run

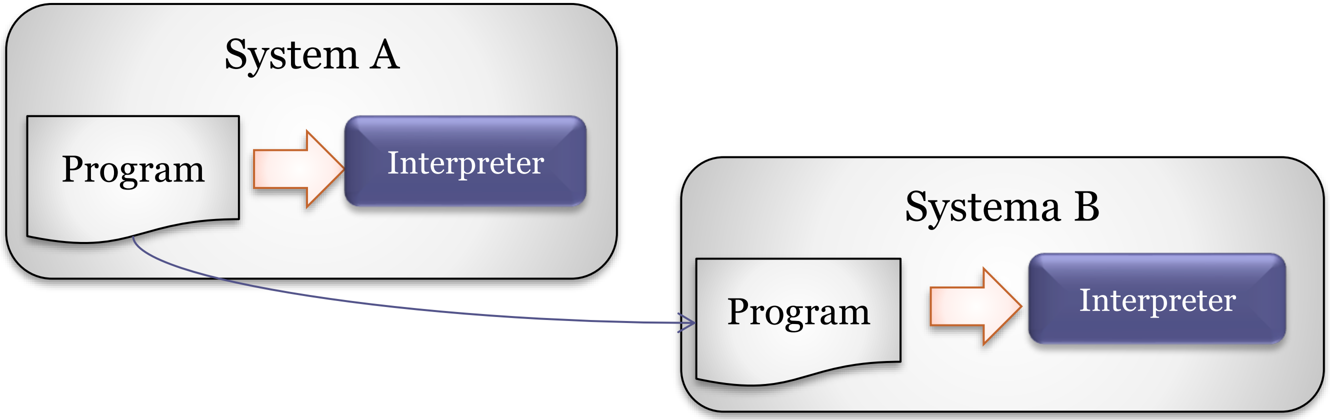
- The process takes its state from machine to machine
- Code can move autonomously



Mobile agents

Elements

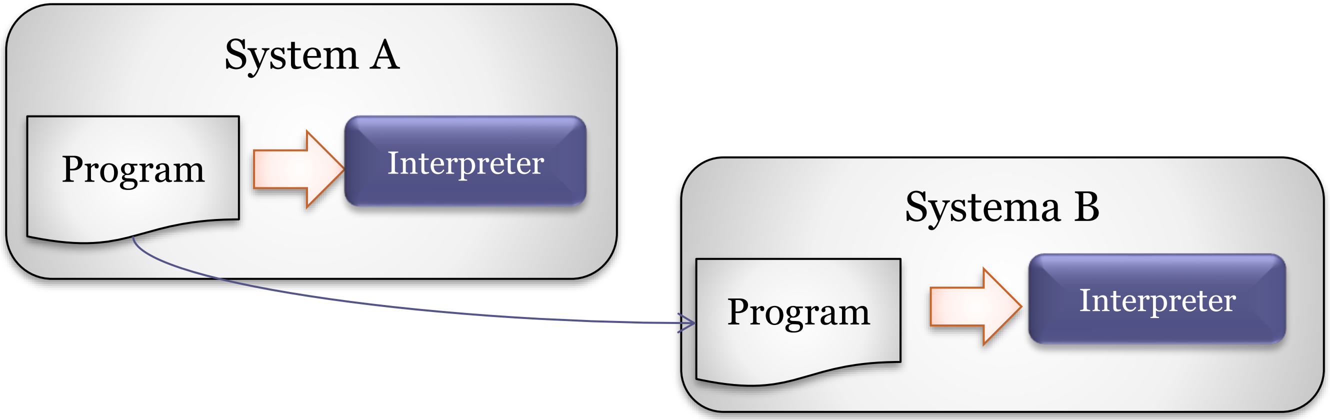
- Mobile agent: Program that travels and is run from one machine or another autonomously
- System: Execution environment where the mobile agents are run
- Network protocol: transfers state between agents



Mobile agents

Constraints

- Systems host and run mobile agents
- Mobile agents can decide to change its running from one system to another
  - They can communicate with other agents



Mobile agents

Advantages

- It can reduce network traffic
  - Code blocks that are run are transmitted
- Implicit parallelism
- Fault tolerance to network failures
- Agents can be conceptually simple
  - Agent = independent unit of execution
  - It is possible to create mobile agent systems
  - Emergent behaviour
- Adaptability to environtment changes
  - Reactive and learning systems

Challenges

- Complexity of configuration
- Security
  - Malicious or incorrect code

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  - Complexity of configuration
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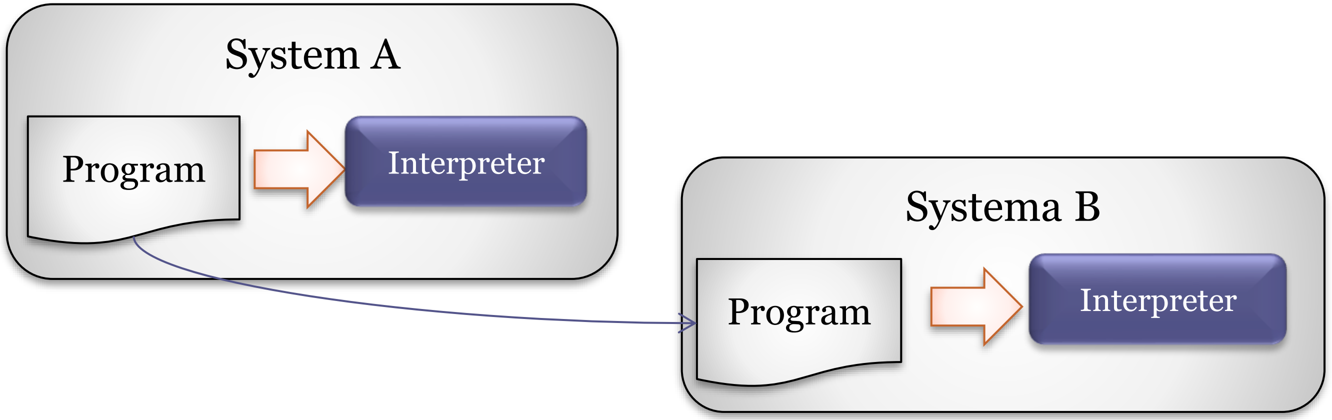

Mobile agents

- Applications
  - Information retrieval
    - Web crawlers
  - Peer-to-peer systems
  - Telecommunications
  - Remote control and monitoring
- Systems:
  - JADE (Java Agent DEvelopment framework)
  - IBM Aglets

End of presentation