Robust Design Strategies

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Course Overview

1. Software Architecture Fundamentals
2. Software Architecture Specification
3. Robust Design Strategies

Robust Design Strategies

Chapter Overview

[3.1] Motivating factors

[3.2] Design principles

[3.3] Architectural styles

[3.4] Design patterns

3.1 Motivating Factors

- Systems are being delivered late and over budget
- Coding and testing dominate development time
- Maintenance and upgrade costs are too high
- Performance levels are inadequate
- Problem: software is treated differently from other kinds of products
  - an engineering mentality is needed
  - the intellectual tools used need to be specific to software development

An Engineering Perspective

- Analysis
  - we seek to understand the function and constraints of the product first
- Experimentation
  - we focus on risk factors and the unknown early in the process
- Planning
  - we use the product design to drive the planning process
- Problem solving
  - we approach the design in a systematic and predictable fashion

An Engineering Perspective

- Tradeoffs
  - we see the design as the art of making the right technical compromises
- Reuse
  - we reuse procedures, designs, and components and build things for reuse
- Evaluation
  - we subject both designs and products to targeted and extensive evaluations

Answers From the Past

An emphasis on programming and requirements

- High-level languages
- Structured programming
- Information hiding
- Top-down functional decomposition
- Structured analysis and design
- Rapid prototyping
- Formal specifications

Modern Thinking

Object-orientation as an enabling technology

- Facilitates conceptualization
  - powerful abstraction mechanisms
- Facilitates model construction
  - direct mapping to the physical world
- Promotes encapsulation
  - programming by contract
- Reduces development effort
  - programming by differences
- Embodies modern programming language thinking
- Promotes reuse

Object-Oriented Analysis

- OOA is a process of discovery and modeling
- Essential software requirements are captured in terms of the following key concepts

  object class relation

- Additional procedural abstractions are included to complete the model
- Graphical notation is commonly used to depict the structural aspects of the model
- It is often expected that the analysis will transfer to design and implementation

Object-Oriented Design

- OOD is a process of invention and adaptation
- The principal concern is the architecture of the software
- The approach is (generally) language independent
- The emphasis is on achieving certain structures having particular desirable properties
- The same concepts are used but the interest is in modularity
- Simple projection of real-world objects to software does not guarantee a good design
  - different domains of knowledge
  - constraints
  - concept versus module emphasis

Object-Oriented Programming

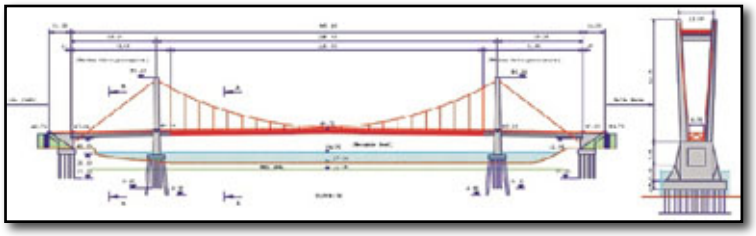
- OOP is a construction process
- It relies on the use of a programming language having many of the following features
  - objects as dynamically created instances of classes
  - classes (instance variables and methods)
  - inheritance (single and multiple)
  - generic classes (templates)
  - abstract classes and virtual methods
  - polymorphism
  - dynamic binding
  - exception handling

Beyond Object Orientation

- Object orientation thinking
  - is dominated by the concern with modular design
  - gained an emphasis on design reusability (patterns)
  - is seeking to address quality of service concerns
- Software architecture stresses two classes of issues
  - modular design
    - functionality coverage, structuring, and distribution
  - system level constraints
    - meeting non-functional requirements
- Constraints determine design complexity

Architecture Revisited

- The software architecture plays a critical role in placing software development on an engineering basis
- Software architecture design is the phase most akin to the design process taking place in other engineering disciplines
- It is the gap between paper and concrete that demands precision



3.2 Design Principles

- General design guidelines
  - modularity
  - encapsulation
  - protection against changes
  - constraint satisfaction
  - constraint evaluation
- Robust design
  - risk assessment
  - risk reduction
  - defensive design
  - defendable design
  - critical constraint driven

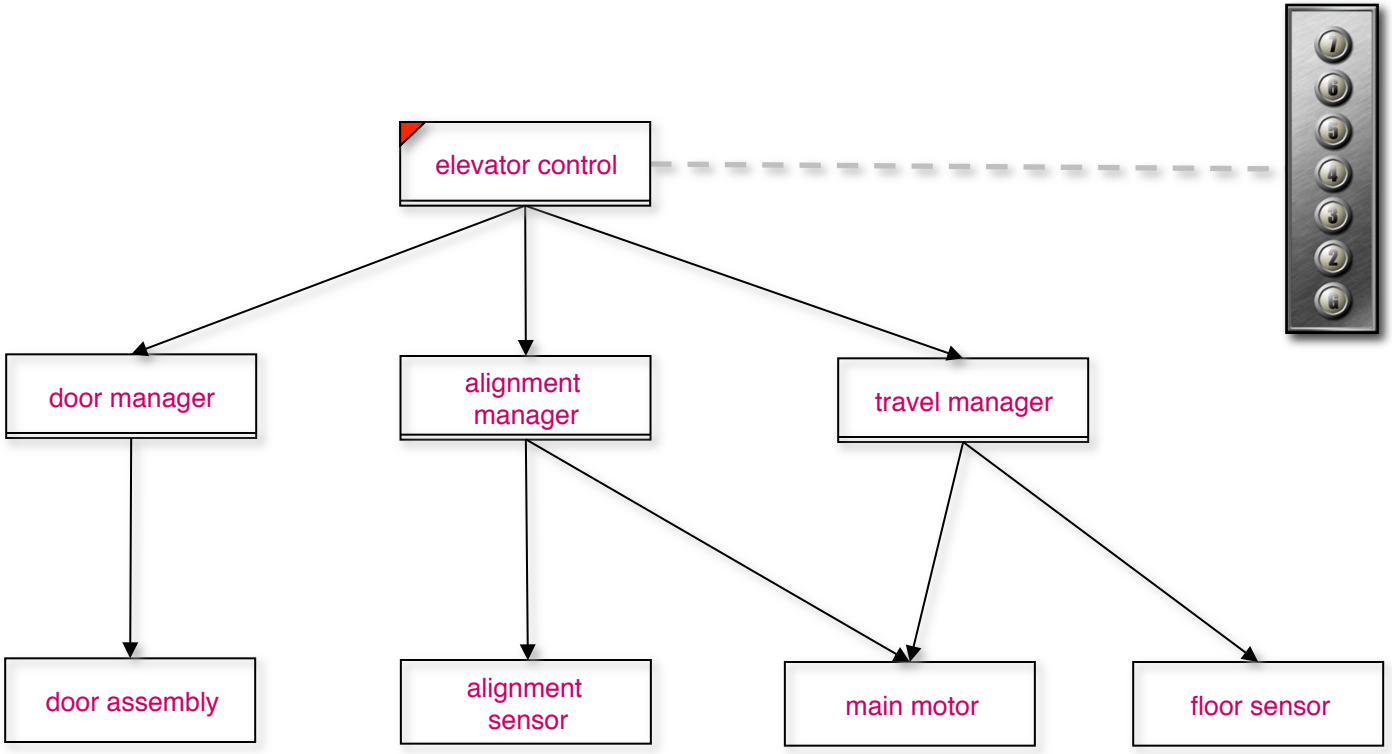
Design Strategy

- Identify the critical constraints
  - assess risk level
  - understand cost implications
- Separate the critical constraints
  - structurally
    - encapsulate at the level of module
  - behaviorally
    - encapsulate as a cross cutting constraint (aspect)
    - ensure independent analyzability
- Build and test along the critical path

Design Technique

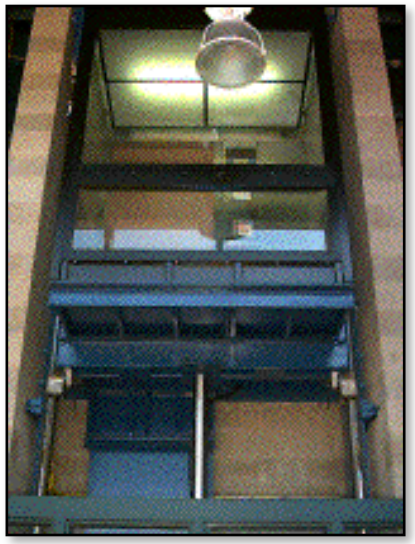
- Facilitators
  - static structures
  - simplicity where it counts
- Core concerns
  - high level of decoupling
  - integrated analysis and design

