Designing Evolutionary Architecture-centric Component-based Software Product Lines

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Overview

- Software Modeling and Design
- Software Modeling and Design Methods
- Designing Evolutionary Systems and Product Lines
- Designing and Evolving Systems from Architectural Design Patterns
- Executable Models of Software Designs
- Dynamic Software Reconfiguration

Software Modeling and Design

- Origins of Modeling
  - Small scale plans in art and architecture
- Modeling in science and engineering
  - Abstraction of system at some level of precision and detail
  - Analyze model to get better understanding of system
- Computer-Aided Design (CAD)
  - Computer models of product before product manufacturing
- Software Modeling
  - OMG: Modeling is designing of software applications before coding

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RT Software Design Methods 1984 - 1993

- 1984 – Support for concurrent task structuring
  - Design Approach for Real-Time Systems (DARTS)
- 1986 - Support for distributed applications
  - DARTS/DA
- 1989 - Support for real-time Ada design
  - ADARTS
- 1993 - Support for concurrent, real-time, & distributed OO design
  - CODARTS
- *H. Gomaa, "Software Design Methods for Concurrent and Real-Time Systems", Addison Wesley SEI Series, 1993*.

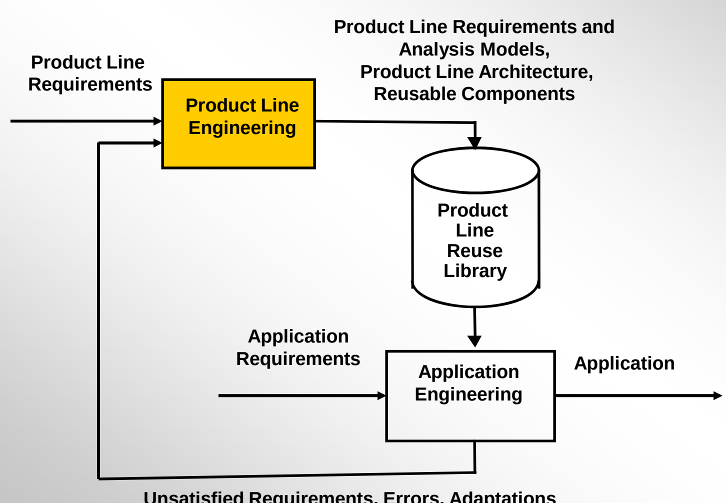
UML and COMET

- Unified Modeling Language (UML)
  - OMG Standardized notation for describing design
  - Methodology independent
- Concurrent Object Modeling and architectural design mEThod (COMET)
  - Object Oriented Analysis and Design Method
  - Targeted for concurrent, distributed, and real-time applications
  - Uses UML notation
- COMET = UML + Method
- *H. Gomaa, "Designing Concurrent, Distributed, and Real-Time Applications with UML", Addison Wesley Object Technology Series, 2000*

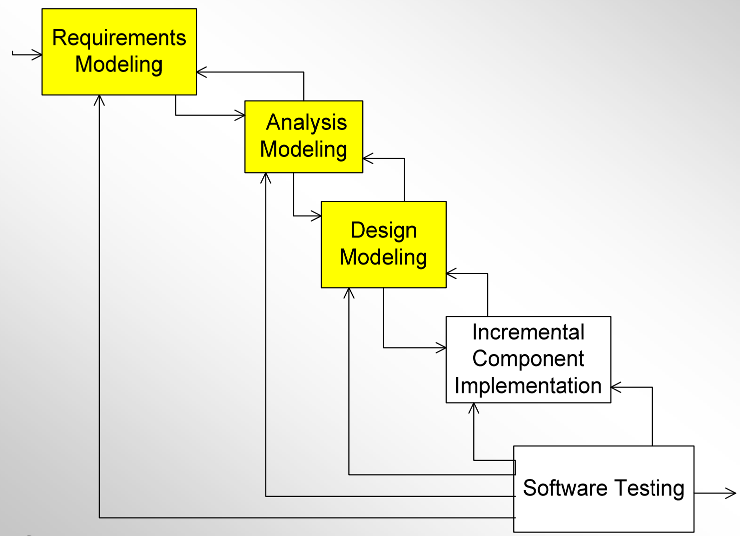
Designing Software Product Lines with UML

- Software Product Line (SPL)
  - Family of products / systems (Parnas, Weiss, SEI)
- OO Analysis and Design for Product Lines (PLUS)
  - Extends COMET, other methods for single systems
  - Model commonality and variability among members of software product line
- Apply standard UML extension mechanisms
  - Stereotypes, constraints, tagged values
- UML 2.0
  - Notation for depicting software architectures and components
- *H. Gomaa, "Designing Software Product Lines with UML", Addison Wesley Object Technology Series, 2005*

Evolutionary Process Model for Software Product Lines



Product Line Engineering



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Designing Evolutionary Systems and Product Lines

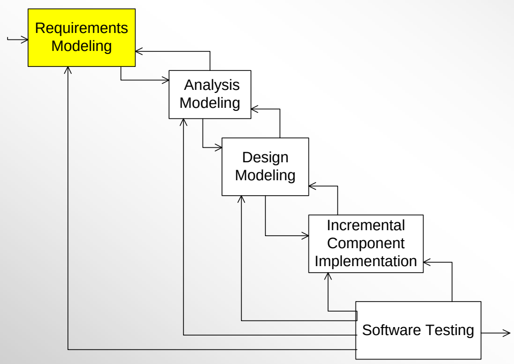
- Software Product Line
  - Model commonality and variability
  - Feature modeling used to explicitly capture variability
- Evolutionary System
  - Software system evolves from version to version
  - Can model as software product line
  - Each version of system is member of SPL
  - Model different features as system evolves
- Evolutionary Software Design
  - Evolution built into design method
  - Architecture-Centric Evolution

Evolutionary Architecture-Centric Development for Systems and SPL

- Kernel First Approach
  - Develop initial version of system or kernel of SPL
  - Kernel is similar to single system
- Evolutionary Development Approach
  - Consider evolution as an iteration in software development
- Model-based evolution
  - Feature-based Impact Analysis
  - Consider impact of optional and alternative features on kernel
    - Emphasis on dynamic modeling

Requirements Modeling
What should Evolutionary Design Method provide?

- For evolutionary systems and product lines
  - Support variability and evolution in use case modeling
  - Integrate feature modeling with other UML views



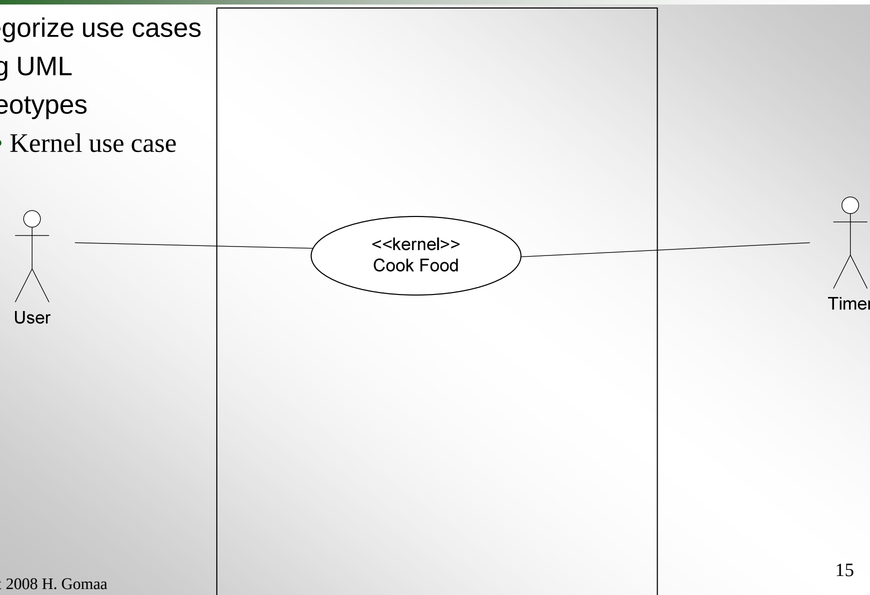
Use Case Modeling for Evolutionary Systems and Product Lines

