Modeling Behavioral Design Patterns of Concurrent Objects

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Overview

- Goals
  - Provide executable behavioral analysis capabilities
    - For concurrent object-oriented software architectures
    - At **design** stage
- Concurrent software architectures are depicted in UML
- Colored Petri nets (CPNs) used as underlying formalism
- CPN templates created to model executable behavioral design patterns
  - Promotes systematic, repeatable model construction

Modeling Executable Software Architectures

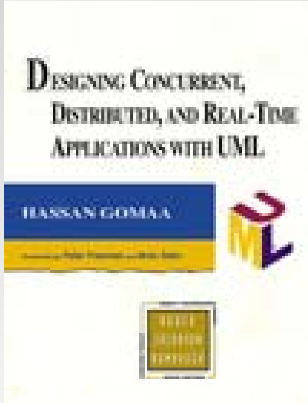
- Design and analyze concurrent software architecture
- Behavioral design patterns
  - Concurrent component
  - Connector
  - Mapped to Colored Petri Net template
- Map concurrent software architecture to CPN model
  - Select and interconnect CPN templates for components and connectors
- Analyze executable 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.*

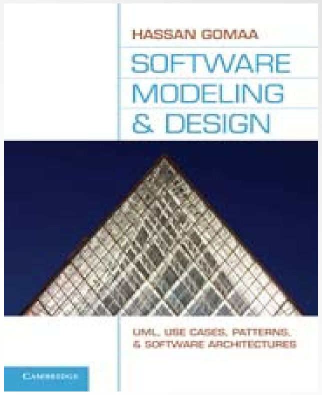
Using Behavioral Design Patterns

- Start with software design captured in UML
  - Depicted on UML 2 communication diagrams
- Structure concurrent system into concurrent objects
  - Categorize concurrent objects by behavioral role
  - Each concurrent object is represented by behavioral design pattern
  - Mapped to CPN template

Software Modeling and Design for Concurrent Systems

- COMET design method
  - From Use Case Models to Software Architecture
  - COMET = method + UML
  - Requirements and Analysis Modeling
    - Use case modeling
    - Static and Dynamic modeling
  - Design modeling
    - Concurrent, distributed, and real-time applications
  - *H. Gomaa, “Designing Concurrent, Distributed, and Real-Time Applications with UML”, Addison Wesley Object Technology Series, 2000*
  - *H. Gomaa, Software Modeling and Design: UML, Use Cases, Patterns, and Software Architectures*, Cambridge University Press, February 2011

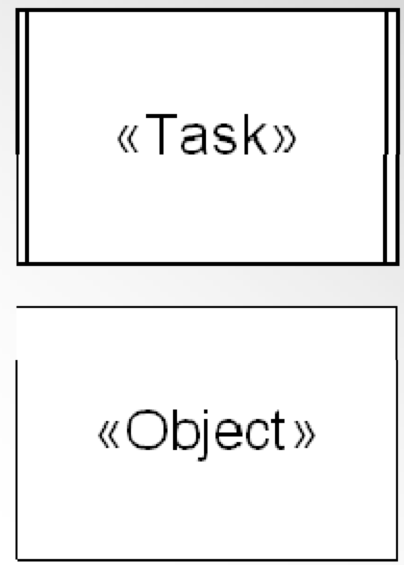




Concurrent and Passive Objects

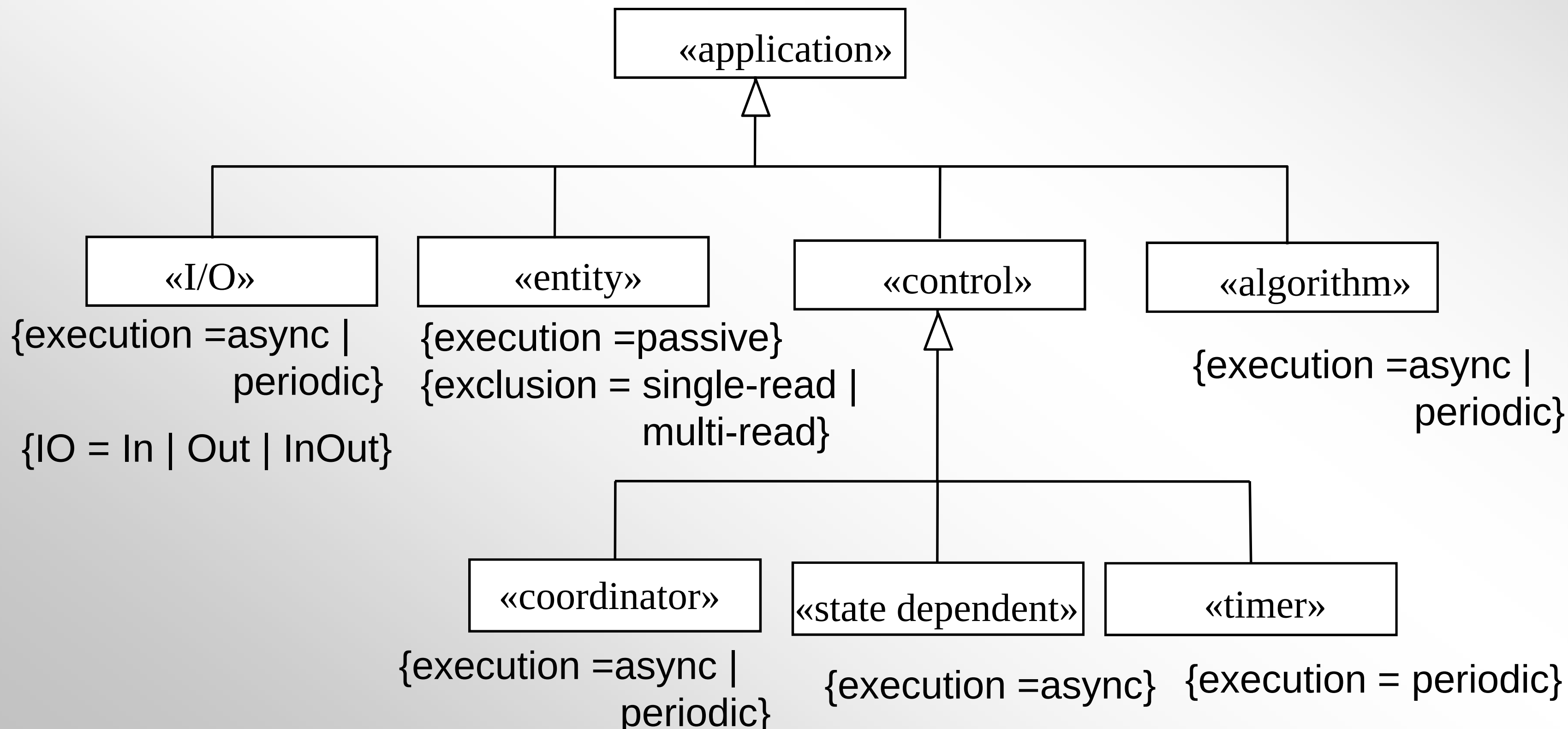
- Concurrent system consists of **concurrent objects** and **passive objects**
- **Concurrent object**
  - Has a **thread** of control
  - Executes autonomously
  - Also known as
    - **Active object**
    - **Concurrent process (lightweight)**
    - **Concurrent task**
    - **Concurrent component**
    - **Thread (Java)**
    - **Processor (Scoop)**
- **Passive object**
  - Has no thread of control
  - Also known as
    - Sequential object
    - Object