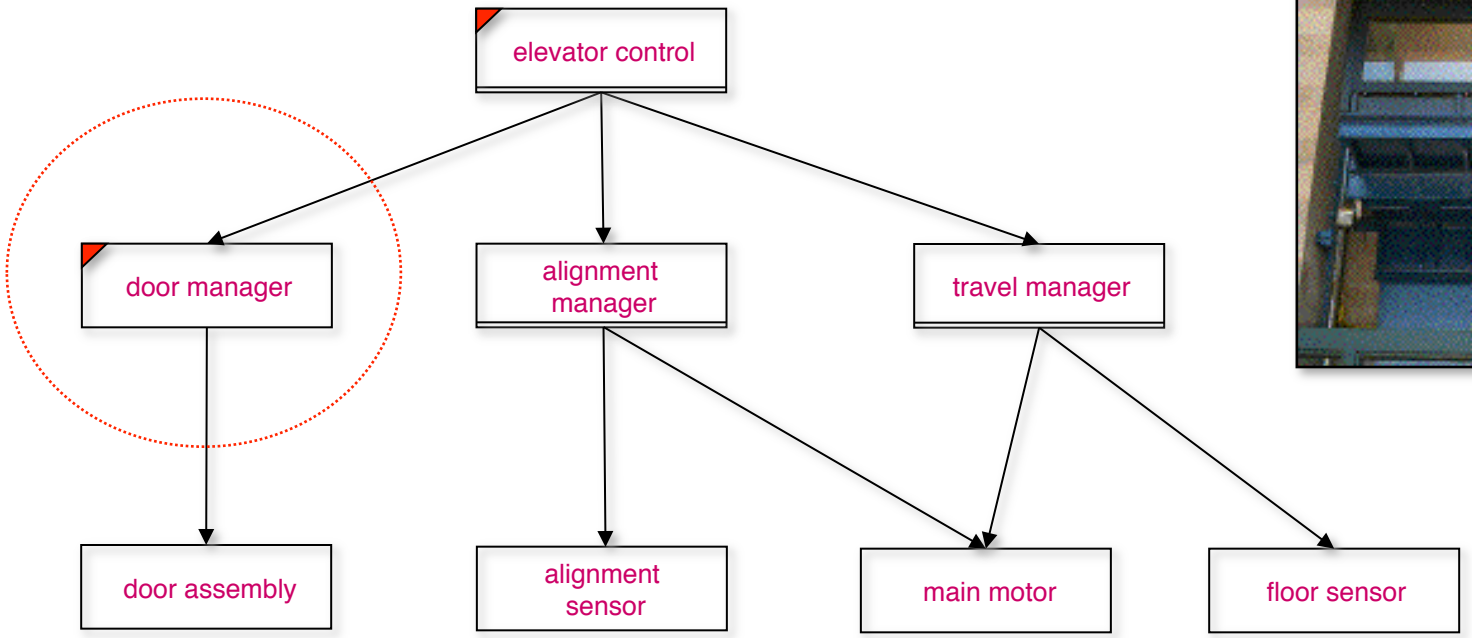
Modular Design



Responsive Design

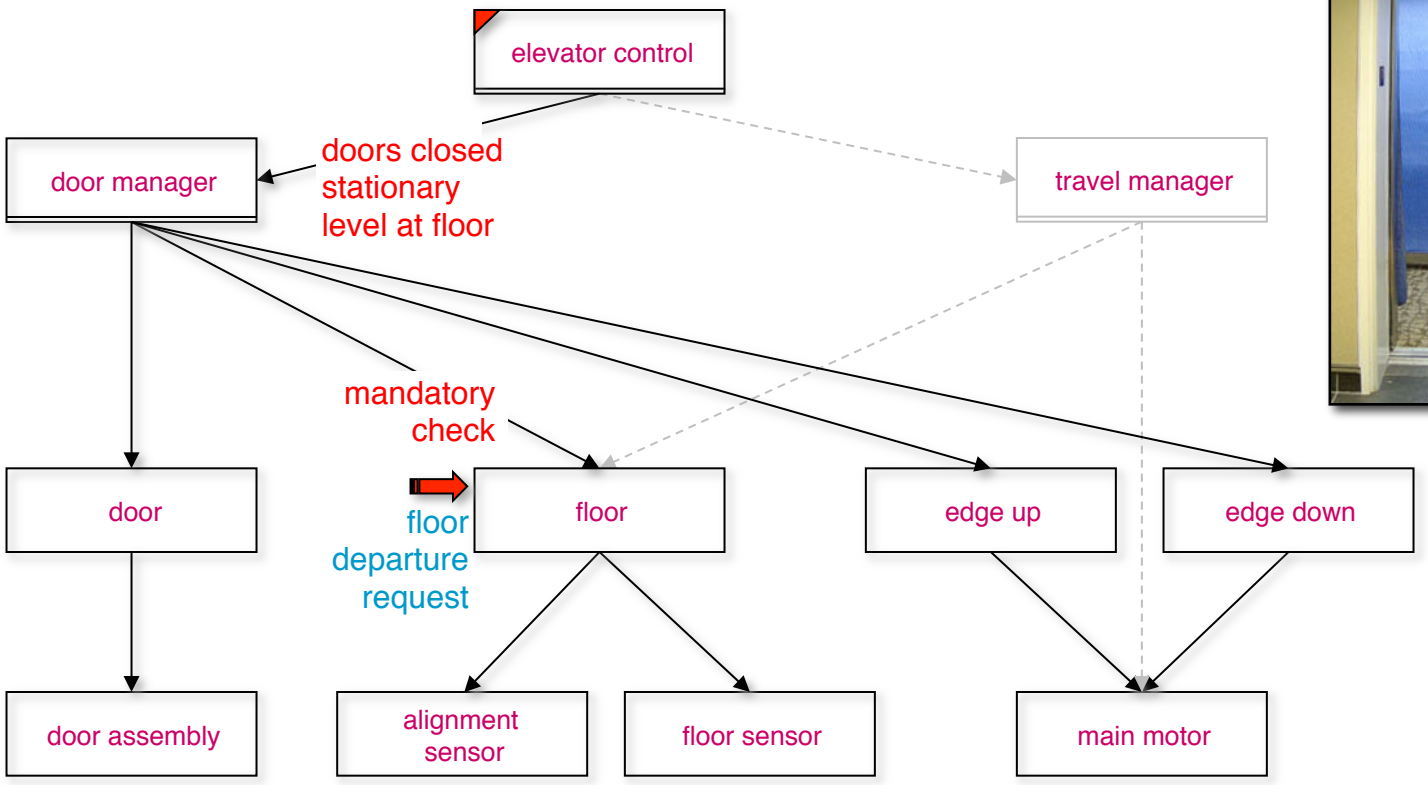
Continuous alignment while at a floor



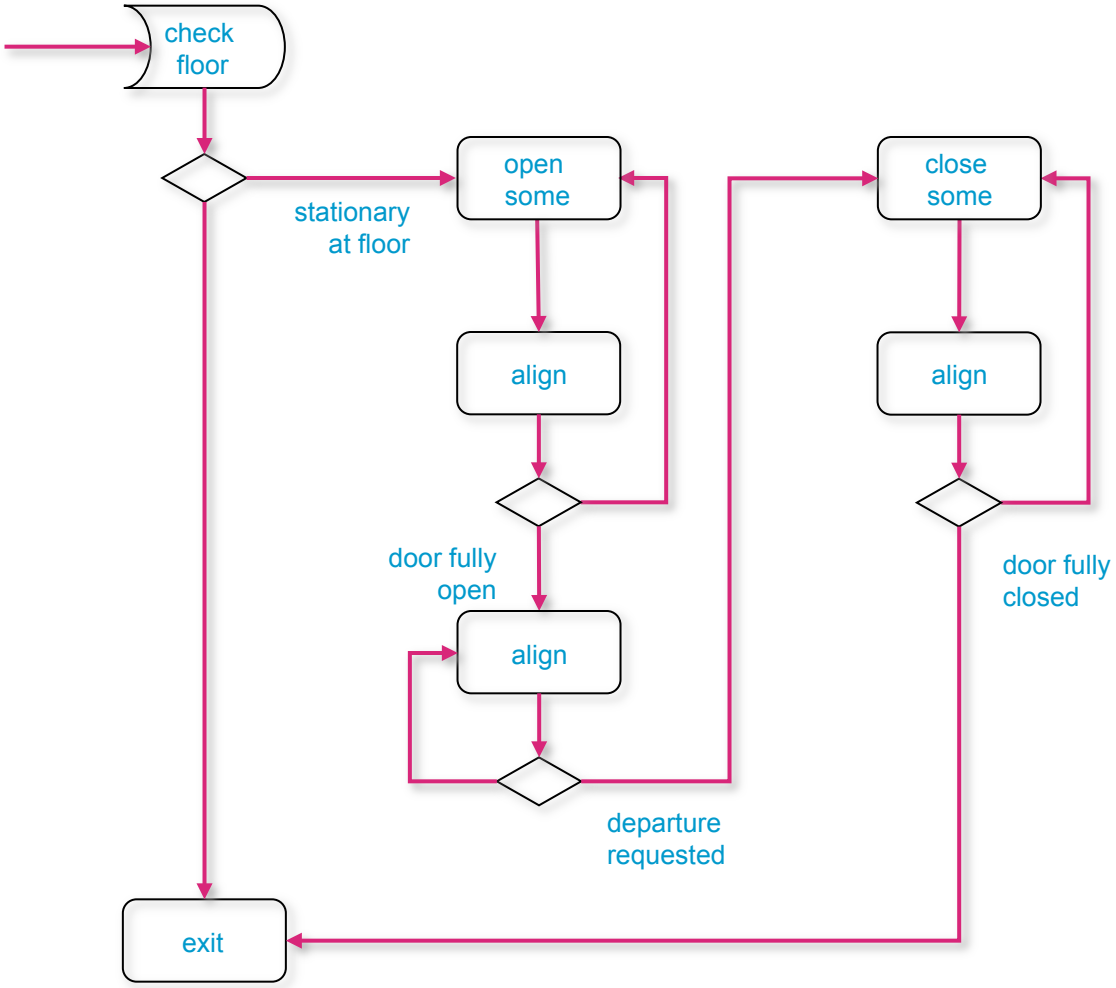


Safe Design

Doors are closed while moving or not at a floor



Behavior Analysis



Formal Analysis

Pre-condition (rechecked)

- doors closed
- level at floor

Post-condition (guarantees)

- doors closed
- level at floor

Invariant (enforced)

- level at floor

Formal Assumptions

Sub-problems

- dependable floor check
  - correct report
- dependable alignment
  - finite bounded motion
  - correct direction
- dependable opening
  - eventual completion
  - accurate report
- dependable closure
  - eventual completion
  - accurate report

Other assumptions

- motor safety guarantees
  - lack of motion implies the motor is off
  - motor needs a control signal to start
- no concurrency
  - no external motor activation
  - no unexpected state changes
- floor departure request limited to single boolean setting

3.3 Architectural Styles

- Architectural styles are abstractions for classes of organizational patterns encountered in software engineering practice
  - structural patterns
    - composition
  - behavioral patterns
    - communication
    - coordination
- Idioms relate to high level organizational patterns
- Patterns relate to design solutions for frequently encountered problems
- Reference architectures relate to classical and influential solutions proven in a specific domain

More about Styles

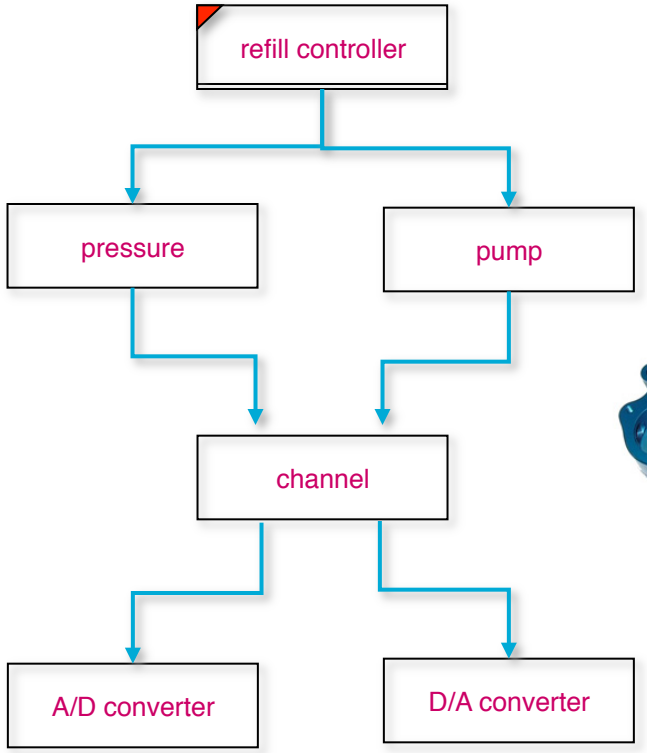
- Characterization
  - vocabulary
  - configuration rules
  - semantics
- Benefits
  - design reuse
  - predictability
  - corporate knowledge
- Taxonomic principle
  - the dominant strategy for achieving separation of concerns
    - composition
    - communication
    - coordination

A Taxonomy of Styles

- Composition
  - static
    - layered
    - controller
    - client/server
    - pipe and filter
    - dataflow
    - peer to peer
    - proxy
  - dynamic
    - object orientation
    - software bus
    - service provision
- Communication
  - explicit
    - message passing
    - event propagation
- Coordination
  - implicit
    - blackboard
    - shared tuple space
    - database
- Emerging styles
  - new software domains
    - mobile computing
    - sensor networks

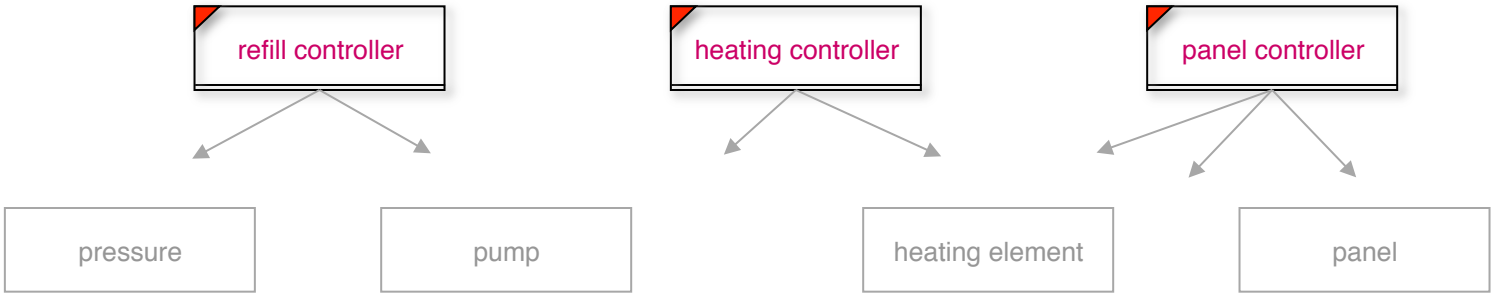
Layered

- Components at one layer share access to resources provided by the layer below
- It is critical to limit or structure sharing
- Hierarchical structuring facilitates
  - clean separation of constraints
  - limited impact of changes