- Categorize use cases using UML stereotypes
- Model commonality
  - «kernel» use cases
- Model variability
  - «optional» use cases
  - «alternative» use cases
  - Model variation points in use cases
    - Specify variability within use case
- Model use case evolution
  - Additional optional and alternative use cases
  - Additional variation points in existing use cases

Kernel Use Case Model for Microwave Oven SPL

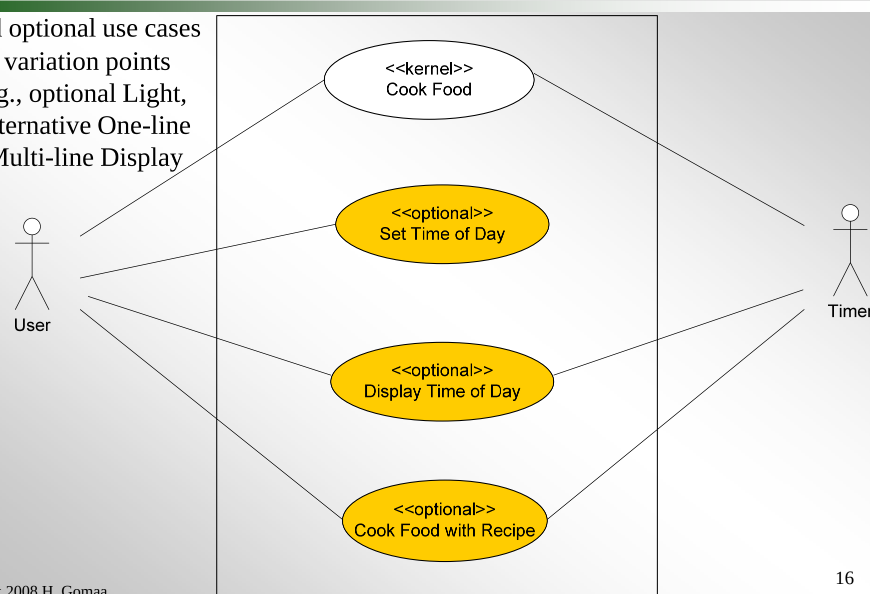
Categorize use cases using UML Stereotypes

- Kernel use case



Evolution of Use Case Model: Microwave Oven SPL

- Add optional use cases
- Add variation points
  - E.g., optional Light,
  - Alternative One-line or Multi-line Display

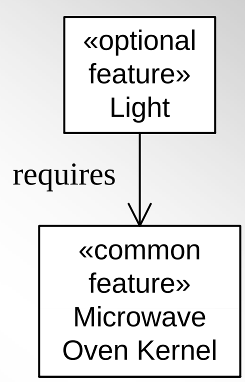


Feature Modeling for Evolutionary Systems and Product Lines

- Feature (Kang, SEI)
  - Function or characteristic that differentiates between members of the software product line
- Feature modeling
  - PLUS integrates feature modeling with other UML modeling views
- Feature modeling in PLUS
  - Determine features from use cases and variation points
  - Concentrate on modeling variability
- Evolutionary Systems and Product Lines
  - Feature modeling guides evolution

Feature Modeling with UML

- Use static modeling meta-class notation
  - Meta-classes depict *features* and *feature groups*
- Features are categorized using UML stereotypes
  - «common feature»
  - «optional feature»
  - «alternative feature»
  - «default feature»
  - «parameterized feature»
- Model Feature Dependencies
  - Requires
  - Mutually includes

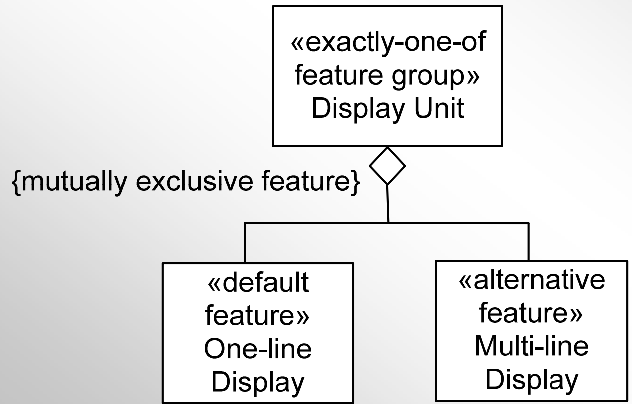


Features and Feature Groups in UML

Feature Relationships: Constraint on using features in group

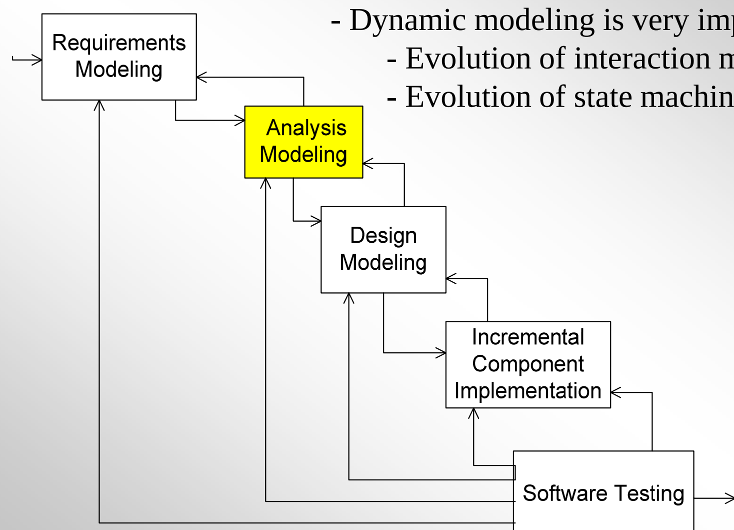
E.g., «exactly-one-of feature group»,

«zero-or-one-of feature group»



Analysis Modeling
What should Evolutionary Design Method provide?

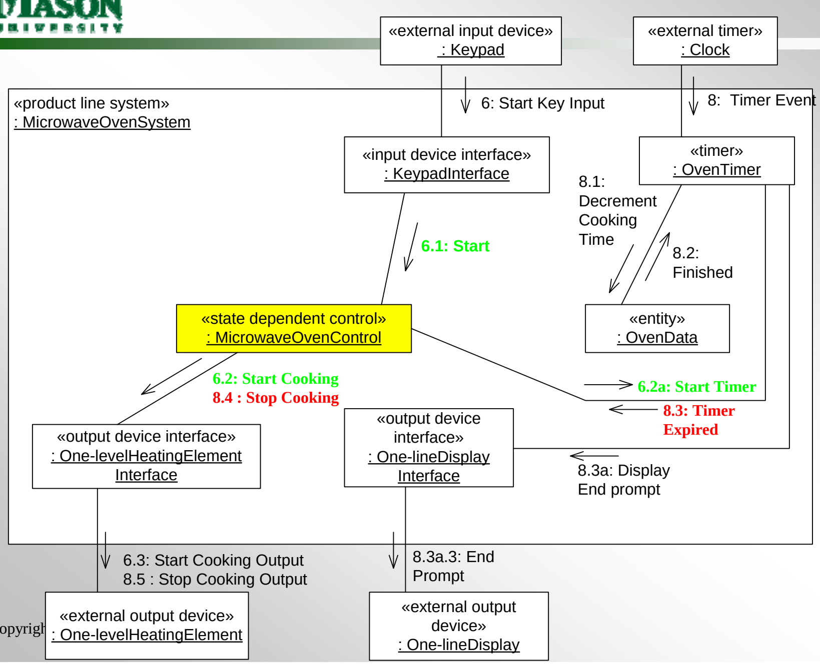
- For evolutionary systems and product lines
  - Dynamic modeling is very important
    - Evolution of interaction models
    - Evolution of state machines