UML notation



Structure and Categorize Concurrent Objects

- Use COMET structuring criteria to categorize concurrent objects
  - Each concurrent object depicted using UML stereotype
  - Specify architectural parameters for each concurrent object
  - Identify concurrent object behavioral design pattern

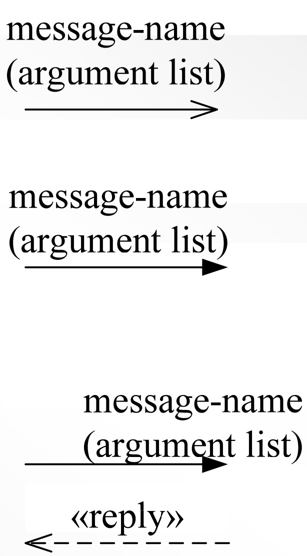


UML Notation for Messages

a) Asynchronous message communication

b) Synchronous message communication

c) Synchronous message communication with reply



Asynchronous I/O Concurrent Object (Component/task/thread)

One concurrent object for each asynchronous I/O device

Activated by device interrupt

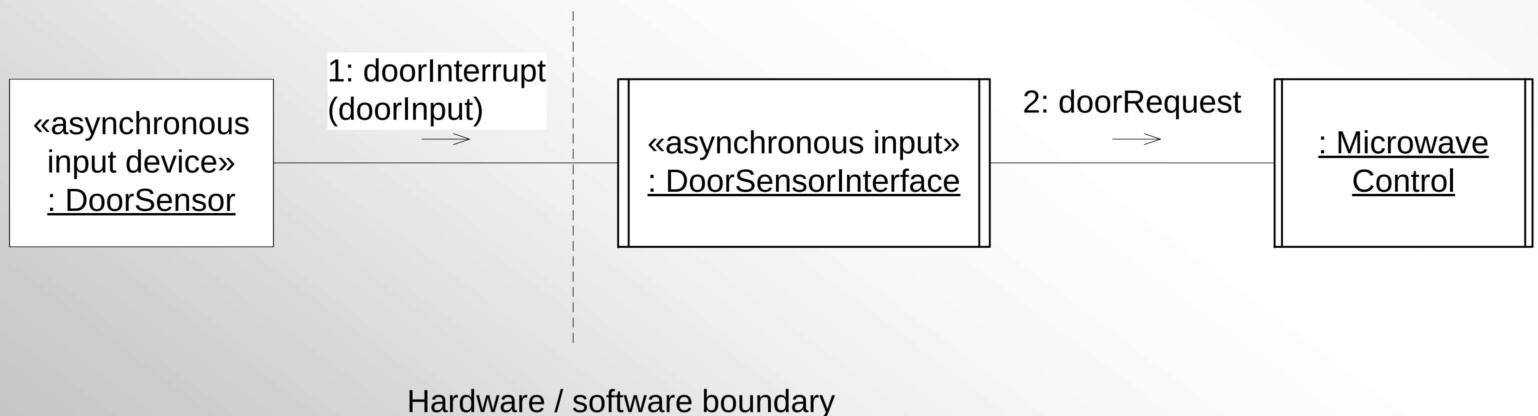
Reads input

Converts to internal format

Sends message containing data

Waits for next interrupt

Figure 14.1b Design model – UML concurrent communication diagram

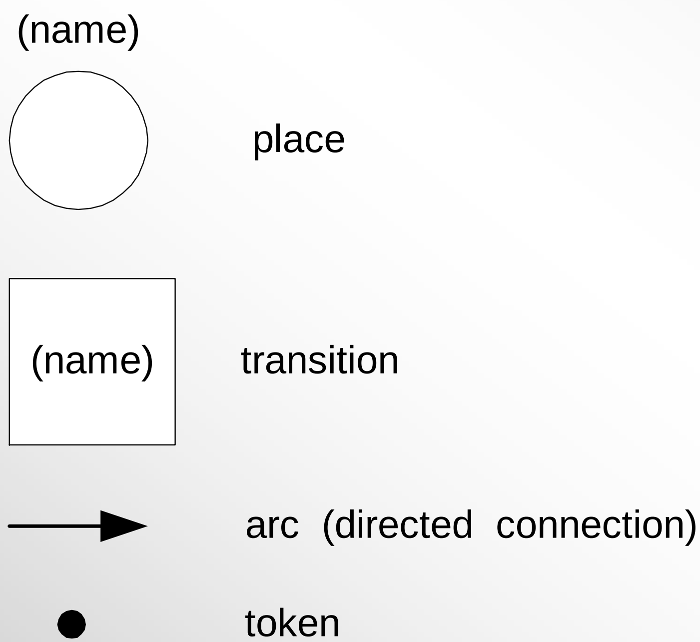


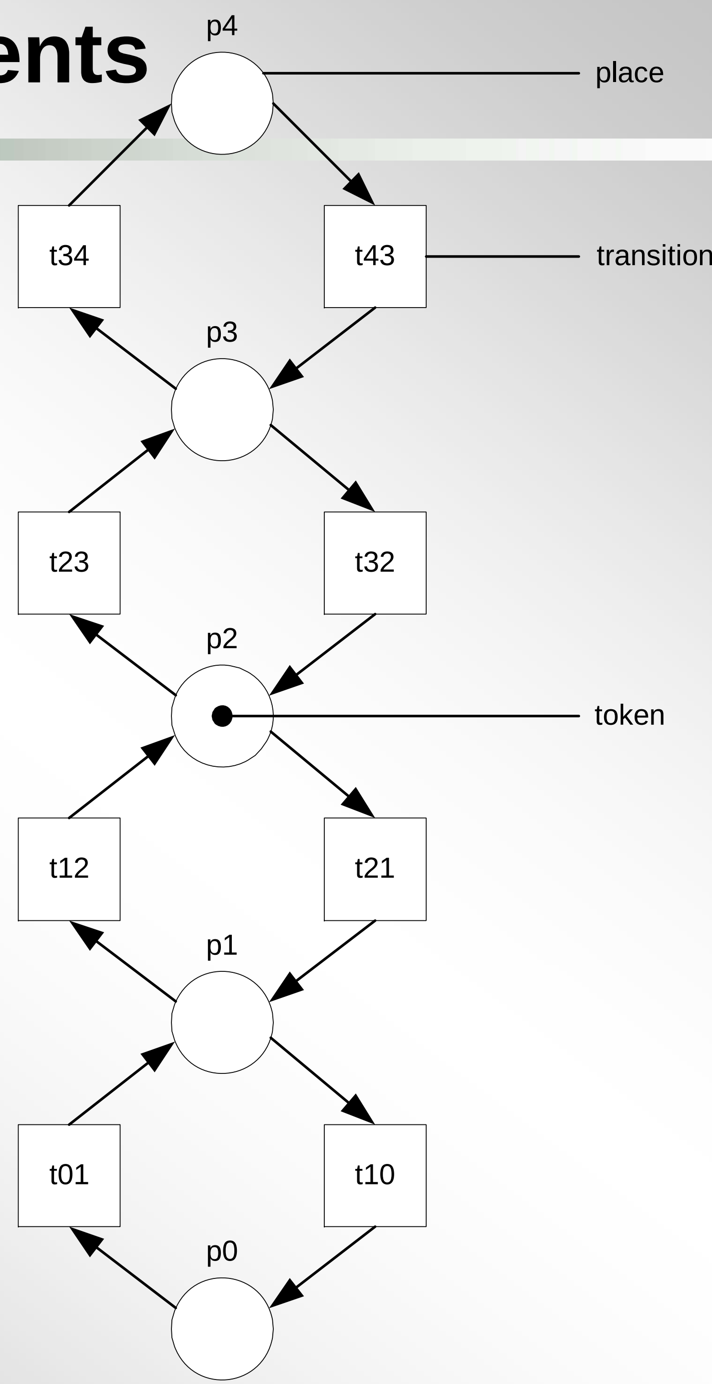
Classical Petri Nets

- Simple concurrency model
  - Just three elements: **places**, **transitions** and **arcs**.
  - Graphical and mathematical description.
  - Formal semantics and allows for analysis.
- History:
  - Carl Adam Petri (1962, PhD thesis)
  - In sixties and seventies focus mainly on theory.
  - Since eighties also focus on tools and applications (cf. Colored Petri Net work by Kurt Jensen).