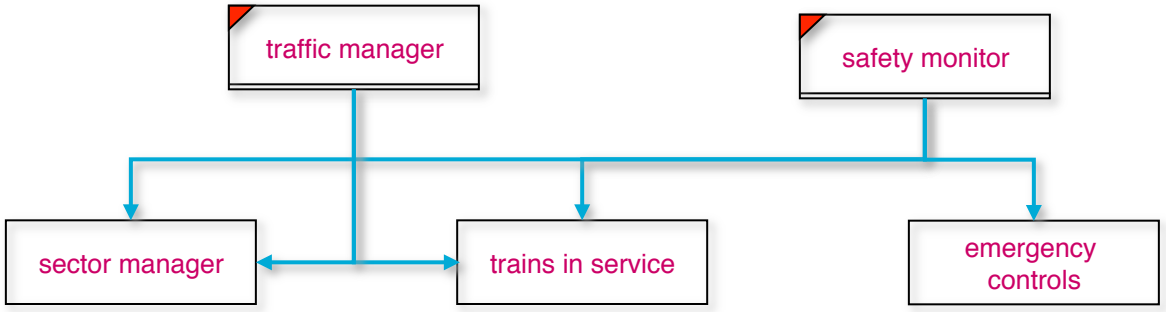
Controller

- System behavior
  - abstracted as a set of finite state machines
  - distributed among a small number of decoupled controllers
  - limited information sharing
  - synchronization limited to situations that demand consistency among decisions
- Complexity control
  - logical and structural separation into multiple modes of operation
    - simple and uniform transitions rules
  - object encapsulation of non-finite state aspects
  - partitioning of the control logic
  - state reduction



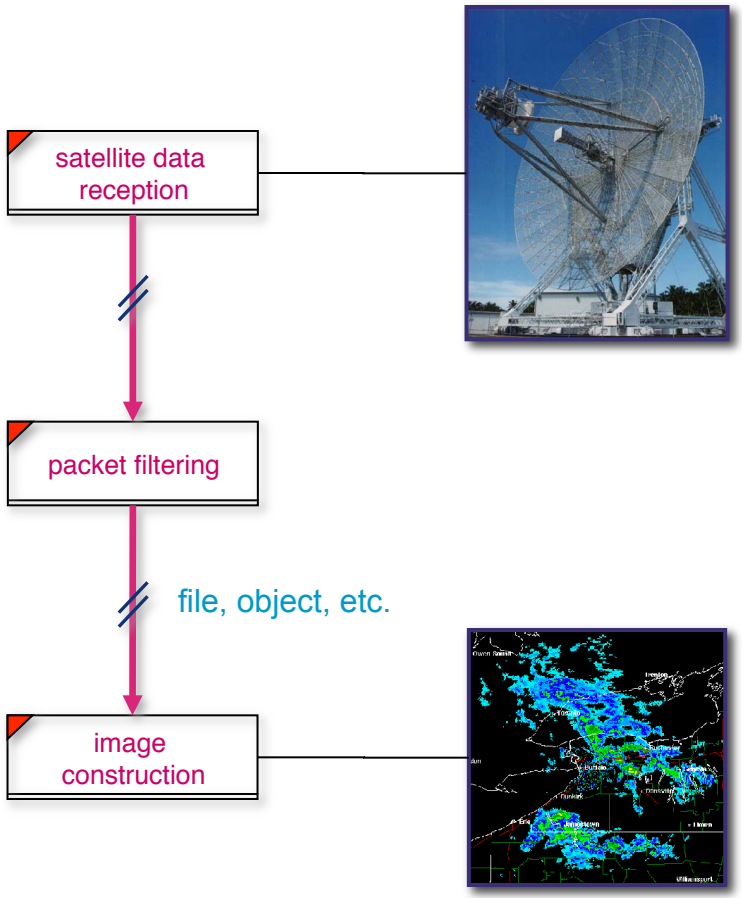
Client Server

- Natural extension of procedure call to distributed computing
- Components are segregated into clients and servers
  - Interactions are via remote procedure calls
  - Servers do not need to know client identities
  - Clients must know the identity of the servers



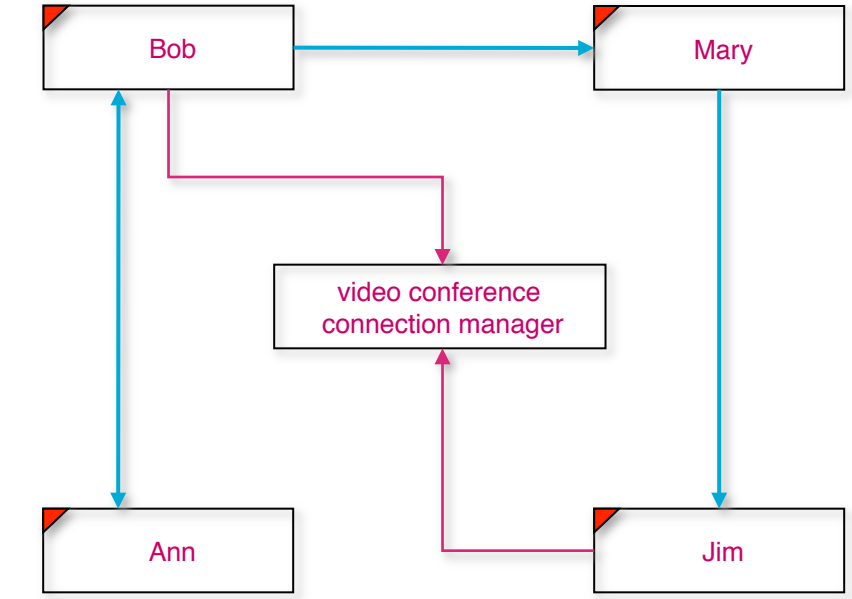
Pipe and Filter

- Independent components process data in an incremental fashion
- Connectors are mechanisms for supporting data streaming between pairs of components
- Standardized and compatible interfaces are the key to composition
- Signal processing, UNIX shells, and image processing are common instances of this style
- ***Dataflow***
  - a generalization to arbitrary directed acyclic graphs
  - image processing, workflow, etc.



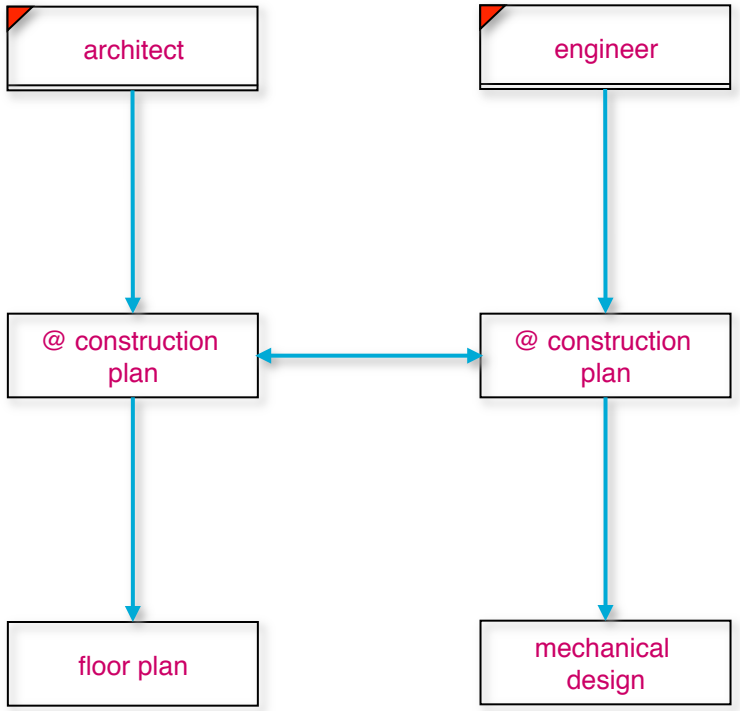
Peer to Peer

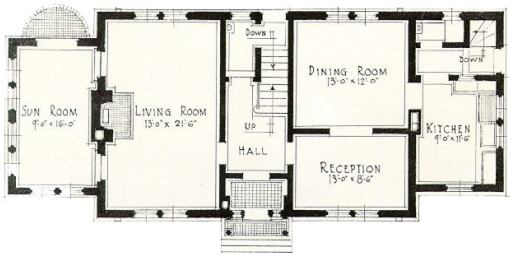
- Components are active objects that know (or learn about) each other
- Interactions are direct
- Server support is often required for discovery and some coordination
- Sample applications
  - music sharing
  - ad hoc network interactions



Proxy

- Interface components that decouple the access to a resource from the resource itself
  - resource updates do not affect the clients
  - different clients may have different views
  - communication protocols are hidden inside the proxy
  - proxy may be remote
  - proxy may be mobile code



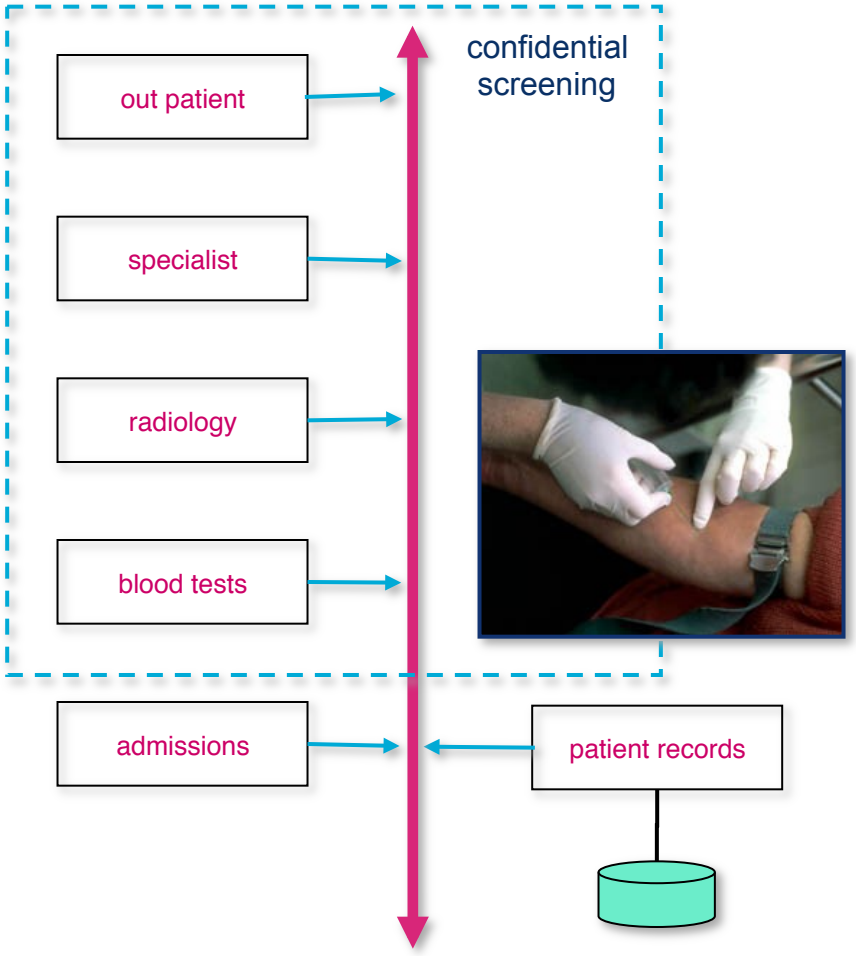


Object Orientation

- Components are objects and connectors are method invocations
- All architectural styles can assume an object oriented flavor
- The stereotypical object oriented style entails
  - web of cooperating objects
  - reference dissemination is often excessive