Dynamic Interaction Modeling
Feature Based Impact Analysis

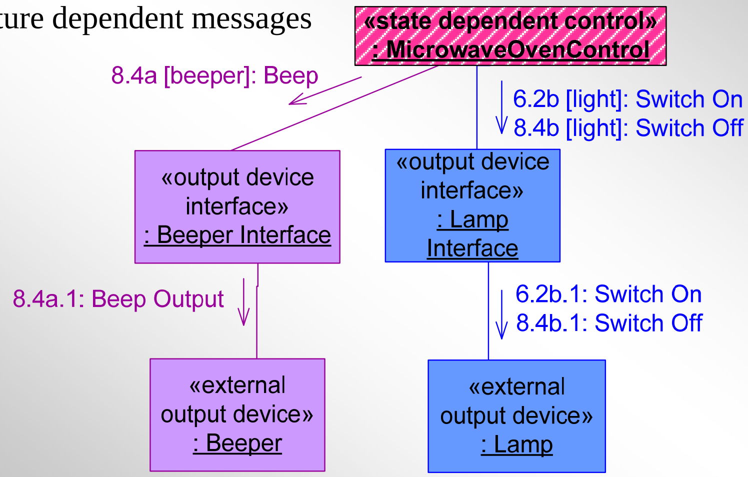
- Kernel First Approach
  - Develop kernel interaction diagrams to realize kernel use cases
  - Realized by kernel and default objects
- Product Line evolution approach
  - Consider impact of optional and alternative features on SPL kernel objects
  - Results in optional and variant objects
- Example of Kernel First Approach
  - Microwave Oven SPL
  - Kernel use case: Cook Food
- Product Line Evolution – impact analysis

Kernel Communication diagram for Cook Food use case



Impact Analysis of Beeper and Light Features

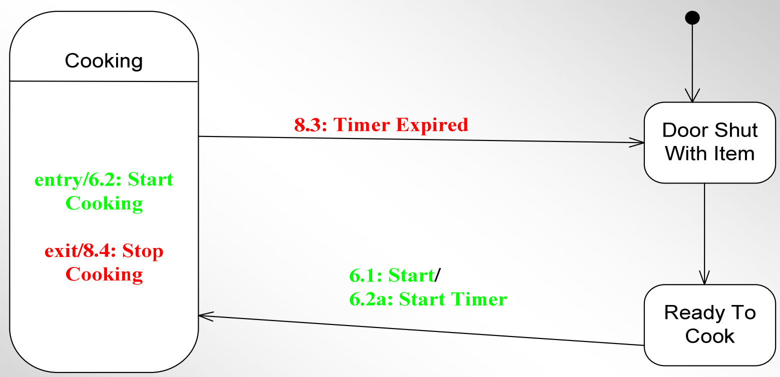
- 2 optional objects added
- Impact on control object
    - Feature dependent messages



Evolution of State Machines Feature Based Impact Analysis

- Kernel First Approach
    - Develop kernel state machines for state dependent control objects
- Product Line evolution approach
    - Consider impact of optional and alternative features on kernel state machines
- Feature dependent state transition
    - Use feature condition as guard on state transition
        - Event [Feature Condition]
- Feature dependent action
    - Action is only executed if Feature Condition is True
    - Action [Feature Condition]

Kernel statechart for Microwave Oven Control

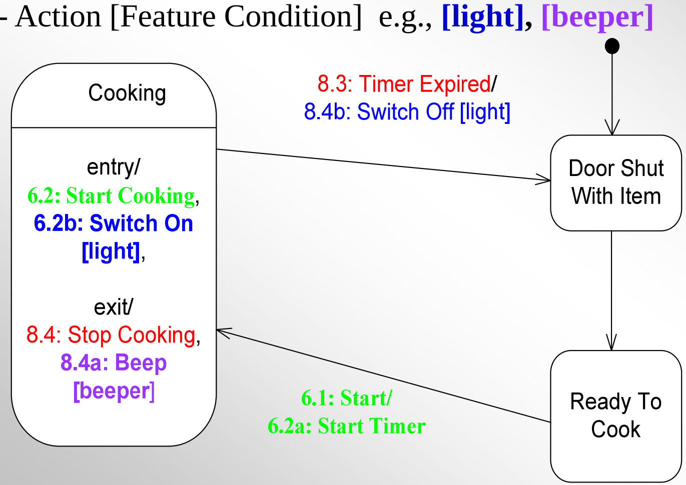


- Incoming message to object-> input event on statechart
- Output event on statechart -> outgoing message from object

Impact on Statechart for Microwave Oven Control

Feature dependent actions:

- Action is only executed if Feature Condition is TRUE
- Action [Feature Condition] e.g., **[light]**, **[beeper]**

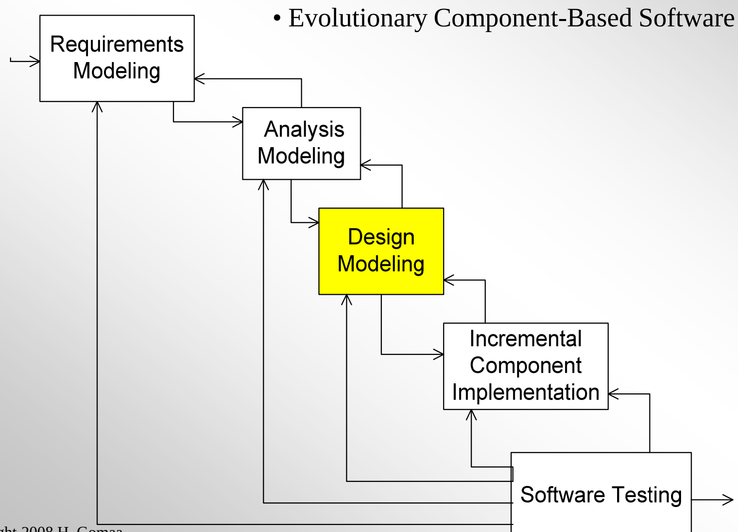


Evolution of State Machine Models

- Model state machine variability
  - Inherited vs Parameterized State Machines
- Inherited State Machine
  - Different state machine for each alternative or optional feature
- Disadvantage:
  - Each feature & feature combination needs an inherited state machine
  - Could lead to combinatorial explosion of inherited state machines
- Often better to design parameterized state machine
  - Feature dependent state transitions and actions

Design Modeling
What should Evolutionary Design Method provide?