- Source: Intro to Petri Nets, Wil van der Aalst

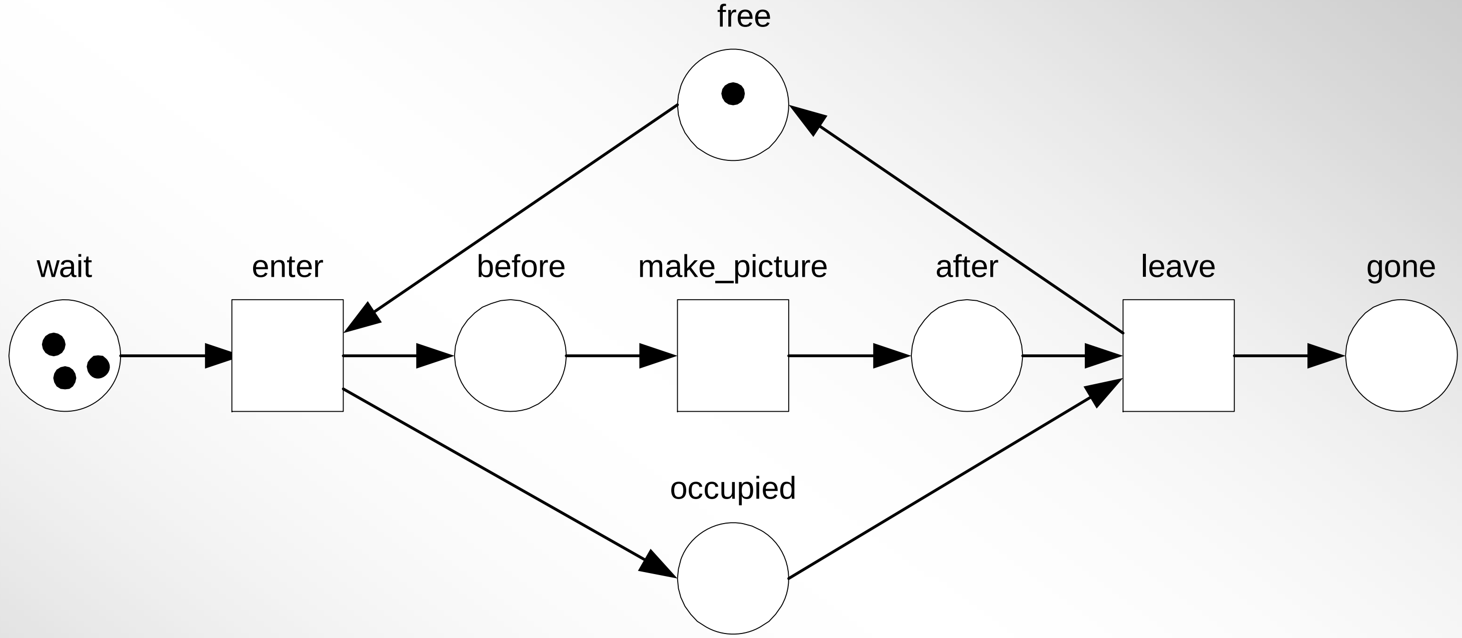
Petri Net Elements





Source: Intro to Petri Nets,
Wil van der Aalst

Petri Net Rules

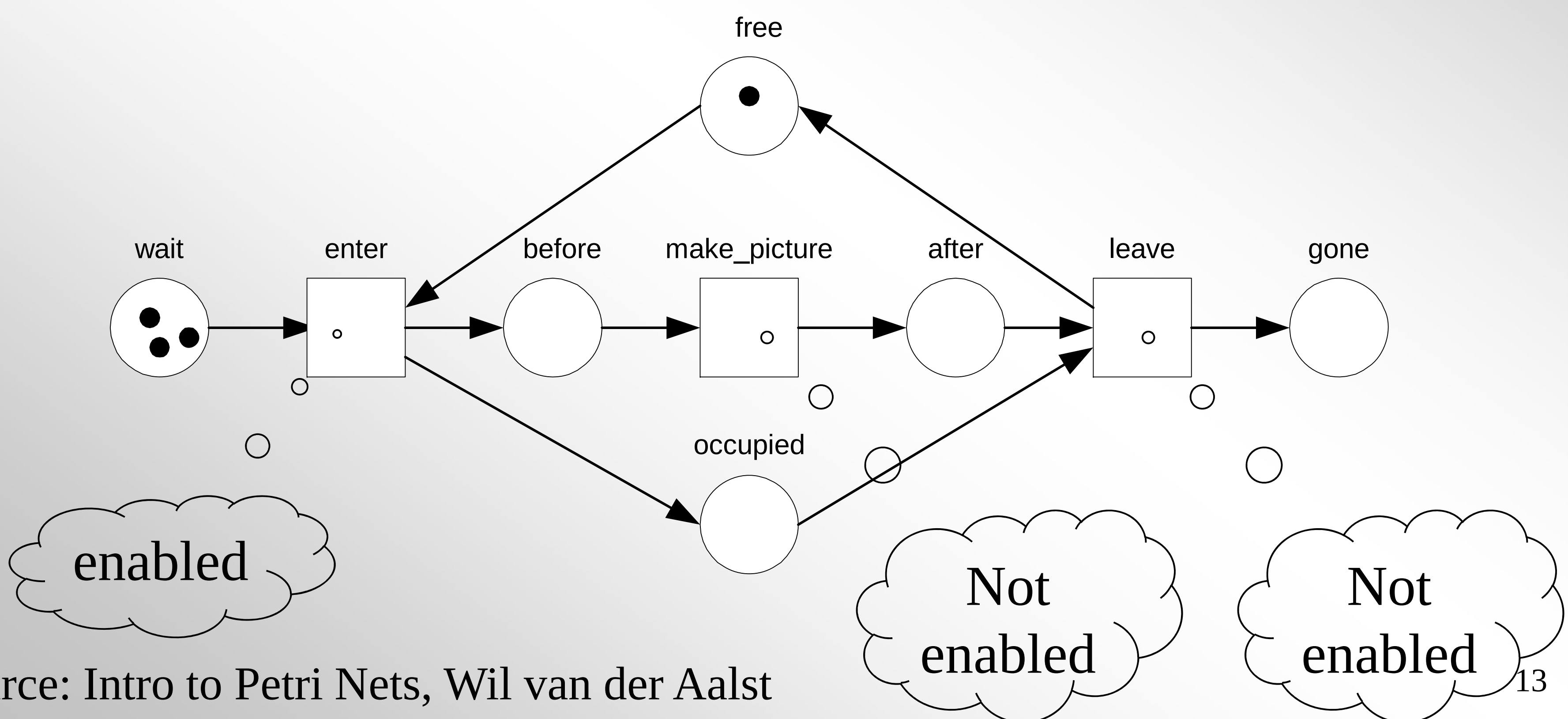


- Connections are directed.
- No connections between two places or two transitions.
- Places may hold zero or more tokens.

Source: Intro to Petri Nets, Wil van der Aalst

Enabled Transition

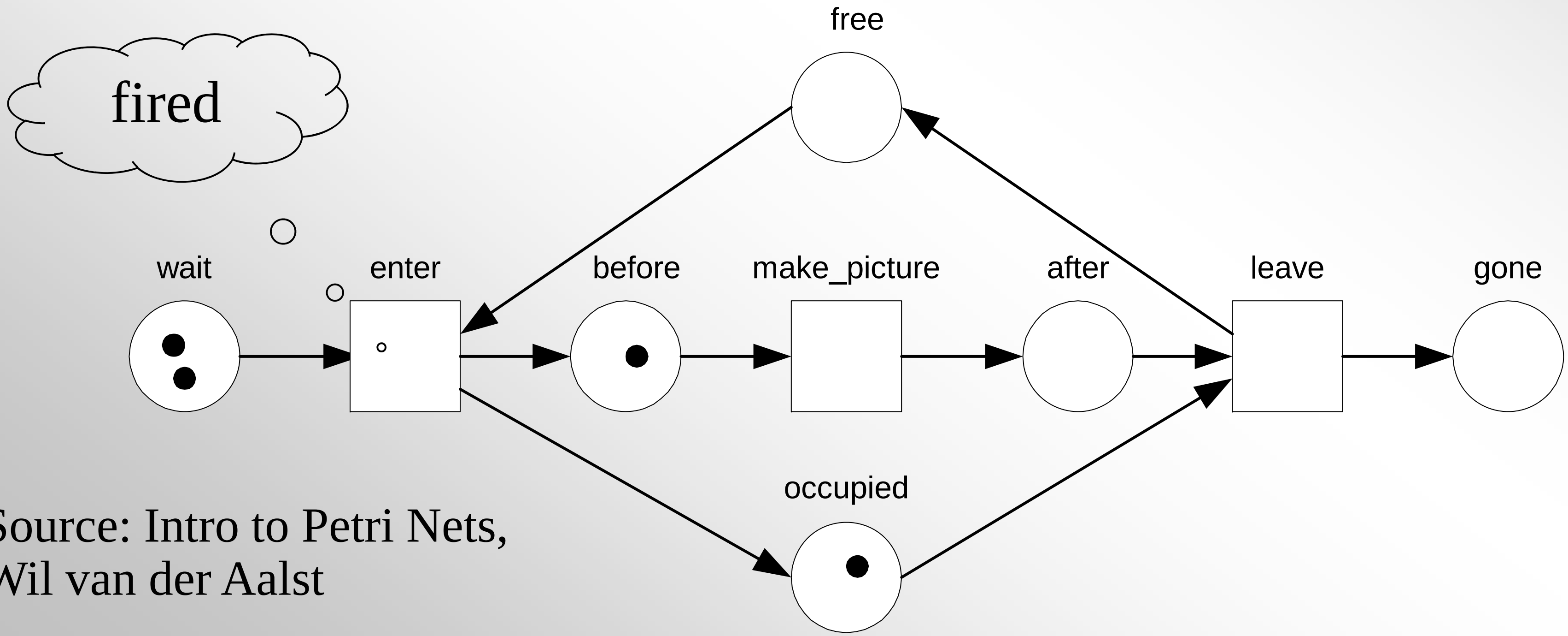
- A transition is **enabled** if each of its input places contains at least one token



Source: Intro to Petri Nets, Wil van der Aalst

Firing of Transition

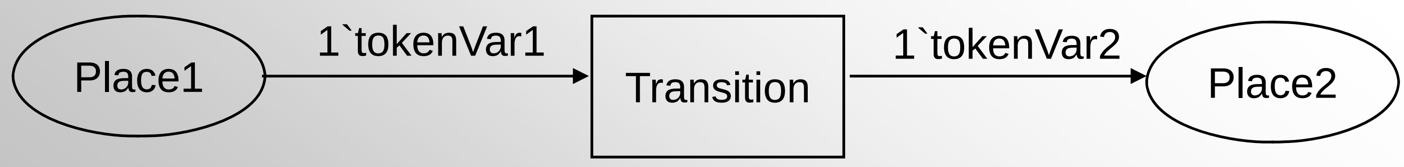
- An **enabled** transition can **fire** (i.e., it occurs).
- When it **fires** it **consumes** a token from each input place and **produces** a token for each output place.



Source: Intro to Petri Nets, Wil van der Aalst

Colored Petri Nets (CPN)

- Developed by Kurt Jensen
- Petri nets extended with:
  - Color
    - Tokens given data value
  - Time
    - Enabled transition fires after specified time
  - Hierarchy
    - Transition can be decomposed to lower level CPN subnet
- Tool support
  - Design CPN



Concurrent Software Architecture

- Uses component / connector paradigm
- Component
  - Concurrent object with single thread of control
  - Passive entity object
    - Encapsulates data
- Connector
  - Provides message communication between concurrent objects
- Model components and connectors using Colored Petri Net templates