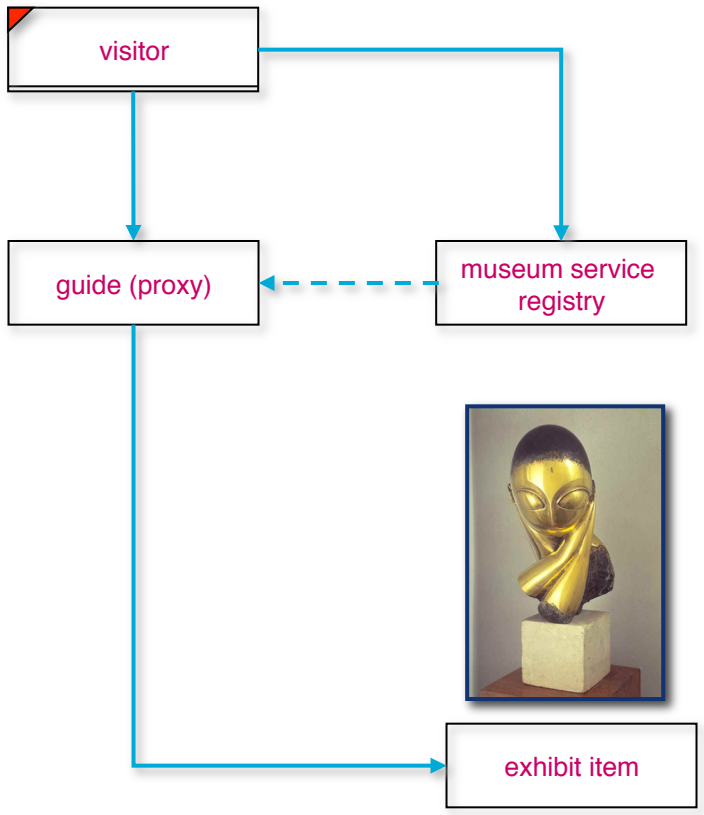
Software Bus

- Mechanism for decoupled access to
  - distributed data
  - services
- Static and dynamic object communities are supported
- Specialized services facilitate object registration, discovery, creation, and invocation
- CORBA is one standard that facilitates software bus construction



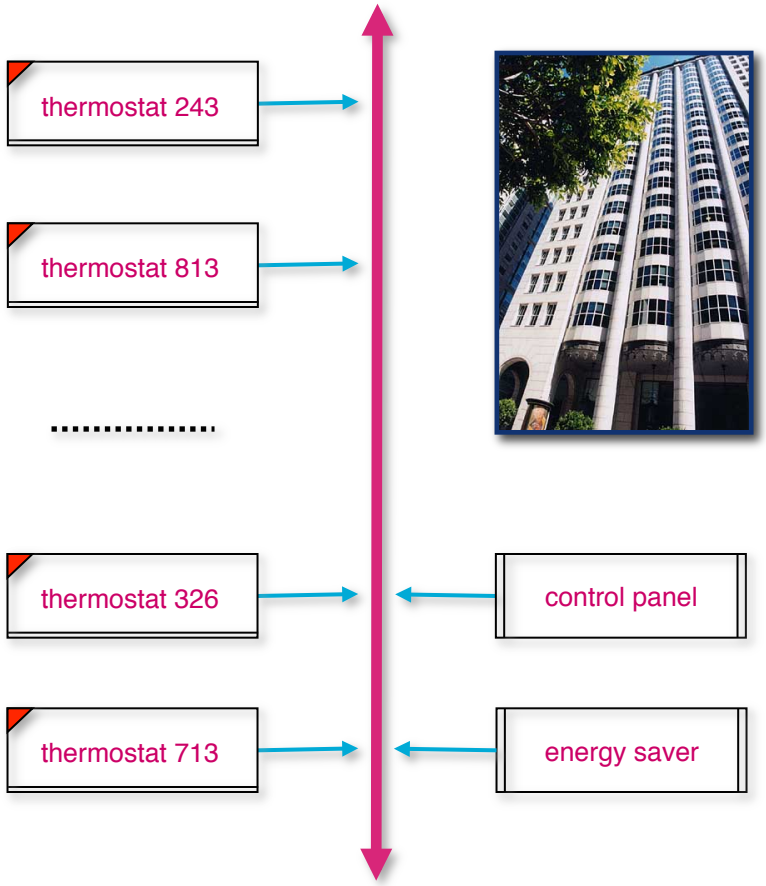
Service Provision

- Service providers register with service registries
  - specialized ontologies facilitate understanding
- Clients
  - services are discovered by querying service registries
  - interactions with services are standardized
    - proxy
    - service access protocols (e.g., SOAP)



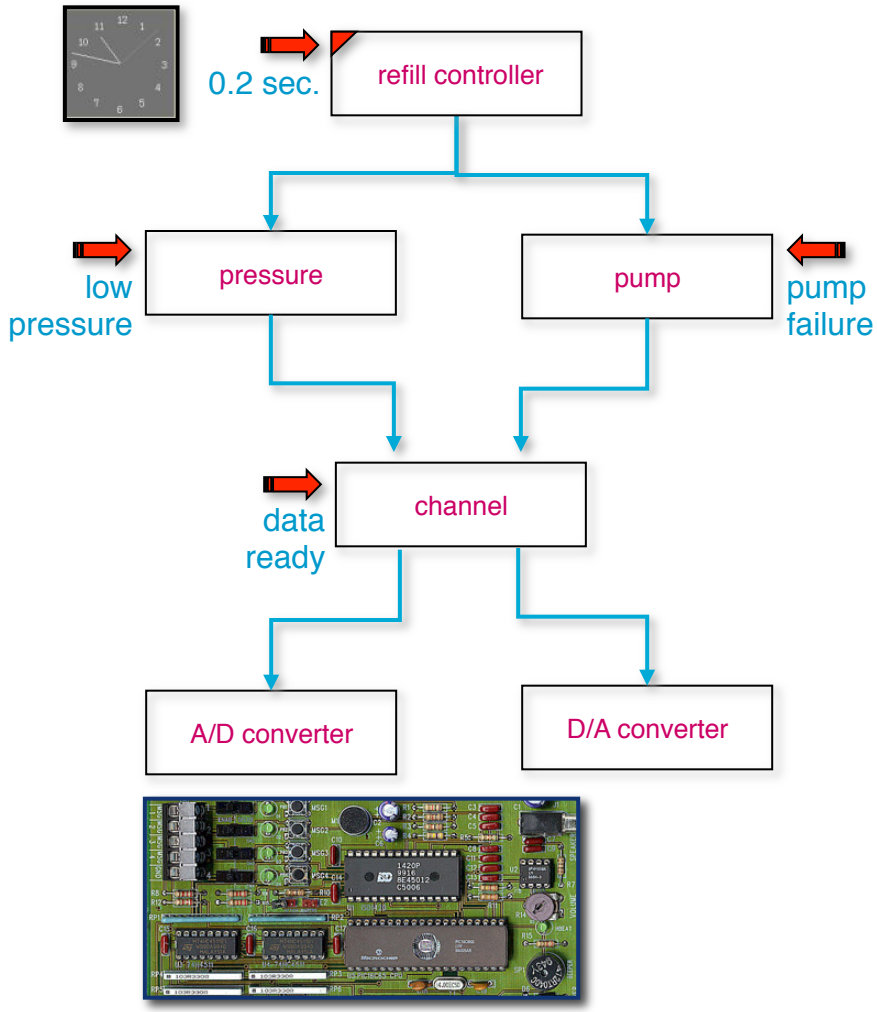
Message Passing

- Connectors are message passing capabilities
  - port (many to one)
  - channel (one to one)
  - mailbox (many to many)
- Component or connector identity is required to enable communication
- Bootstrapping requires some initial acquaintance
- Shared message interpretation and format
- High degree of decoupling and modularity is achievable
- Analysis relies on sequence and interaction diagrams



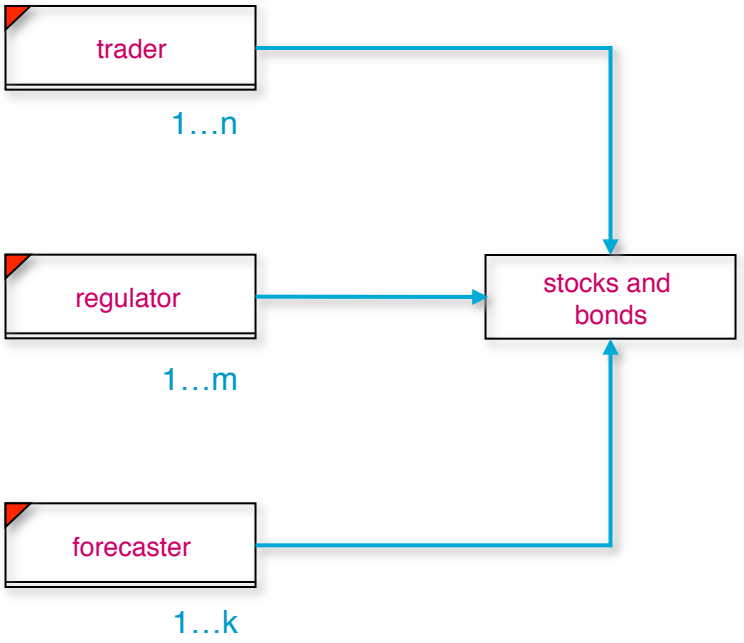
Event Propagation

- Publish/subscribe models
  - are meant to function in distributed settings
  - achieve a high level of decoupling
  - client subscribes to specific events
  - notifications are delivered automatically
- Explicit event propagation simplifies the design of reactive systems
  - low level events are mapped to abstract events
  - language support is available



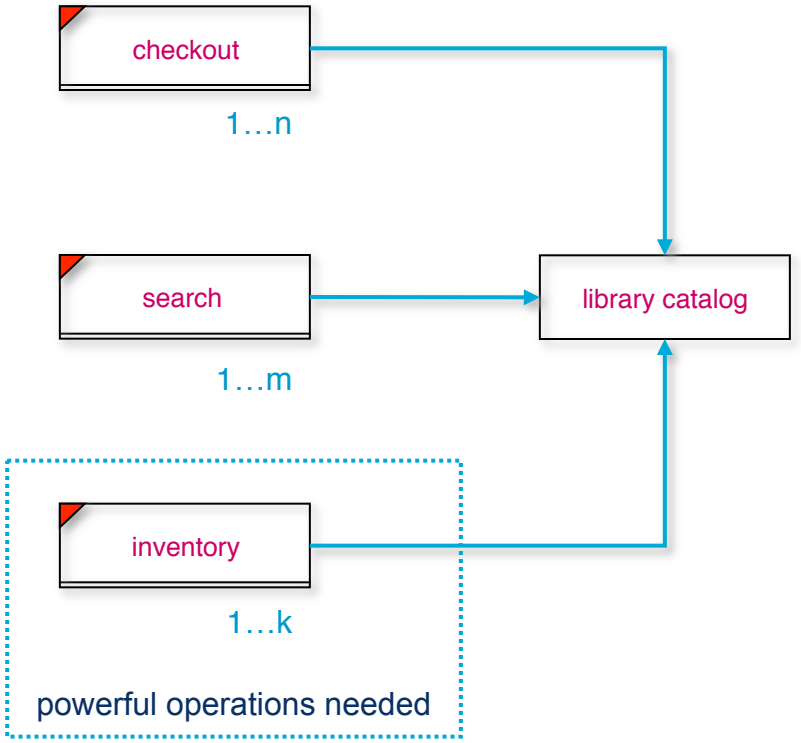
Blackboard

- A shared data repository
  - stores all key system data
  - controls system activities through its own state
- Other components
  - communicate with each other via the blackboard
  - respond to changes in the state of the blackboard
- Sample systems
  - planners
  - rule-based decision
  - compilers