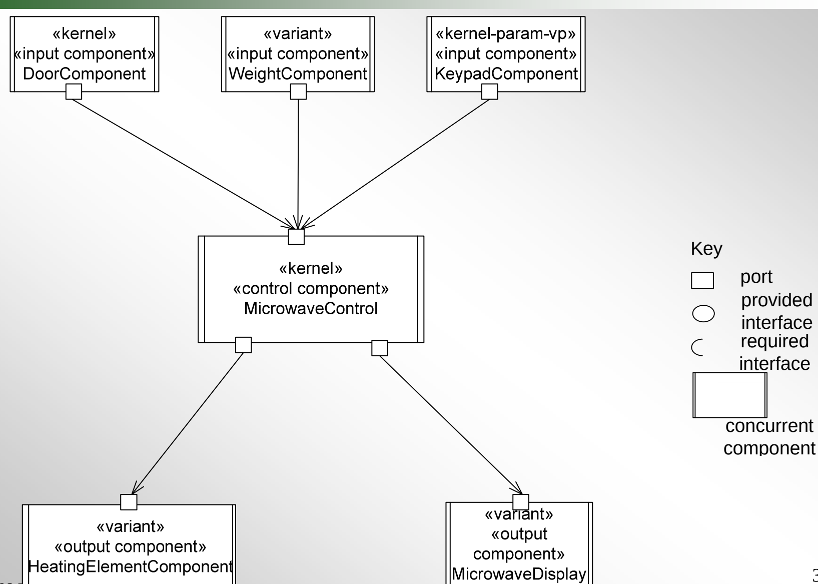
- Software Architectural Patterns
- Evolutionary Component-Based Software Architectures



Component-based Distributed Software Architecture

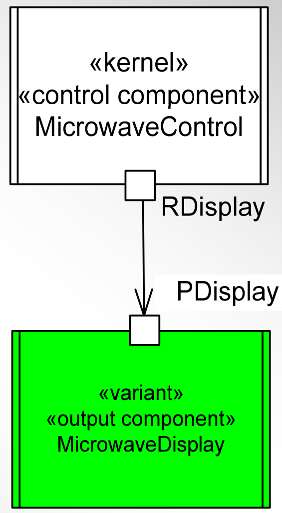
- Distributed component
  - Logical unit of distribution and deployment
  - Well-defined *provided* and *required* interfaces
- Modeling Components in UML 2.0
  - Components modeled as UML 2.0 structured classes
  - Depicted on UML 2.0 composite structure diagrams
  - Provides support for
    - Composite and simple components
    - Interfaces, ports, connectors
- PLUS component categorization using stereotypes
  - Application role category
  - Reuse category

Software Architecture for Microwave Oven – Before Evolution

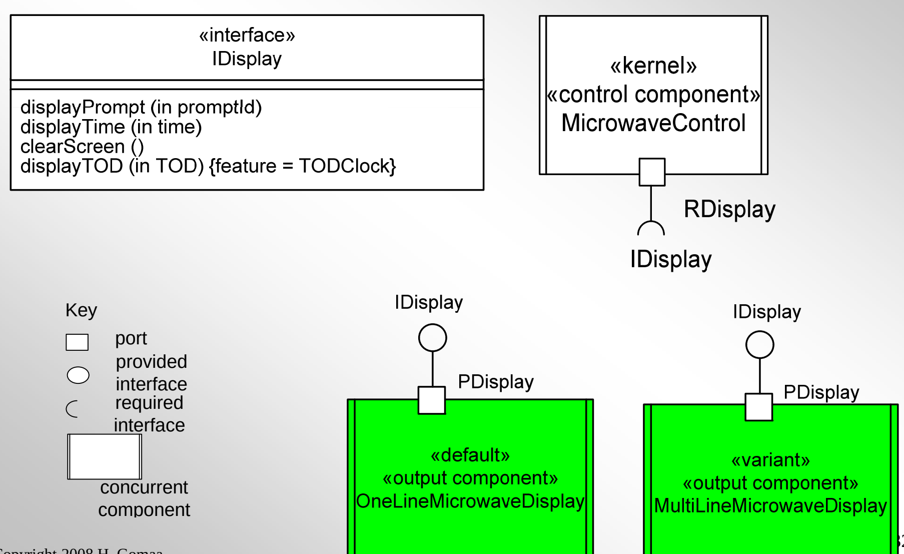


Design of "Plug Compatible" Components

- Connector
  - Joins *required* port of one component to *provided* port of another component
- "Plug compatible" components
  - One interface
  - Realized by different components
- E.g., Microwave Control can be connected to one-line or multi-line version of Microwave Display
- If interface needs to be extended
  - Use component inheritance

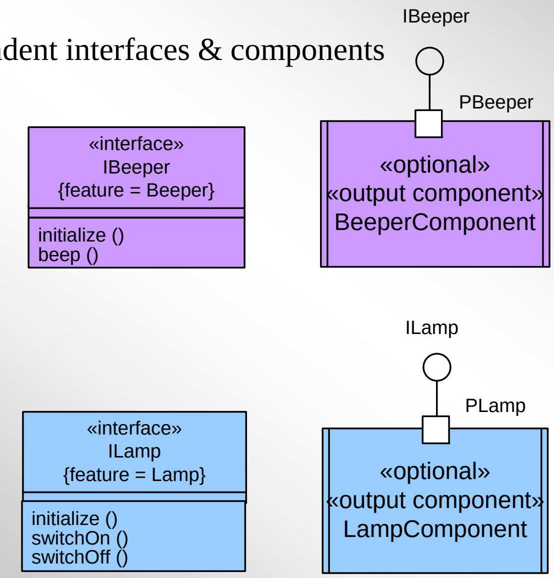


Design of individual components



Design of Optional Components

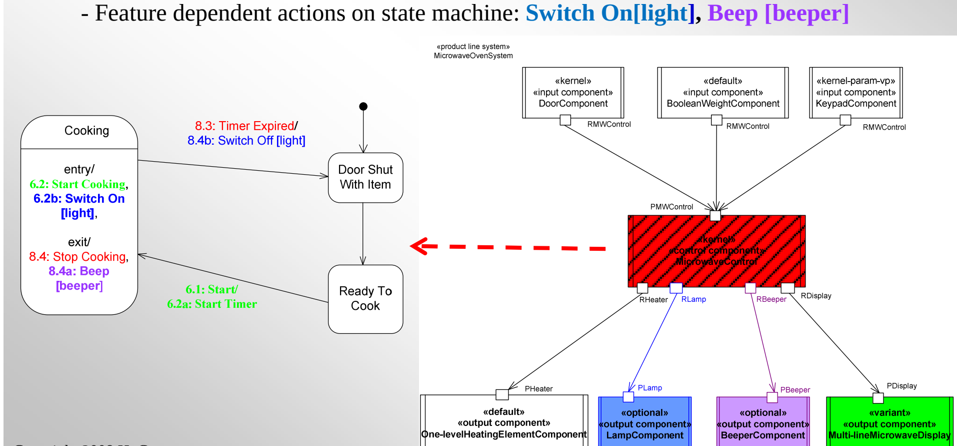
- Feature dependent interfaces & components



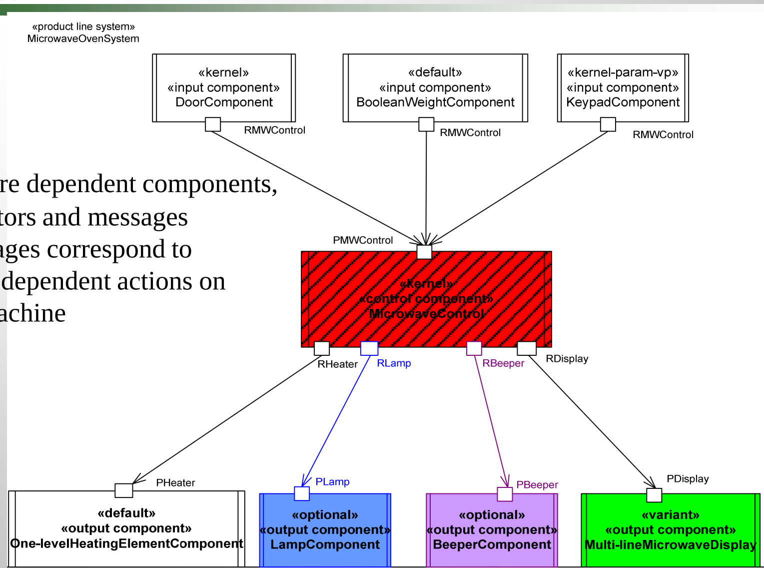
Evolution of Microwave Oven Architecture