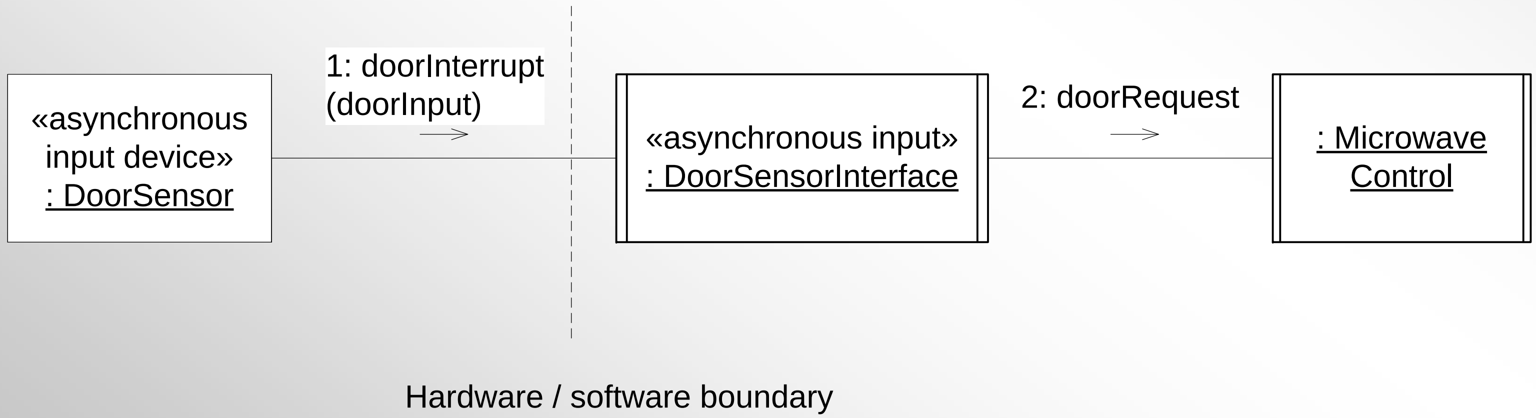
Mapping Concurrent Software Architecture to Colored Petri Nets

- CPN behavioral design template designed for each
  - Component
  - Connector
- Colored Petri Net notation
  - Transition executes function when fired
    - Consumes colored tokens from input places
    - Produces colored tokens on output places
    - Transitions can have timing parameters

Asynchronous I/O Component

- One concurrent component for each asynchronous I/O device
- Activated by device I/O interrupt
- Reads input
- Converts to internal format
- Sends message containing data
- Waits for next interrupt

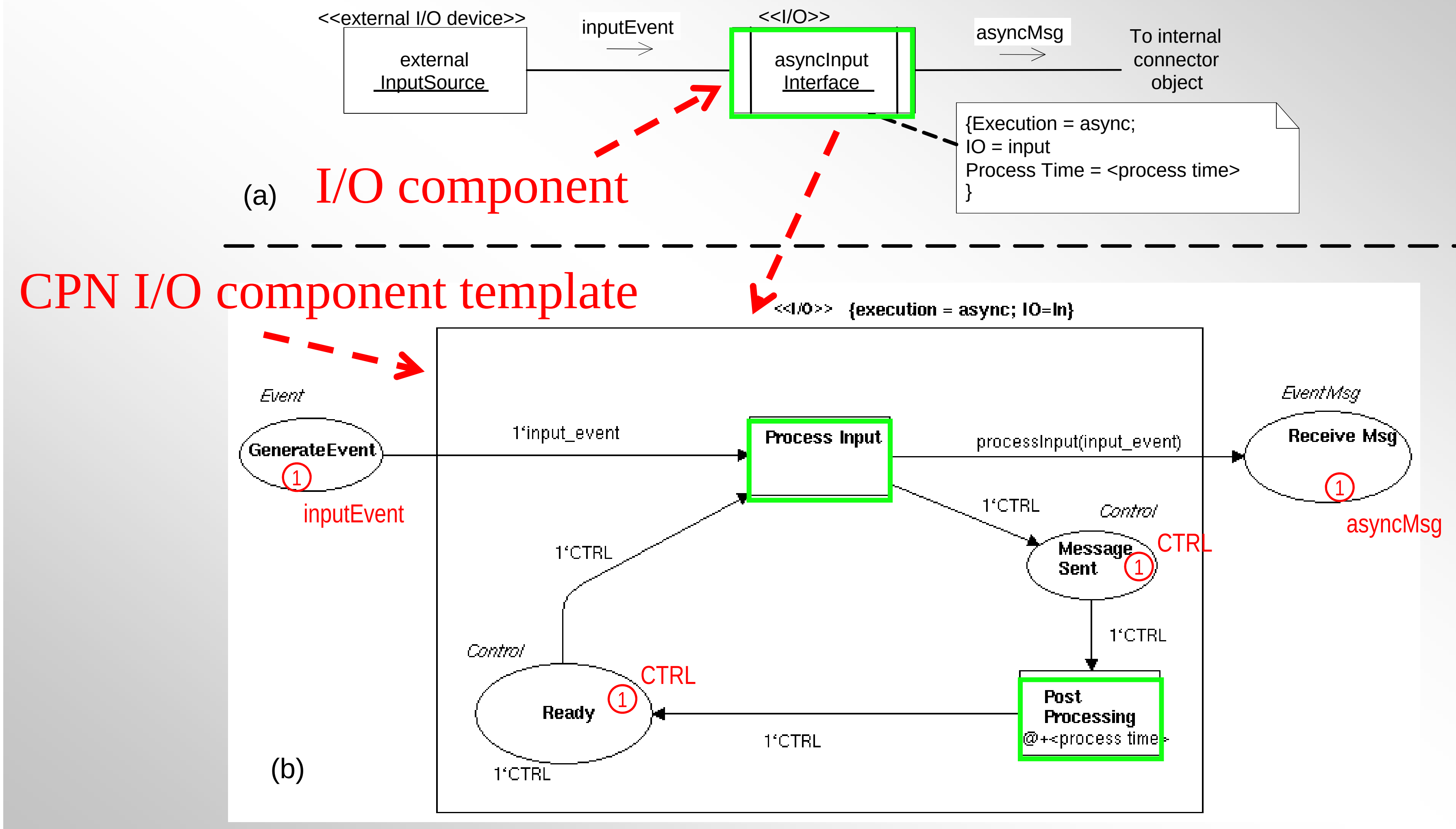
Figure 14.1b Design model – concurrent communication diagram



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

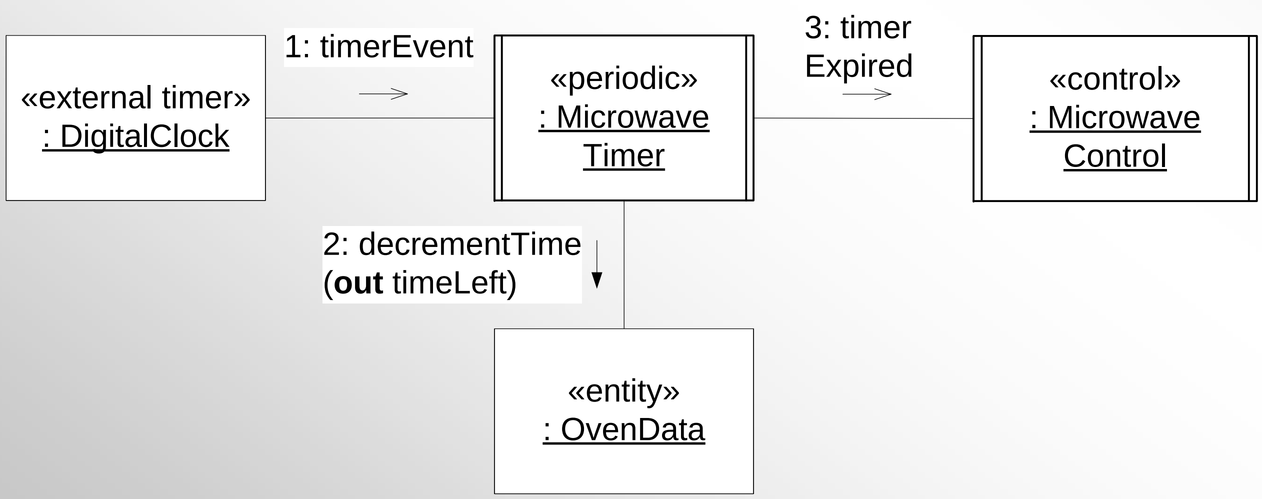
Asynchronous I/O Pattern



Periodic Algorithm Component

- Component for each periodic algorithm
- Component activated periodically
  - Activated by timer event
  - Executes algorithm
  - Waits for next timer event