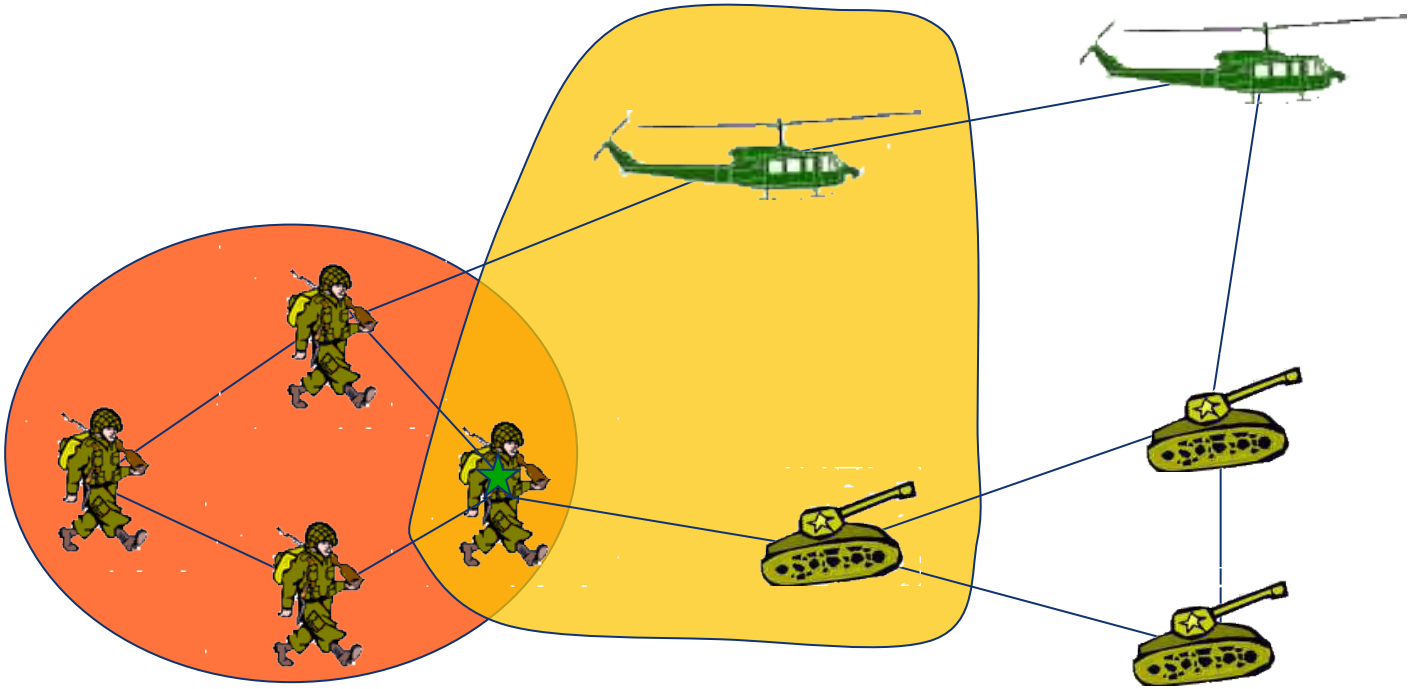


Shared Tuple Space

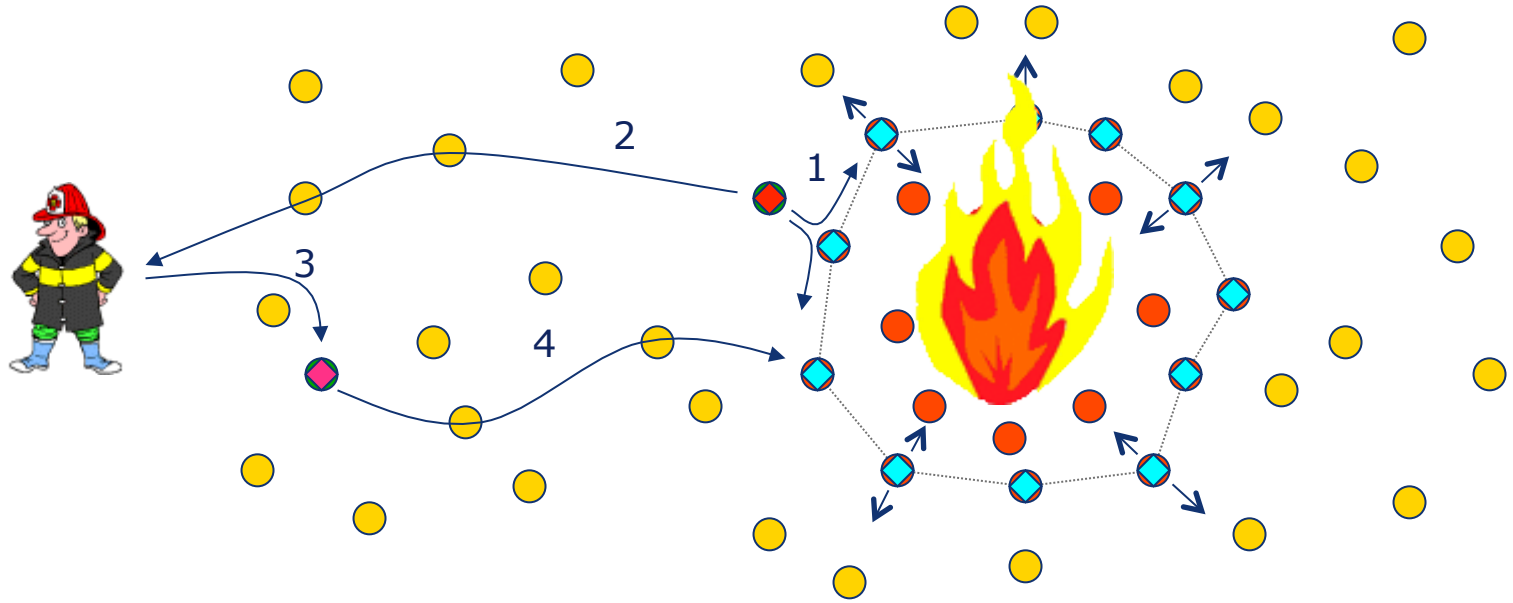
- The tuple space serves as a central data repository
  - out inserts a tuple
- Retrieval is contents-based (pattern matching)
  - read obtains a tuple copy
  - in removes a tuple
- High level of decoupling
- Minimal interface
- ***Databases***
  - large scale
  - complex queries
  - optimized processing
  - reuse



Mobile Computing



Sensor Networks



Observations

- The architectural style impacts the properties of the system up to a certain level
  - distinct architectures may share a common style
  - similar architectures may exhibit distinct properties
- Design rules may enforce the extent to which resulting architectures acquire specific properties
- Architectural styles may be associated with specific application domains
- Management and study of architectural styles
  - is mostly an art
  - has strong engineering implications

3.4 Design Patterns

- Role of architecture
  - relies on fundamental modeling assumptions
  - captures essential aspects of the system behavior
  - provides a basis for behavior analysis
- Designer goal
  - an architecture that ensures specific product qualities
- Mode of operation
  - reuse design patterns as a starting point
  - exploit know-how embodied in design patterns

Fundamental Principles

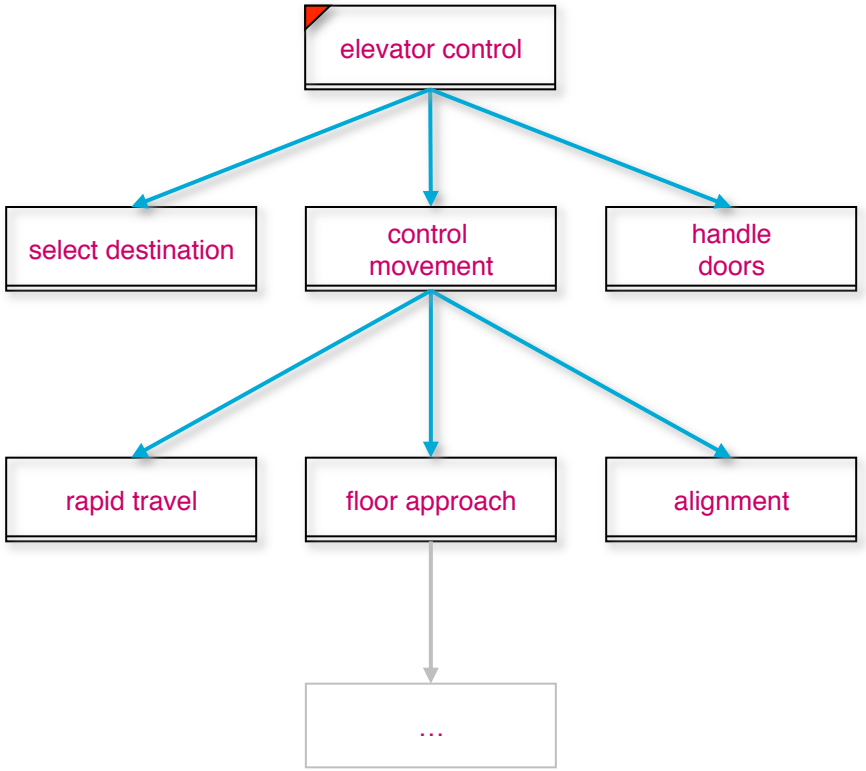
- Understand product goals and critical concerns
- Reuse design and analysis strategies
- Design for analyzability
  - with respect to critical concerns
- Practice design and analysis integration

Pattern Description Strategy

- Critical concern
  - systems are highly complex
  - multiple critical considerations may be relevant
  - patterns focus on single dimensions
- Solution sketch
  - initial designs are only a starting point
  - creativity and experience guide the refinement process
- Analytical method
  - reliance on specification techniques generally used in architectural design

3.4.1 Predictable Behavior

- Functional composition ensures predictability
  - the behavior of one function is always the same for the same input (system state)
  - functions are independent of each other
  - there are no side effects
  - there is no concurrency
  - computations are deterministic



Analysis

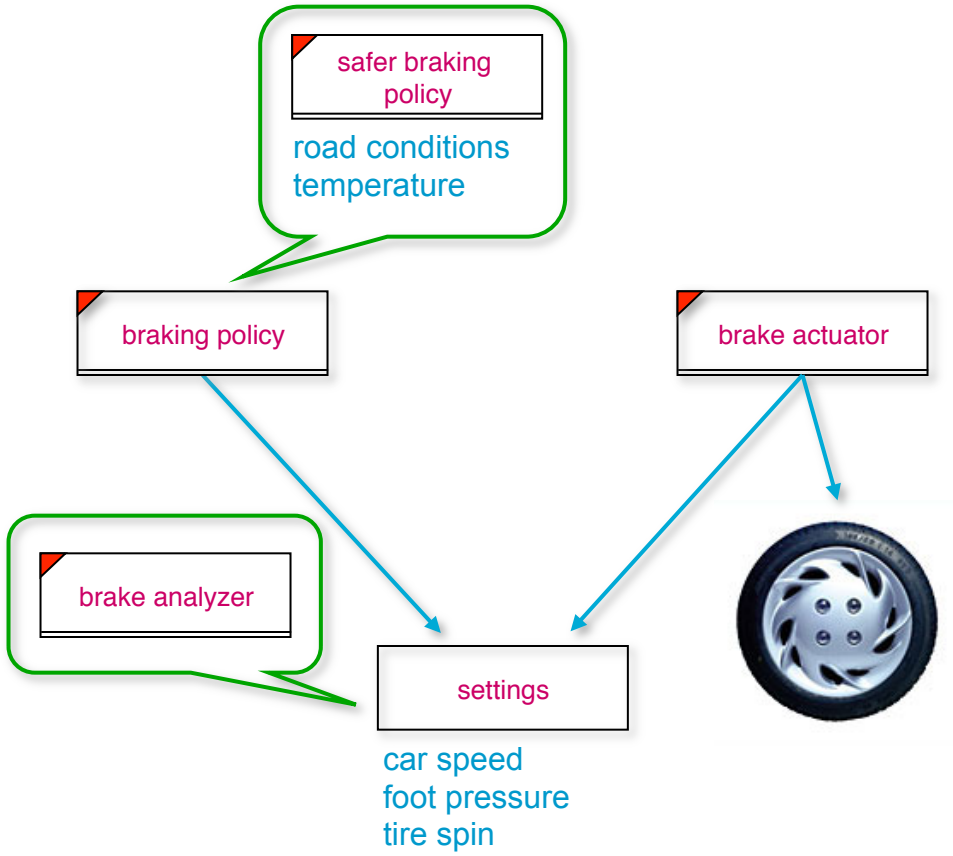
- Composition mechanics
  - localized and readily identifiable for analysis
  - components of interest
    - *elevator control*
    - *control movement*
  - strict sequential behavior: (a (x y z) b)*
    - deterministic
    - repeatable
- No concurrency anywhere in the system
- Interface consistency
  - parameter syntax and interpretation
    - e.g., null vs. empty message
  - implicit parameters (e.g., shared objects)