- Feature dependent components, connectors and messages
- Messages correspond to feature dependent actions on state machine

- Microwave Control
  - Feature dependent actions on state machine: **Switch On[light]**, **Beep [beeper]**



Evolution of Microwave Oven Architecture



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Software Architectural Patterns

- Software Architectural Patterns [Buschmann, Shaw]
  - Recurring architectures used in various software applications
- Goal: Design Software Architecture from
  - Software Architectural Patterns
- Architectural Structure Patterns
  - Address structure of major subsystems
- Architectural Communication Patterns
  - Reusable interaction sequences between components

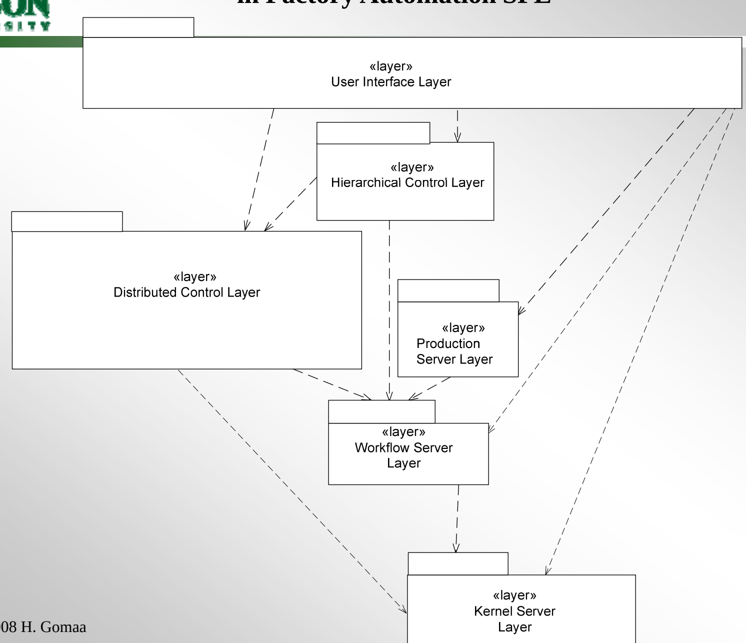
Architectural Structure Patterns for Software Product Lines

- Layered patterns *very important for evolution*
  - Layers of Abstraction
  - Kernel
- Client/Server patterns
  - Basic Client/Server
  - Client/Broker/Server
  - Client/Agent/Server
- Control Patterns *very important in RT Design*
  - Centralized Control
  - Distributed Control
  - Hierarchical Control

Layers of Abstraction Pattern

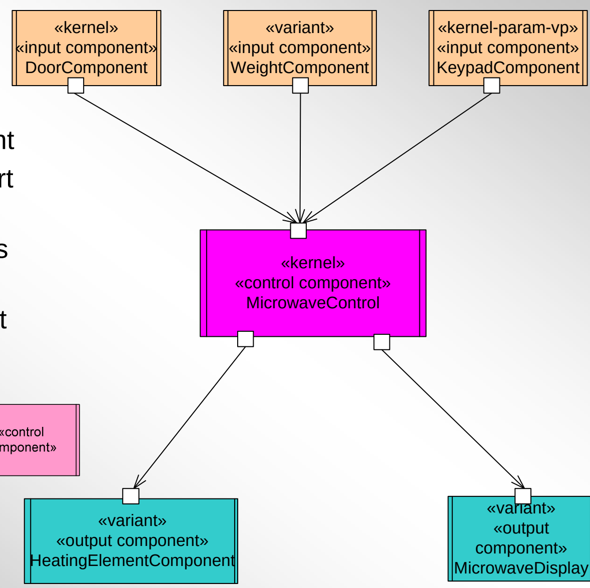
- Structure system into hierarchical layers [Parnas]
  - Each layer provides services for higher layers
- Layers of Abstraction in Product Lines
  - Allows design of variable and extensible software
  - Kernel components at lowest layer
  - Optional and variant components at higher layers
- Software Evolution
  - Add components at higher layers
  - Depend on services provided at lower layers

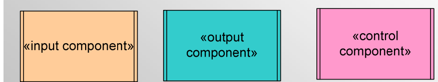
Flexible Layers of Abstraction Pattern in Factory Automation SPL



Centralized Control Pattern
E.g., Microwave Oven Control Architecture

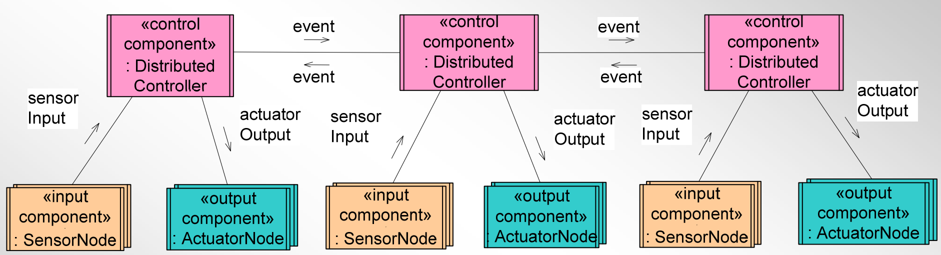
- Centralized Control Pattern
  - One control component
    - Executes statechart
  - Receives sensor input from input components
  - Controls external environment via output components





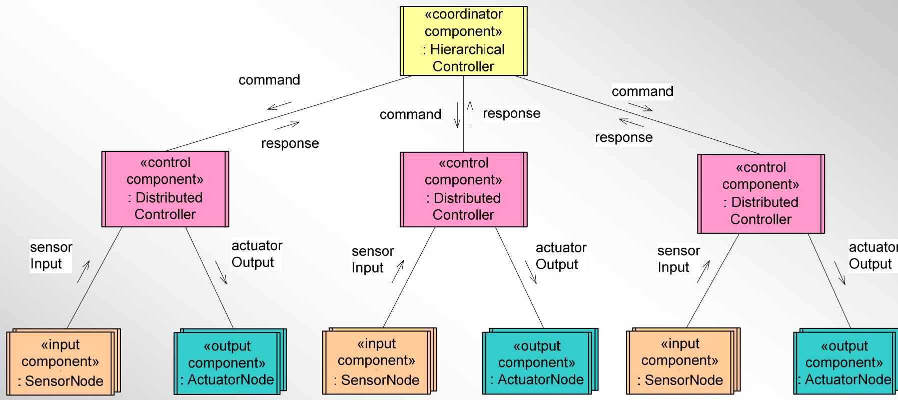
Key

Distributed Control Pattern



- Several control components
- Control is distributed among the components
- Each component controls part of system
  - Executes statechart
- Control components communicate with each other to provide overall control

Hierarchical Control Pattern



- Hierarchical Controller
  - Coordinator component
    - Provides high level control
    - Sends commands to each control component