Figure 14.5b Design model – concurrent communication diagram

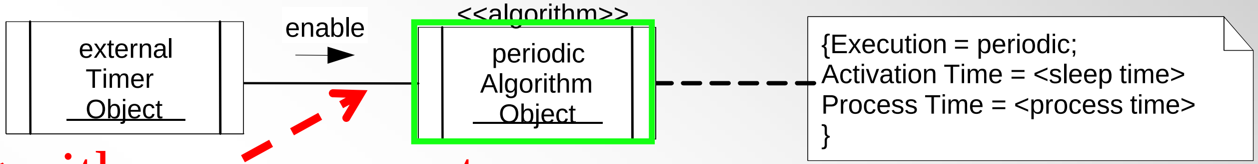


Periodic Algorithm Pattern

- Algorithm component
  - Encapsulate application logic
    - Modeled by transition
  - Execute asynchronously or periodically
- Periodic behavior modeled by
  - Sleep – Wakeup – Ready – Timeout cycle

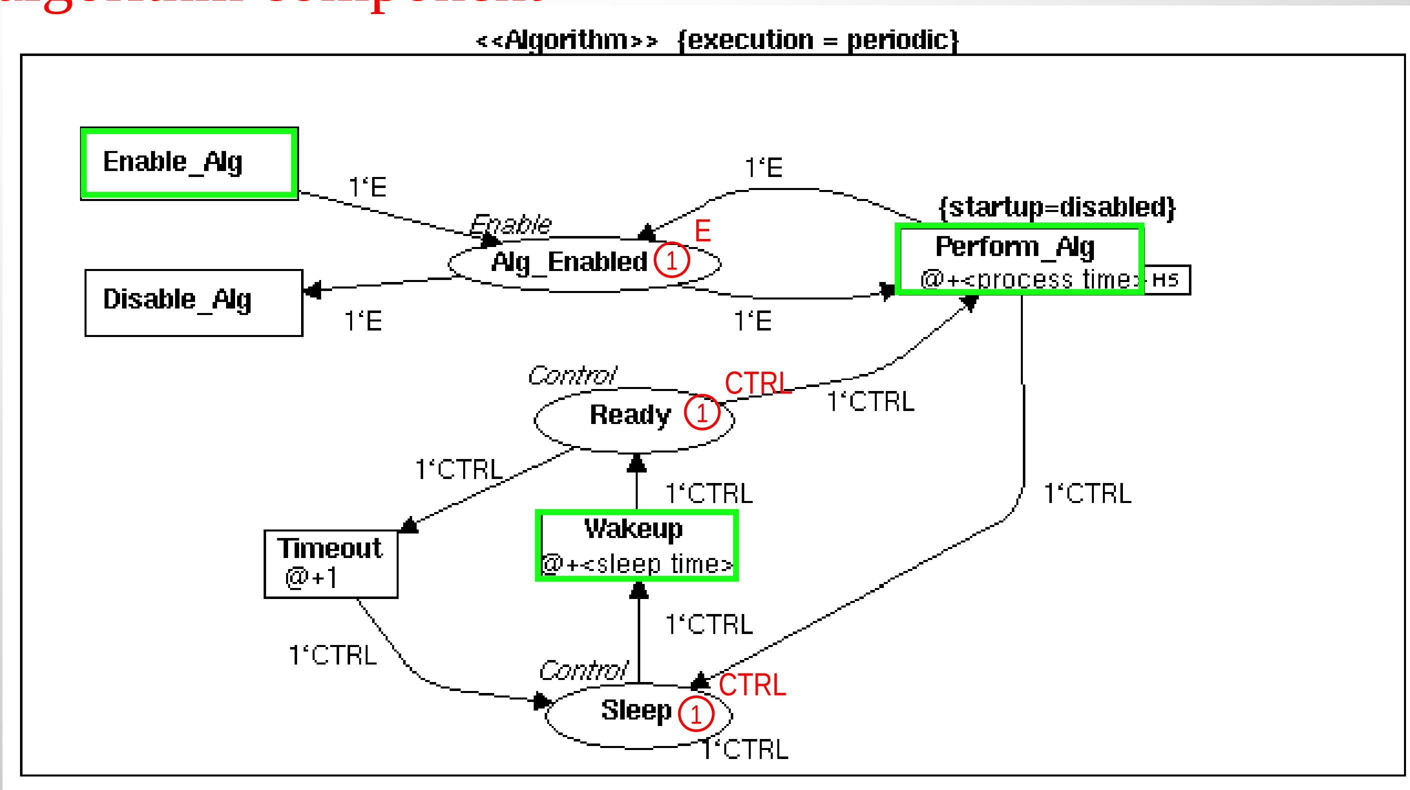
Periodic Algorithm Pattern

(a)



algorithm component

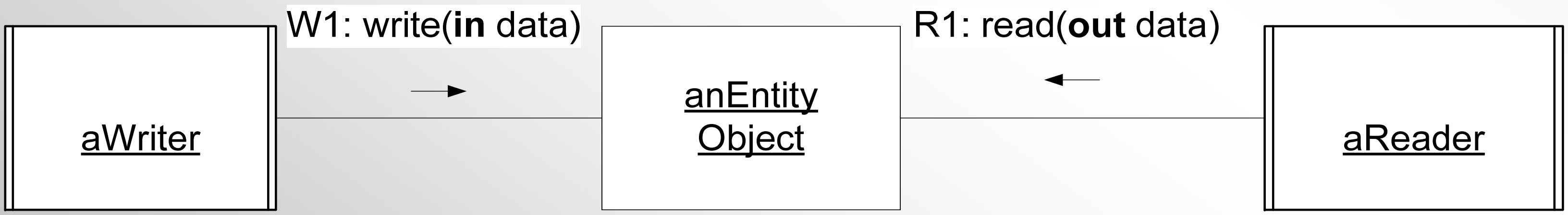
(b)



CPN algorithm template

Entity Object

- Entity object is a passive object
  - Encapsulates data
  - Hides contents of data structure
  - Data accessed indirectly via operations
- Passive object accessed by two or more components
  - Operations must synchronize access to data
    - E.g., by mutual exclusion
  - Use semaphore or monitor object