Analysis

- The specification method impacts analysis
- Use of pre and post assertions is critical
  - defines behavior independently of implementation
  - provides the basis for independent testing
  - promotes interface consistency
  - makes static analysis possible
  - makes run-time checking feasible
  - enables run-time self-healing
- Example: alignment
  - pre: stopped at some floor; ± 20 cm of horizontal; confirmed
  - post: stopped at some floor; ± 1 cm of horizontal; confirmed

3.4.2 Expandability

- Decoupled computing facilitates reconfiguration
  - adding/removing of components and data
- Blackboard architecture
  - access by name
- Tuple space coordination
  - access by contents
- Decoupling by design
  - encoding a traditional design is not a good solution



Analysis

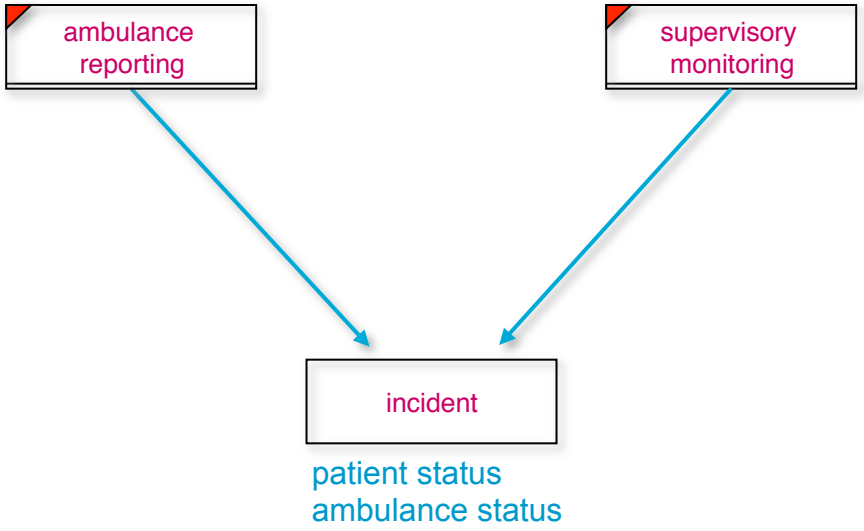
- Invariant property
  - characterization of the system state
  - holds at initialization
  - holds after every operation
    - precise definition of an “operation” is required
    - procedure invocation, block, statement, etc.
- Static analysis offers maximal benefits
  - isolated evaluation of each individual operation
- Run-time enforcement and verification is feasible
  - testing during development
  - protection during field operation

Analysis

- Structural invariants for dynamic systems
  - one and only one brake actuator
- Data representation
  - all measurements are in the metric system
  - <“speed”, 12, m/s, “at”, 1236, ms>
- Data consistency
  - brake application and cruise control cannot coexist
- Operating assumptions
  - freshness and accuracy

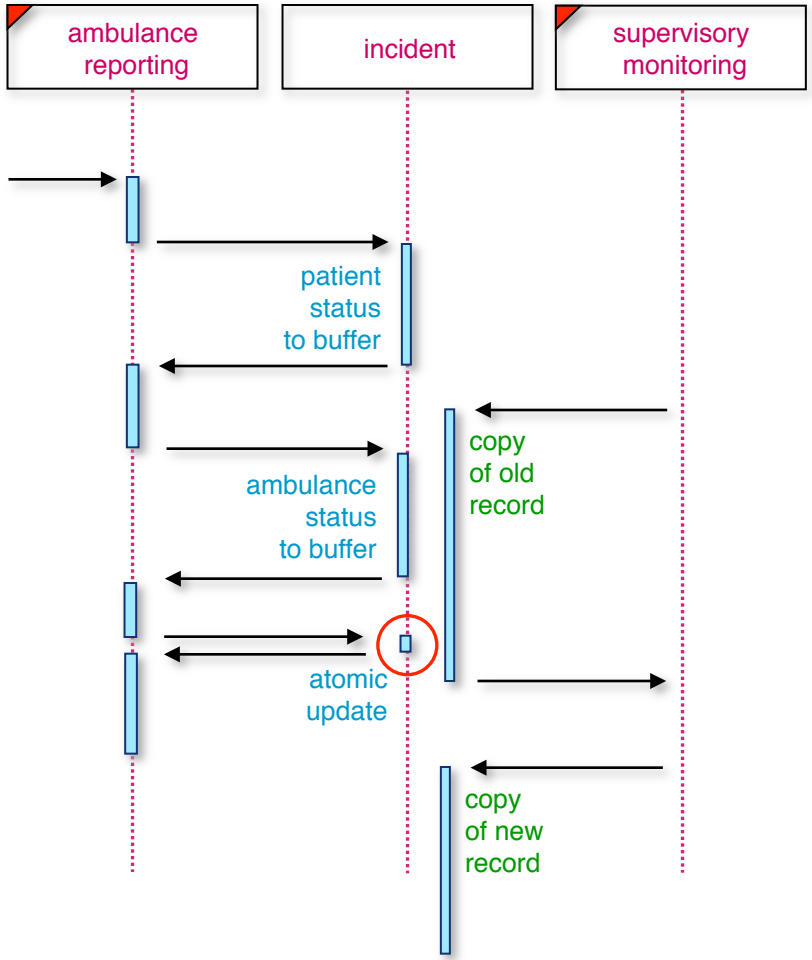
3.4.3 Non-Interference

- Concurrent processes can interfere with each other
- Data inconsistencies lead to incorrect conclusions
  - patient loaded
  - ambulance empty
- Wide range of patterns specialized to varying situations



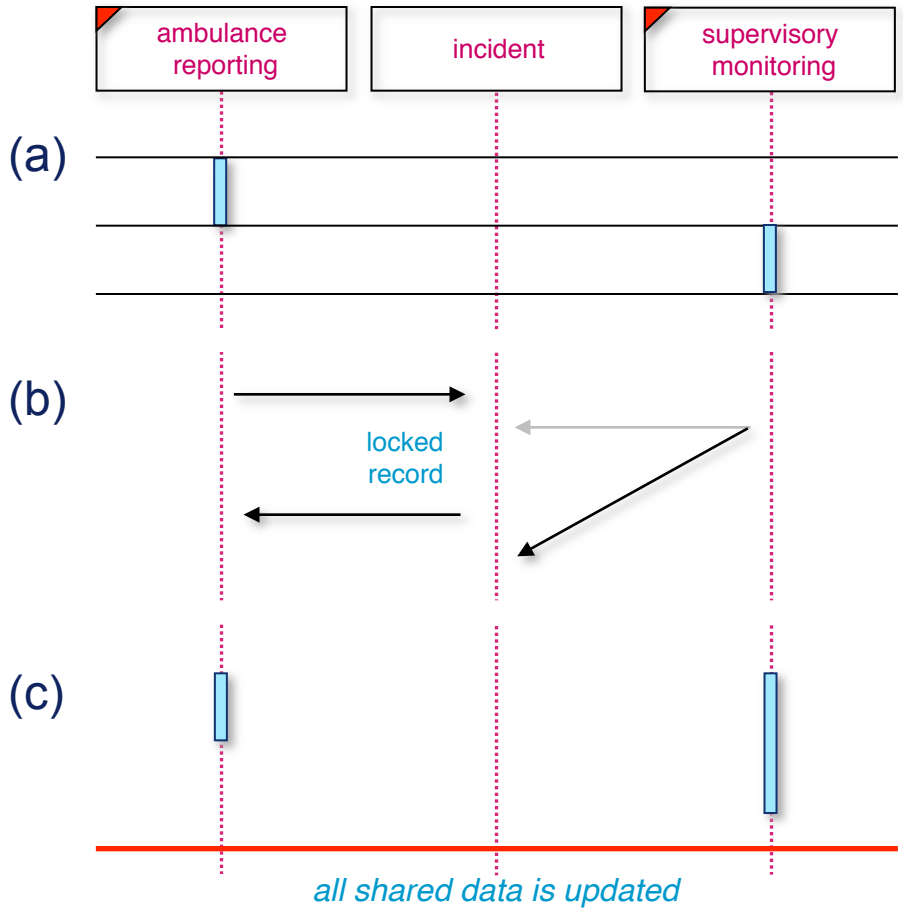
Analysis

- Assessing non-interference
  - syntactic methods: no shared data
  - semantic methods: no concurrent access to shared data (by analysis)
- Design: double buffer
  - atomic copy on read
  - atomic swap on write
- Analysis:
  - no interference possible



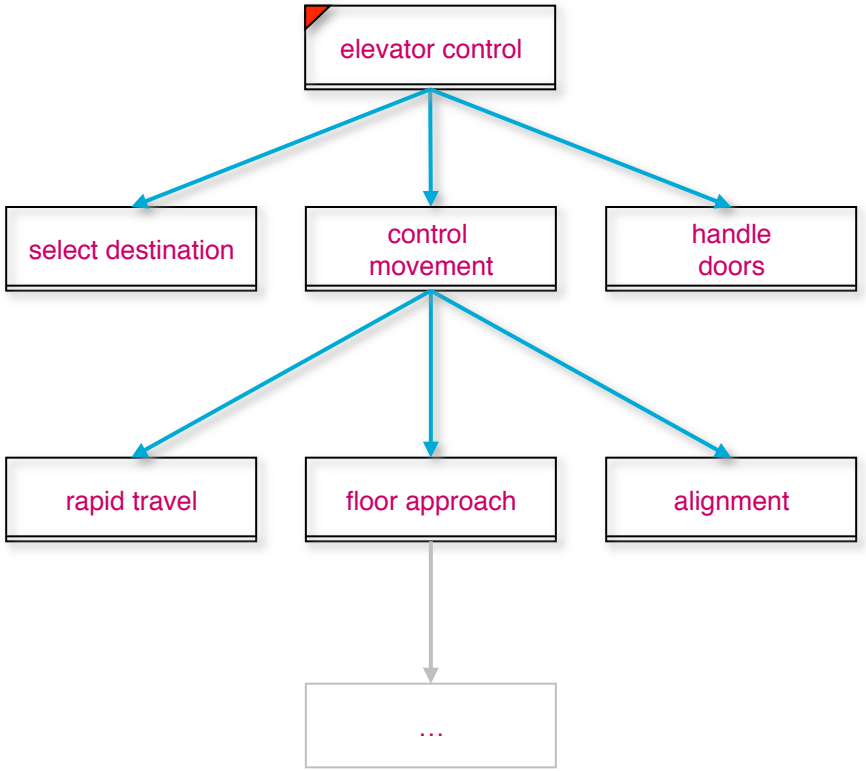
Analysis

- Controlling interference
  - explicit scheduling
  - record locking
  - barrier synchronization