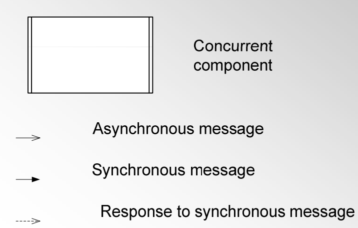
Architectural Communication Patterns for Software Product Lines

- Asynchronous communication patterns
- Synchronous communication patterns

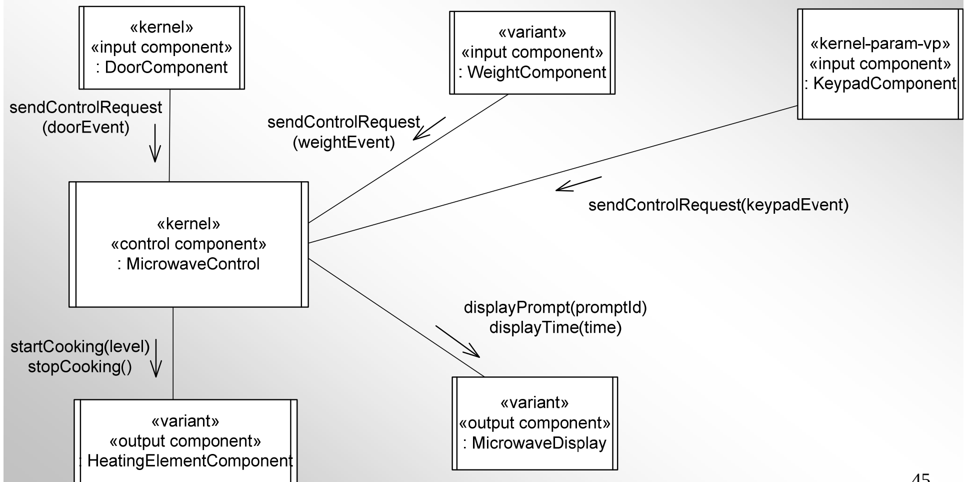
- **Very important for evolutionary design:**

- Broker Communication Patterns
  – Broker forwarding
  – Broker handle
  – Discovery

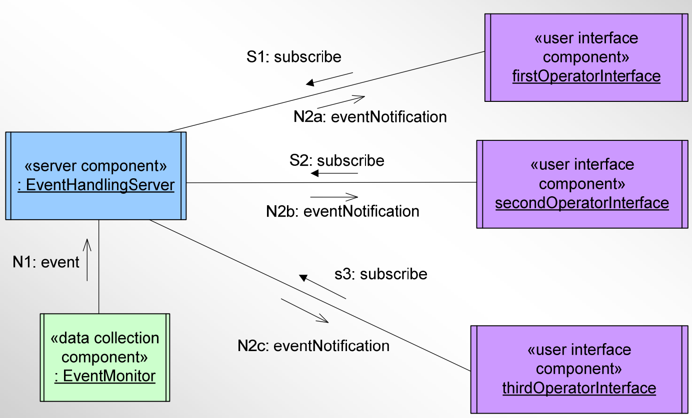
- Group Communication Patterns
  – Broadcast
  – Subscription/notification



Software Architecture for Microwave Oven - asynchronous communication Pattern



Subscription/Notification Pattern

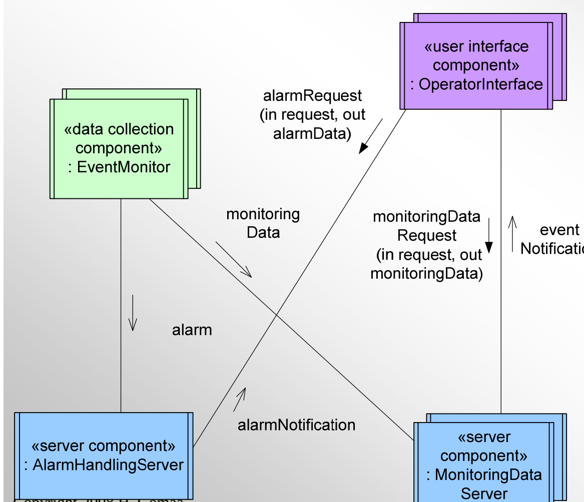


- Subscription/Notification Pattern
  - Client subscribes to join group
  - Receives messages sent to all members of group

Building Systems and SPL from Software Architectural Patterns

- Consider architectural structure patterns
  - Different patterns can be combined
- Start with layers of abstractions pattern
  - Incorporate client/server patterns
  - Incorporate control patterns
- Apply architectural communication patterns

Building Emergency Monitoring System From Software Architectural Patterns

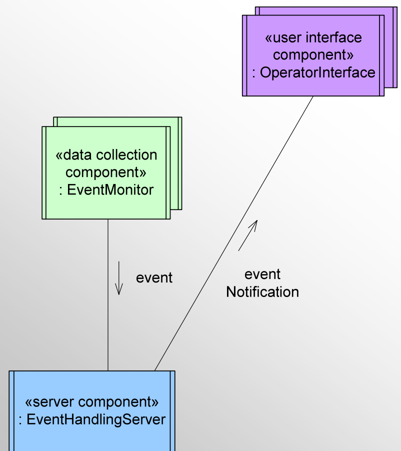


Architectural Structure Patterns
- Layered pattern
- Client/Server patterns

Architectural Communication Patterns
- Synchronous
- Asynchronous
- Broker
- Subscription/Notification

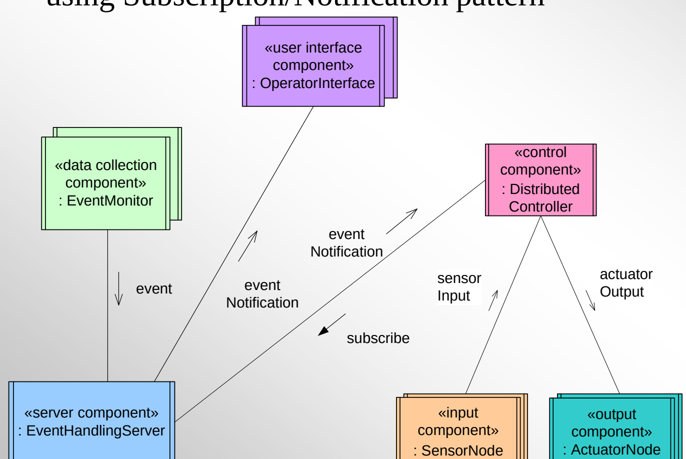
Software Architectural Patterns in
Emergency Monitoring and Distributed Control System

- Evolve **Emergency Monitoring** System



Software Architectural Patterns in
Emergency Monitoring and Distributed Control System

- Evolve **Emergency Monitoring** System
- Integrate **Distributed Control pattern** using Subscription/Notification pattern



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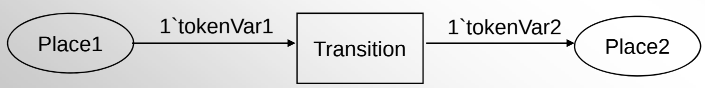
Modeling Executable Software Architectures

- Design and analyze concurrent software architecture
- Behavioral design patterns
  - Concurrent component
  - Connector
  - Mapped to Colored Petri Net template
- Map concurrent software architecture to CPN model
  - Select and Interconnect CPN templates for components and connectors
- Analyze CPN model
  - Application behavior
  - Application performance
- *R. Pettit and H. Gomaa, “Modeling Behavioral Design Patterns of Concurrent Objects”, Proc. Int. Conf. on Software Eng. (ICSE), Shanghai, May 2006.*