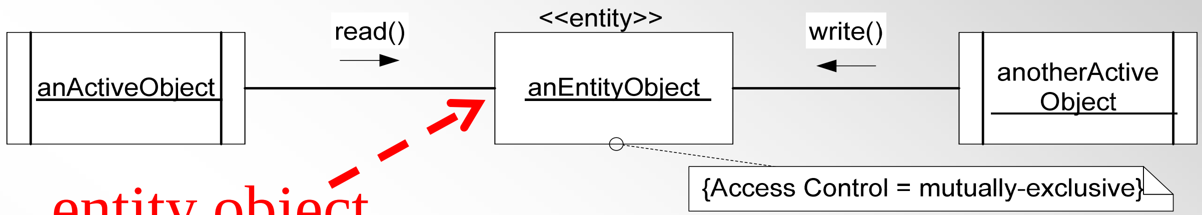


Entity Object Pattern

- Entity objects are passive
  - Encapsulate data
  - No thread of control
    - > No control token
  - Interfaces are through places rather than transitions
    - Facilitates connection to concurrent objects
  - Interfaces represent access operations
    - Operation behavior modeled with transition
    - Execution uses caller's control token

Entity Object Pattern

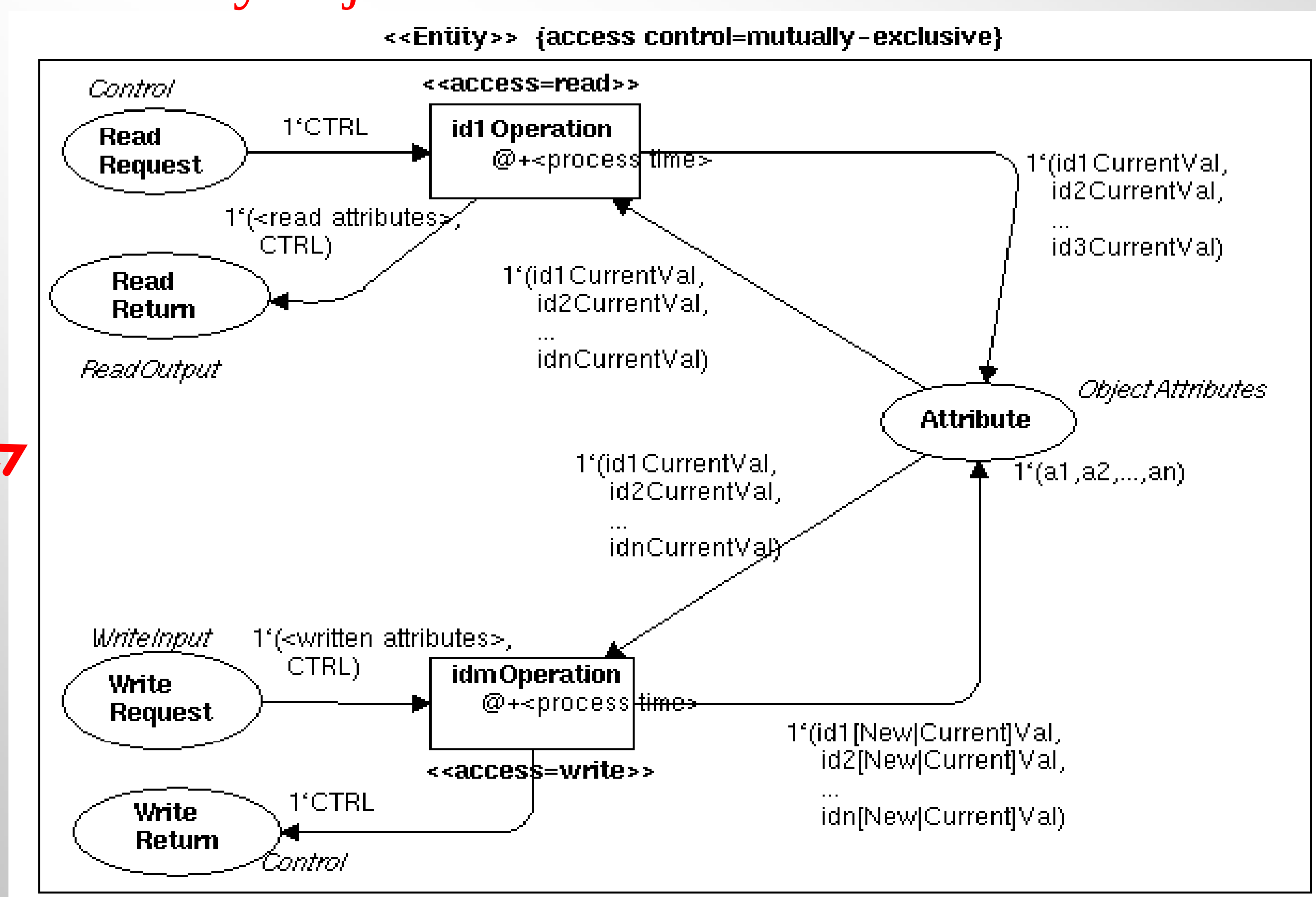
(a)



entity object

CPN entity template

(b)

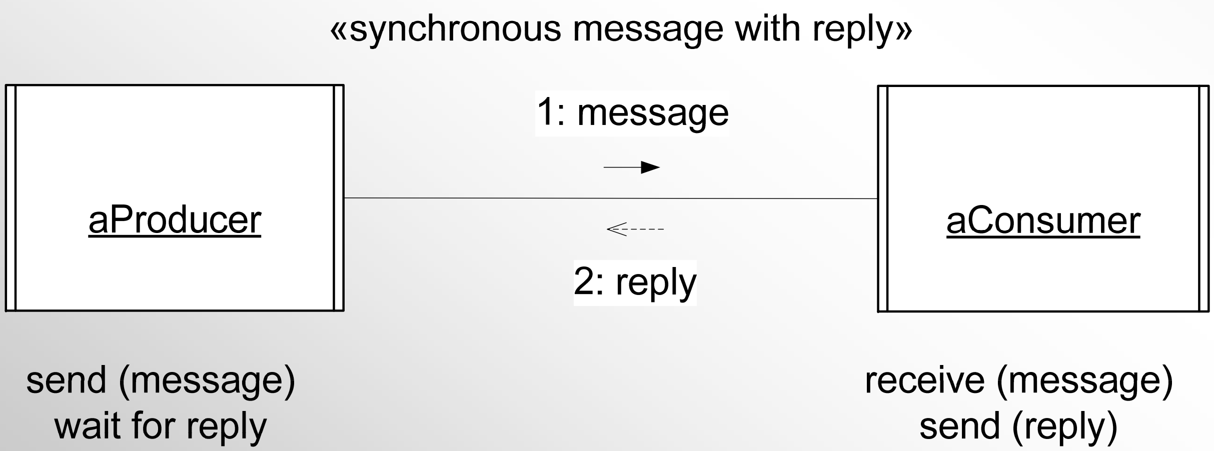


Connectors

- 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 Message Communication With Reply