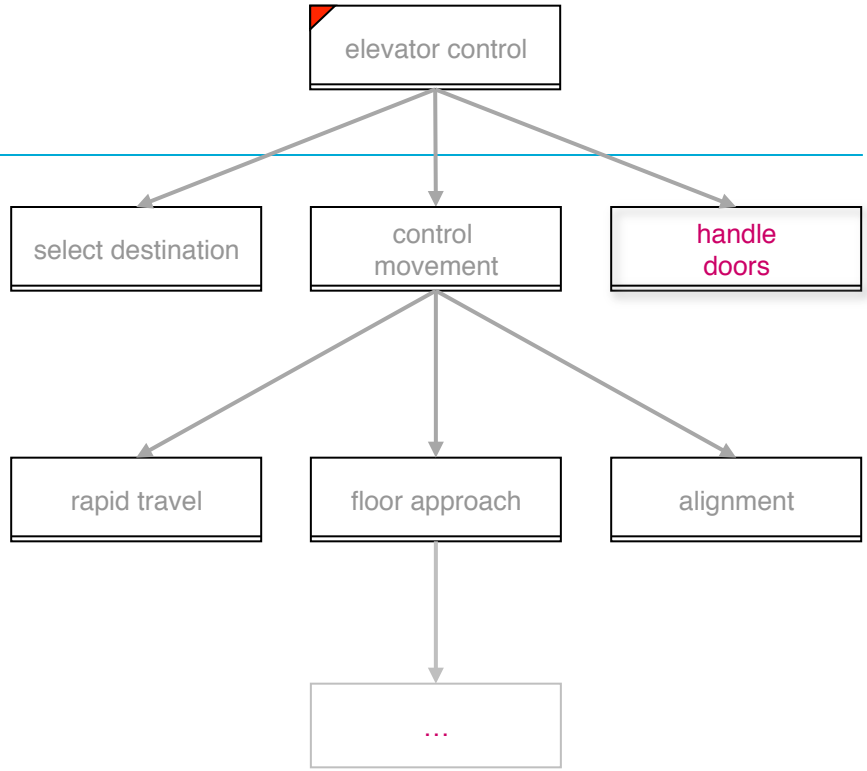
3.4.4 Strong Guarantees

- Precise specification of relevant requirements
- Designed partitioned for
  - analyzability
  - separation of concerns
- Design rules limit scope and cost of analysis
- Partition enhance ability to carry complete analysis



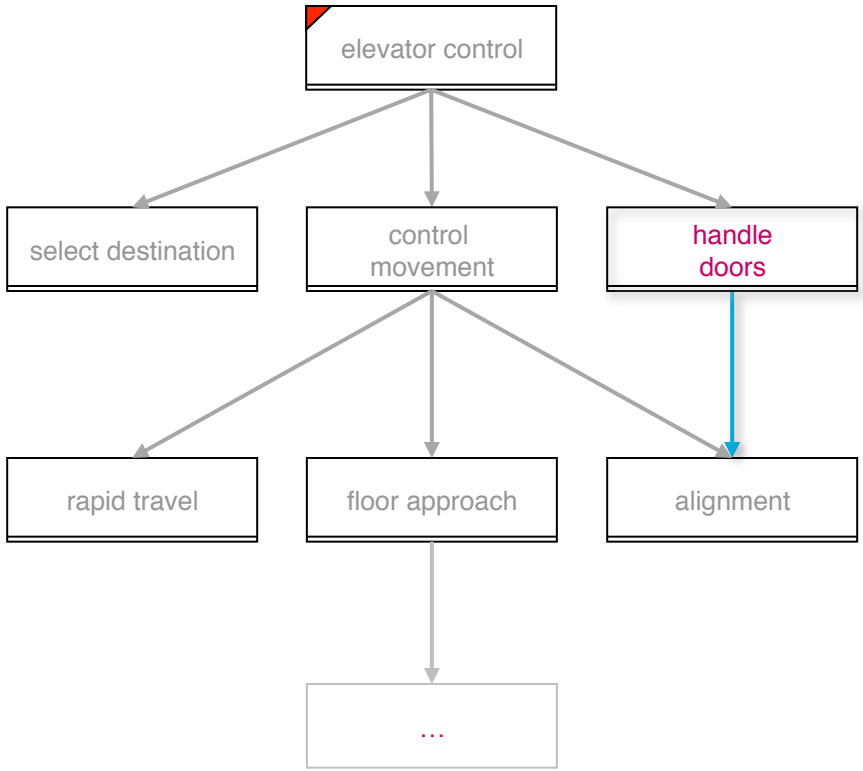
Analysis

- Requirement
  - when doors are open elevator must be stopped at some floor
- Architectural implications
  - handle doors:
    pre: stopped at floor
    post: doors closed
  - invariant:
    inside handle doors elevator is stopped at floor
    [no access to elevator travel motor]
    outside handle doors doors are closed
    [no access to door activation motor]



Analysis

- Requirements
  - when doors are open
    - elevator must be stopped at some floor
    - alignment must be within tolerance
- New design is needed to ensure analyzability
  - elevator motor is in use while doors are open
- New alignment guarantee
  - invariant: inside alignment if stopped at a floor the elevator remains at that floor

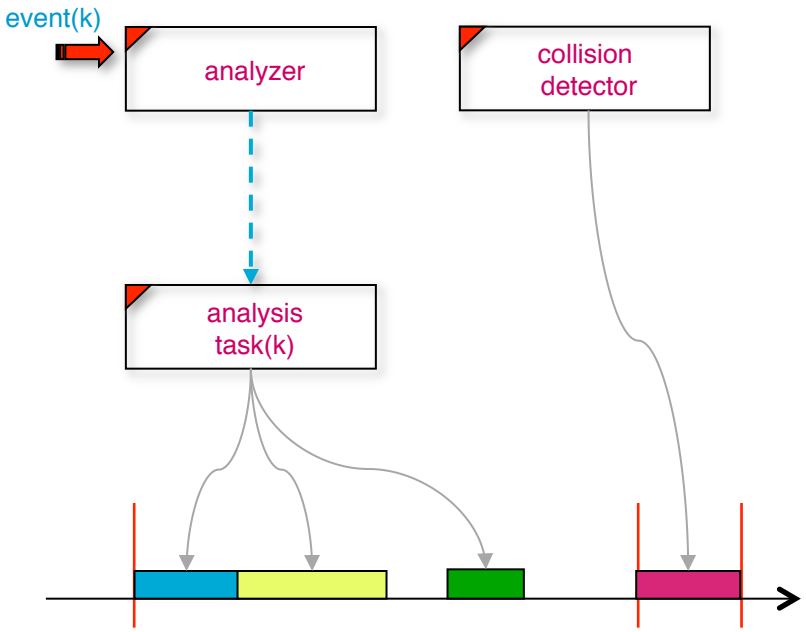


3.4.5 Real Time Guarantees

- Strong real time guarantees demand strict design rules
- Predictable scheduling
  - deterministic order
  - analyzable
- Predictable component behavior
  - restricted constructs
    - bounded loops
    - no recursion
  - computable worst case behavior

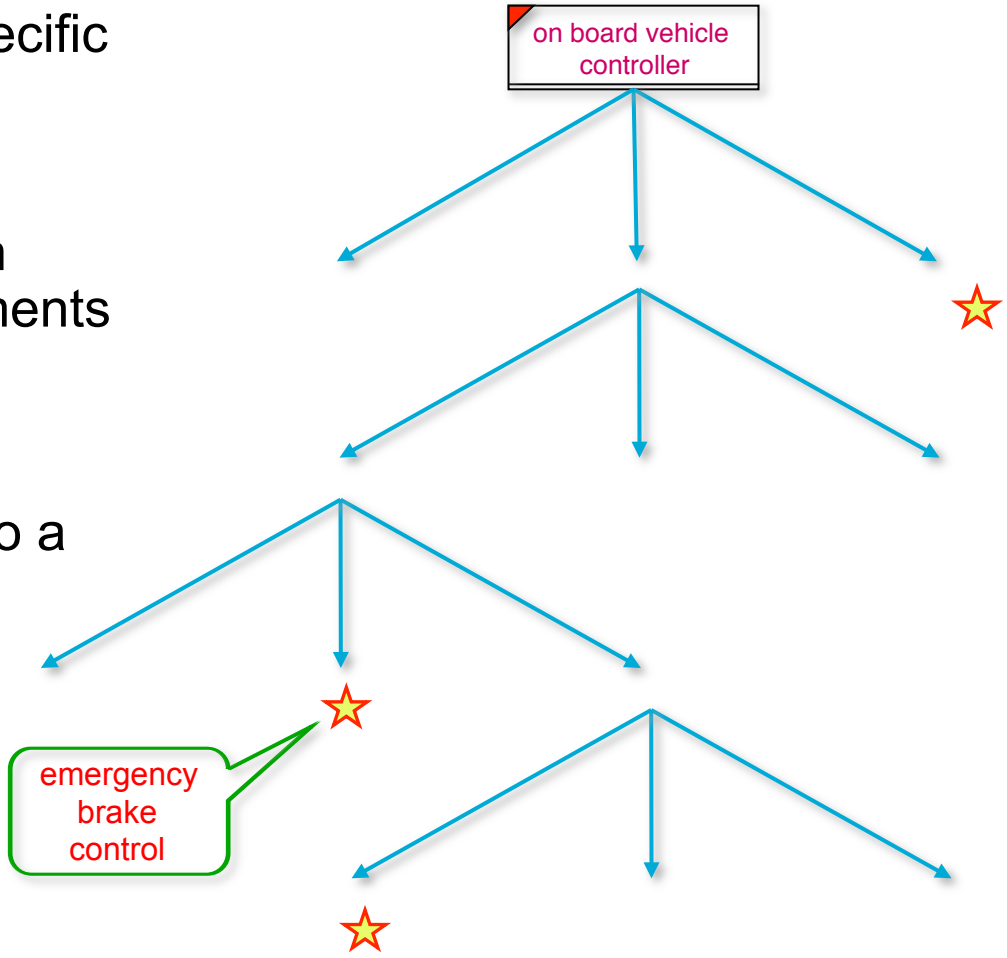
Analysis

- Static analyzer
  - T sec. allocation
  - worst case bound t_k
  - $\sum t_k \leq T$
- Dynamic analyzer
  - priority based preemption
  - admission control
- Collision detection
  - most critical task
  - long duration
  - must run in the background
  - reserved fraction of time



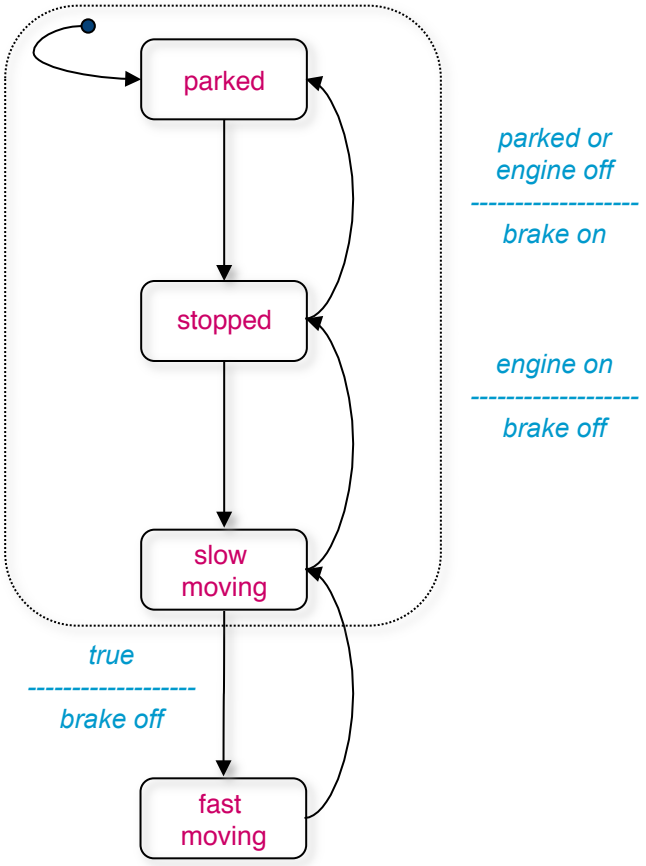
3.4.6 Safety Guarantees

- Safety is a requirement driven concern under design specific faults
- Precise specification
- Easy traceability between architecture and requirements
  - isolation
  - visibility
- Analyzable with respect to a specific set of faults
  - failure analysis
  - fault model