Concurrent Software Architecture

- Uses component / connector paradigm
- Component (application object)
  - Concurrent object with single thread of control
  - Use COMET concurrent object (task) structuring criteria
  - Define behavioral design pattern for component
- Connector
  - Provides message communication between components
- CPN behavioral design template provided for each
  - Component
  - Connector

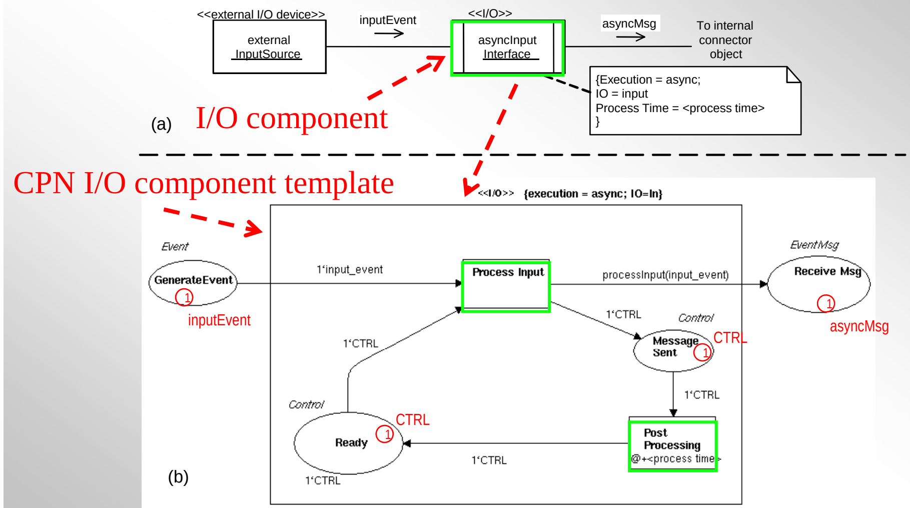


Colored Petri Net notation

Asynchronous I/O Pattern

- I/O component
  - Handles external input/output on demand
- CPN pattern
  - Thread of control maintained by control token
  - Each component has its own control token
- CPN Transition executes function
  - Processing time associated with transition
- Colored tokens to differentiate role of tokens
  - Control token
  - Input event
  - Output message

Asynchronous I/O Pattern



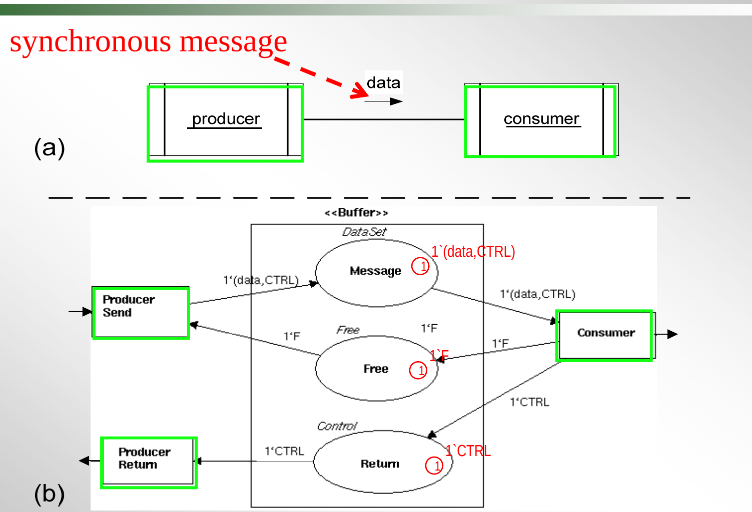
Connectors

- Connector
  - Provides message communication between concurrent components
    - Queue - Asynchronous communication
    - Buffer - Synchronous communication
- Interface to connector uses CPN places
  - Facilitates interconnection between concurrent component templates and connector templates

Synchronous Communication Pattern

- Synchronous buffer models synchronous communication
- Producer sends message and waits for reply
- One message at a time allowed in the buffer
- Producer and consumer are blocked until message has been passed

Synchronous Communication Pattern

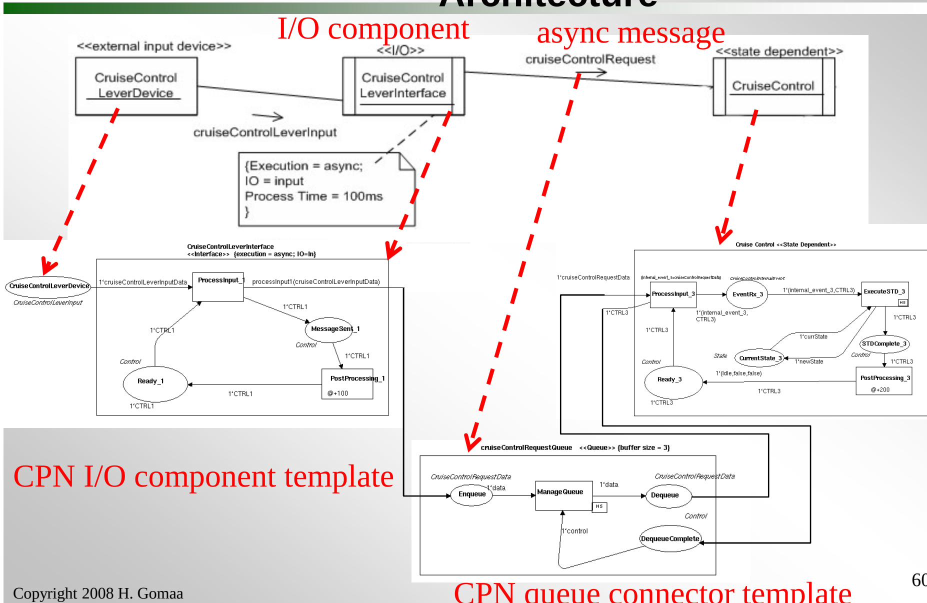


CPN buffer connector template

Constructing CPN Model from UML Concurrent Design Model

1. Develop COMET/UML design model
   – COMET structuring criteria
2. Construct Architecture-Level CPN Model
   – Represent each component & connector by CPN template
   – Templates developed using DesignCPN
   – Interconnect CPN templates
3. Model characteristics of individual component
   – Customize CPN templates for application
4. Exercise model in DesignCPN simulator
   – Analyze functional behavior
     • Detect and correct design problems
   – Analyze performance characteristics
     • Does software architecture meets timing constraints?