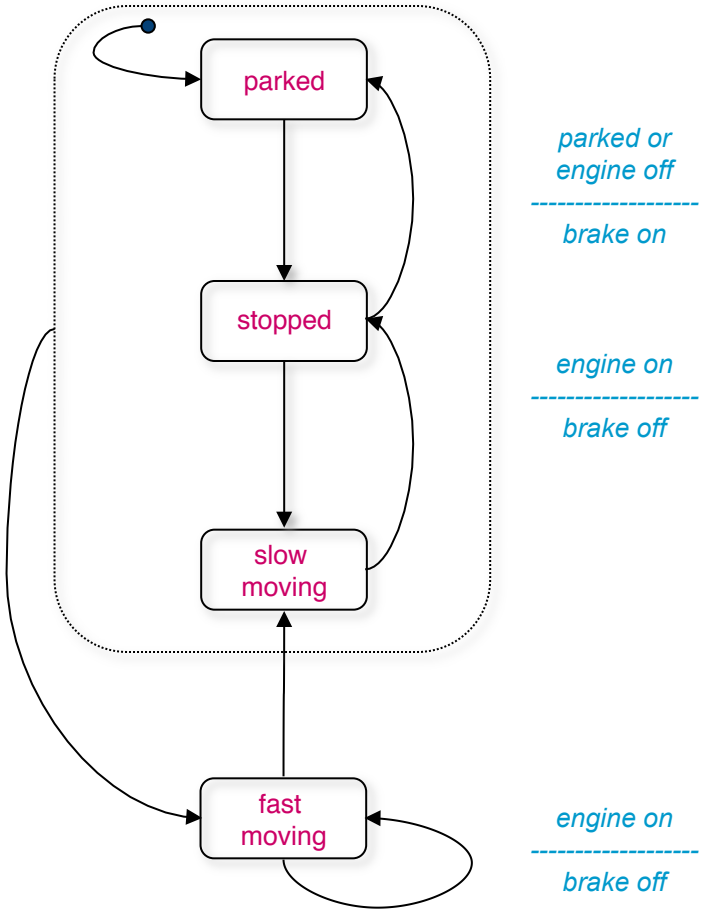
Analysis

- Drive-by-wire emergency brake safety specifications
  - brake can be engaged only when the car is parked
    - stalled on a ramp?
  - brake can be engaged when the car is parked or the engine is off
    - even at high speed?
  - brake can be engaged when the car is parked or the engine is off at a low speed



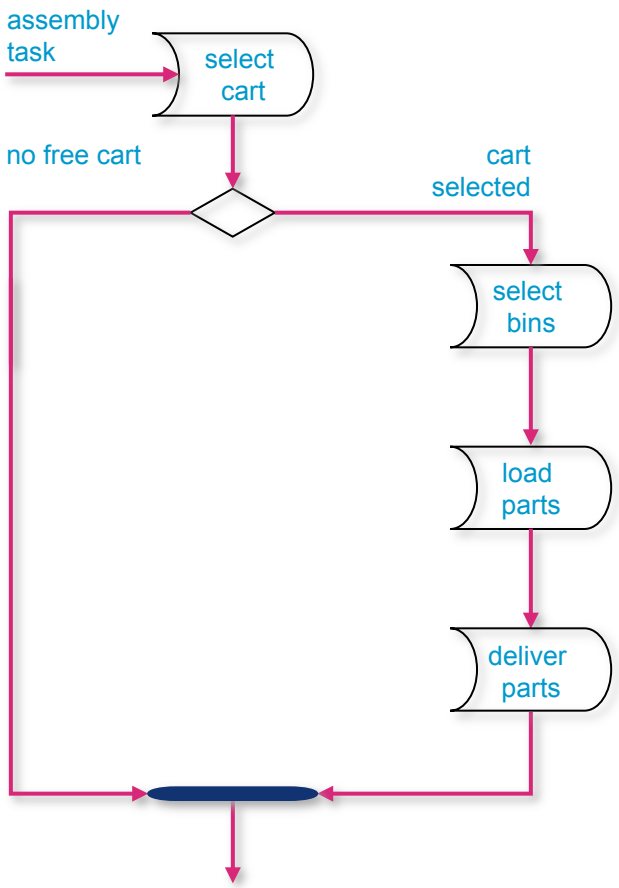
Analysis

- Drive-by-wire emergency brake hazard analysis
  - car may accelerate fast if hit from behind
  - missing transitions must be added and implications on the specification must be clarified
  - visibility make both analysis and modification feasible



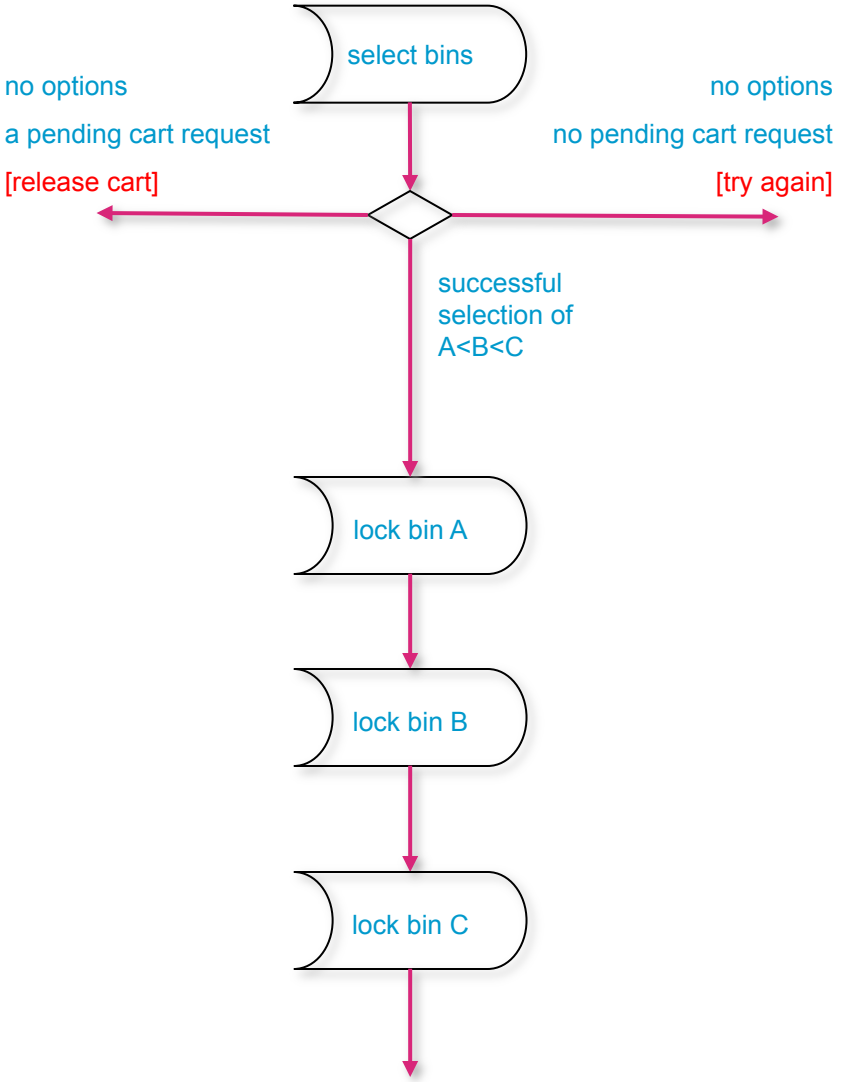
3.4.7 Anomaly Prevention

- Certain behavior anomalies are well understood and offer standard remedies
- Encapsulating relevant behaviors as part of controllers simplifies analysis
- Deadlock prevention
  - impose ordering on processes of resources
- Livelock avoidance
  - introduce asymmetry in the decision process



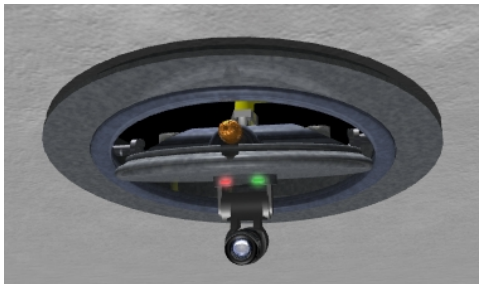
Analysis

- Livelock may happen when a cart unable to find the required parts is reselected repeatedly
  - reselection must be inhibited if other requests are pending
- Deadlock may occur when groups of parts are needed together, e.g., (A, B, C) or (X, Y)
  - bins must be reserved in the same order by all carts



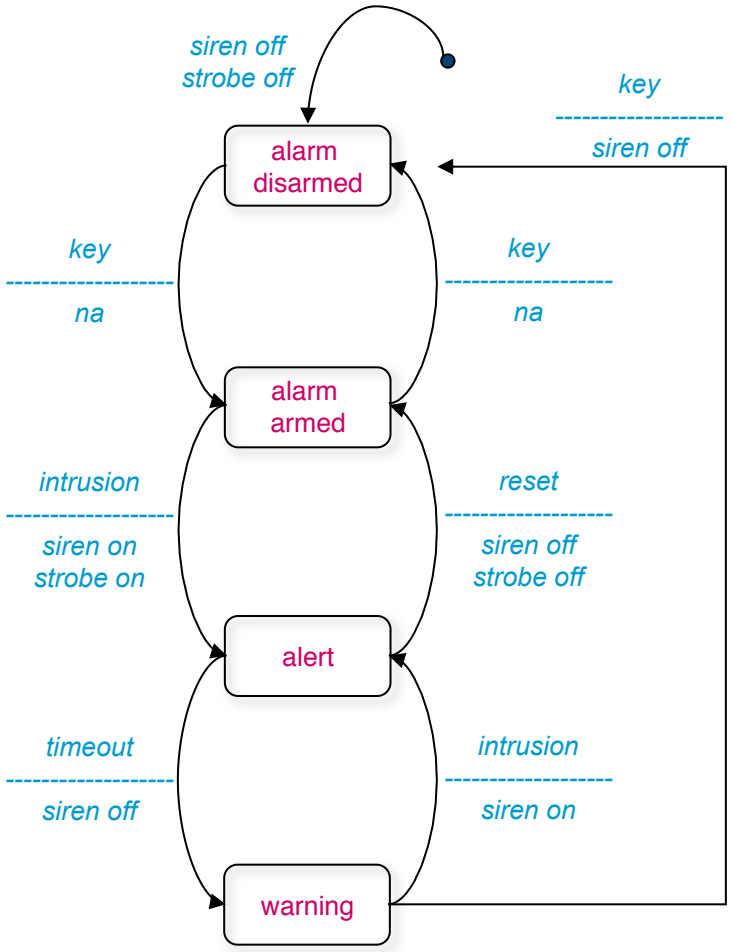
3.4.8 Behavioral Integrity

- Object integrity
  - prescribed patterns of usage are often required
  - must be enforced for proper functioning
  - objects may be unable to provide proper enforcement
  - exception handling may be undesirable
- Global consistency
  - objects are not used alone
  - local states may need to be consistent across multiple objects
- Behavior encapsulation and analysis facilitate enforcement



Analysis

- Home security alarm
  - audible alarm activation must be of limited duration due to local ordinances
  - visual alarm must be on any time the audible alarm is on due to disabled protection legislation
  - easy traceability to requirements is required by contractual obligation



Conclusions

- Software architecture design is central to
  - bridging requirements and implementation
  - ensuring and assessing the satisfiability of both functional and non-functional requirements
  - effective planning of the development effort
- Design patterns provide a reasonable starting point for formulating the architectural features
- Analysis must be an integral part of the design process
- Designing for analyzability is critical to ensuring credibility in the design, reducing analysis costs, and achieving desired level of quality