Connecting CPN Templates to form CPN Architecture



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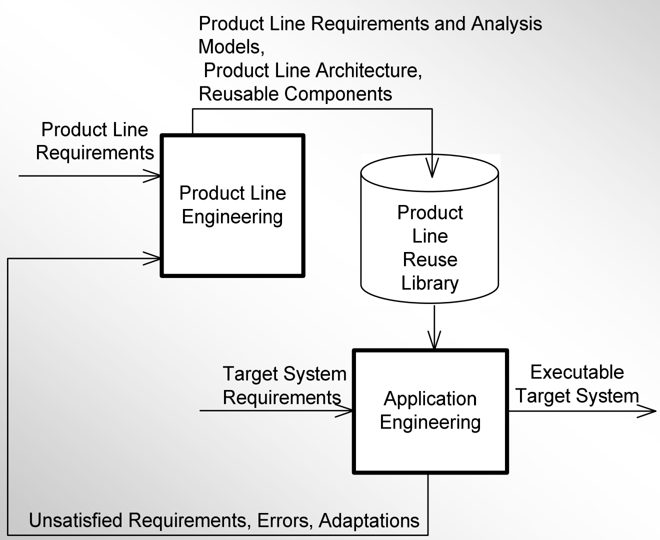
Dynamic Software Reconfiguration in Safety Critical Systems

- Safety Critical Systems
  - Highly available, Time critical
- Examples: air traffic control systems, spacecraft, automotive and aircraft control systems
- Challenge
  - Evolve the configuration of software application
    - At run-time
  - Application must be operational during dynamic reconfiguration
- *H. Gomaa and M. Hussein, "Software Reconfiguration Patterns for Dynamic Evolution of Software Architectures", Proc. Working IEEE/IFIP Conf. on Software Architecture, Oslo, Norway, June, 2004.*

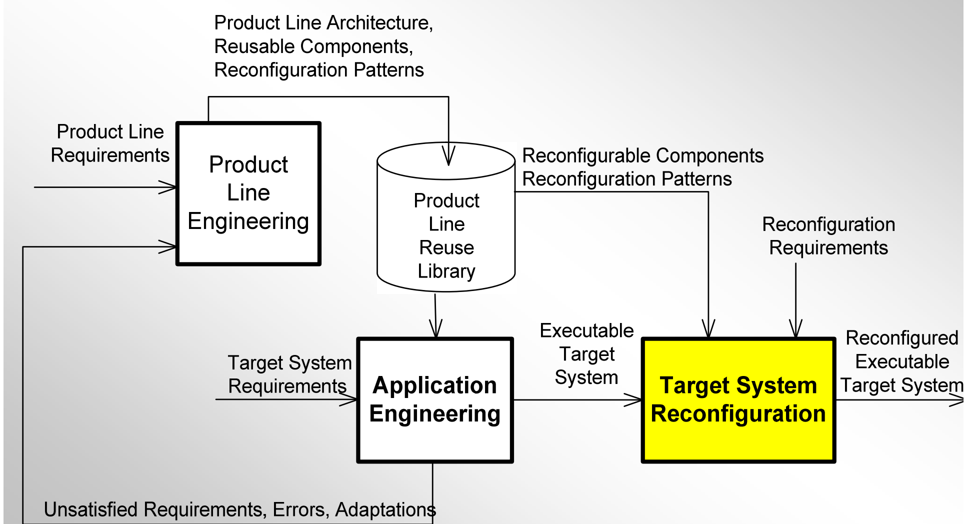
Approach

- Most product line research aimed at deriving different family members from
  - Product line architecture + implementation
  - At Configuration Time
  - NOT at Run Time
- Research approach
  - Model all configurations of safety critical system as product line members
  - Dynamically change from one family member to a different family member at Run Time
  - Develop Software Reconfiguration Patterns

Evolutionary Product Line Life Cycle - Build, then Deploy



Reconfigurable Evolutionary Product Line Life Cycle
Reconfigure *after* Deployment

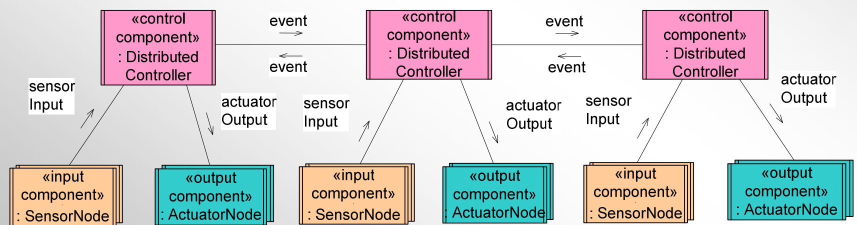


Software Reconfiguration Patterns

- Concept
  - Develop software reconfiguration patterns for well-known software architectural patterns
  - Reconfiguration Pattern
    - Specifies how set of components cooperate to dynamically change system configuration
- Software Reconfiguration Patterns developed
  - Master-Slave pattern
  - Centralized Control pattern
  - Client / Server pattern
  - Decentralized Control pattern

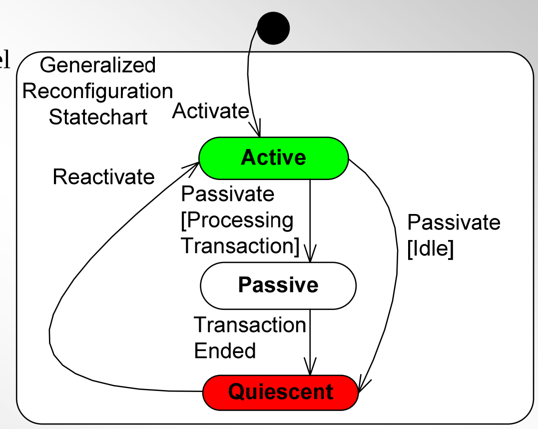
Decentralized Control Reconfiguration Pattern

- Decentralized Control components communicate with each other
  - Components must notify each other if going quiescent
  - Component can cease to communicate with neighbor but can continue with other processing



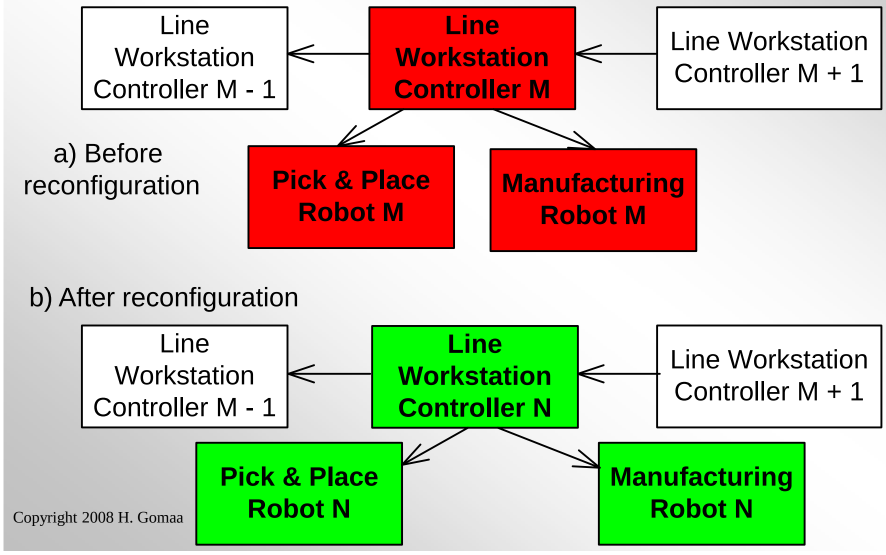
Reconfiguration State Machine

- Reconfiguration state machine model
- Component transitions to a state where it can be reconfigured
  - Active State
    - Component is operational
  - Quiescent State
    - Component Idle
    - Can be removed from configuration



Example of Reconfiguration Scenario

- Reconfigurable factory automation SPL architecture
  - Uses: Master-Slave, Client / Server, & Decentralized Control patterns



Summary and Conclusions

- Software Modeling and Design
- Designing Evolutionary Systems and Product Lines
  - Evolution built into software design method
  - Architecture-Centric Evolution
- Designing and Evolving Systems from Architectural Patterns
- Executable Models of Software Designs
- Dynamic Software Reconfiguration
- Other related research
  - Software performance modeling (with D. Menasce)
  - Multiple-view meta-modeling (with M. Shin)
  - Tool support for SPL development and product derivation (many)
  - SPL model-based testing (with E. Olimpiew)
  - Separation of concerns in multiple-view models (with Saleh & Shin)
  - Software process modeling (with L. Kerschberg)
  - Design of Service-Oriented Architectures (with J. Street)