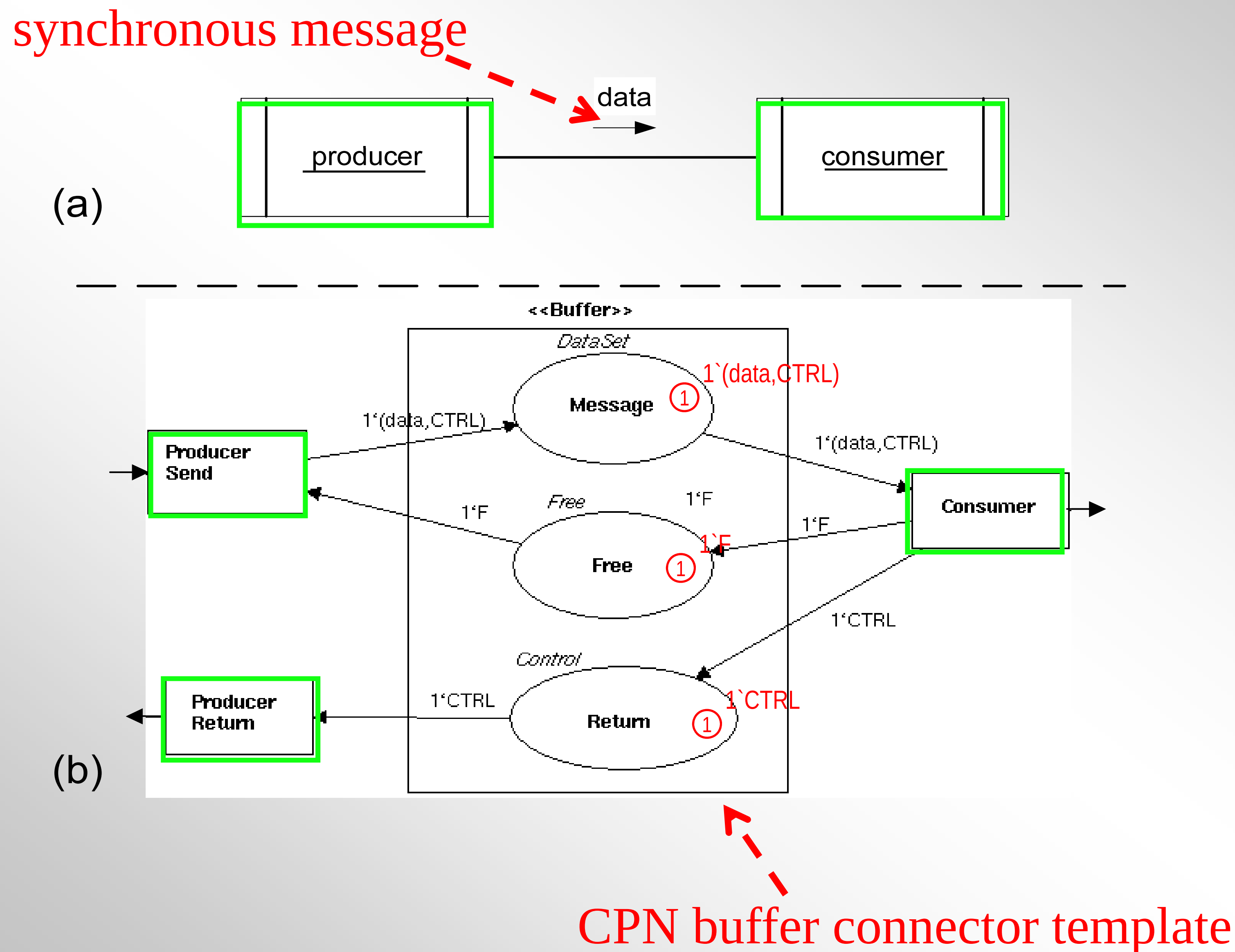
- Producer sends message and waits for reply
- Consumer receives message
  - Suspended if no message is present
  - Activated when message arrives
  - Generates and sends reply
- Producer and Consumer continue



Synchronous Communication Pattern

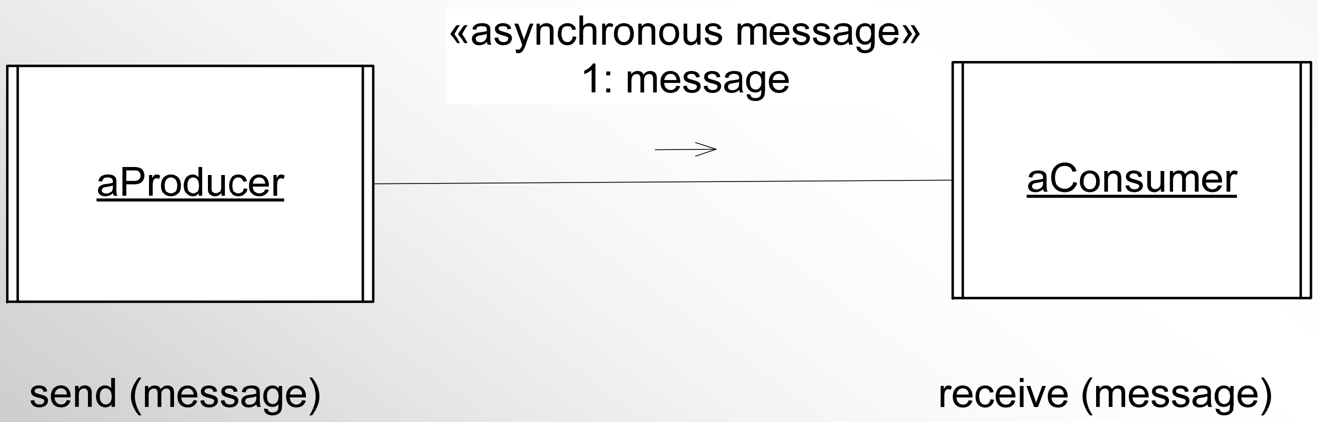
- Synchronous buffer models synchronous communication
- Producer sends message and waits for reply
- One message at a time allowed in the buffer
- Producer and consumer are blocked until message has been passed

Synchronous Communication Pattern



Asynchronous Message Communication

- Producer sends message and continues
- Consumer receives message
  - Suspended if no message is present
  - Activated when message arrives
- Message queue may build up at Consumer



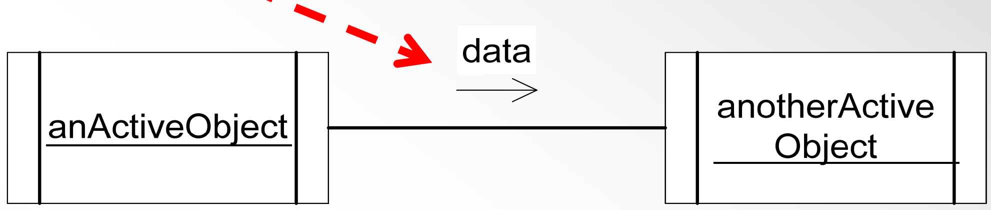
Asynchronous Message Communication (Queue) Pattern

- Asynchronous communication
  – Modeled using FIFO message queue
- Producer is not blocked during the communication
- Consumer is only blocked if no messages in queue

Asynchronous Message Communication (Queue) Pattern

asynchronous message

(a)



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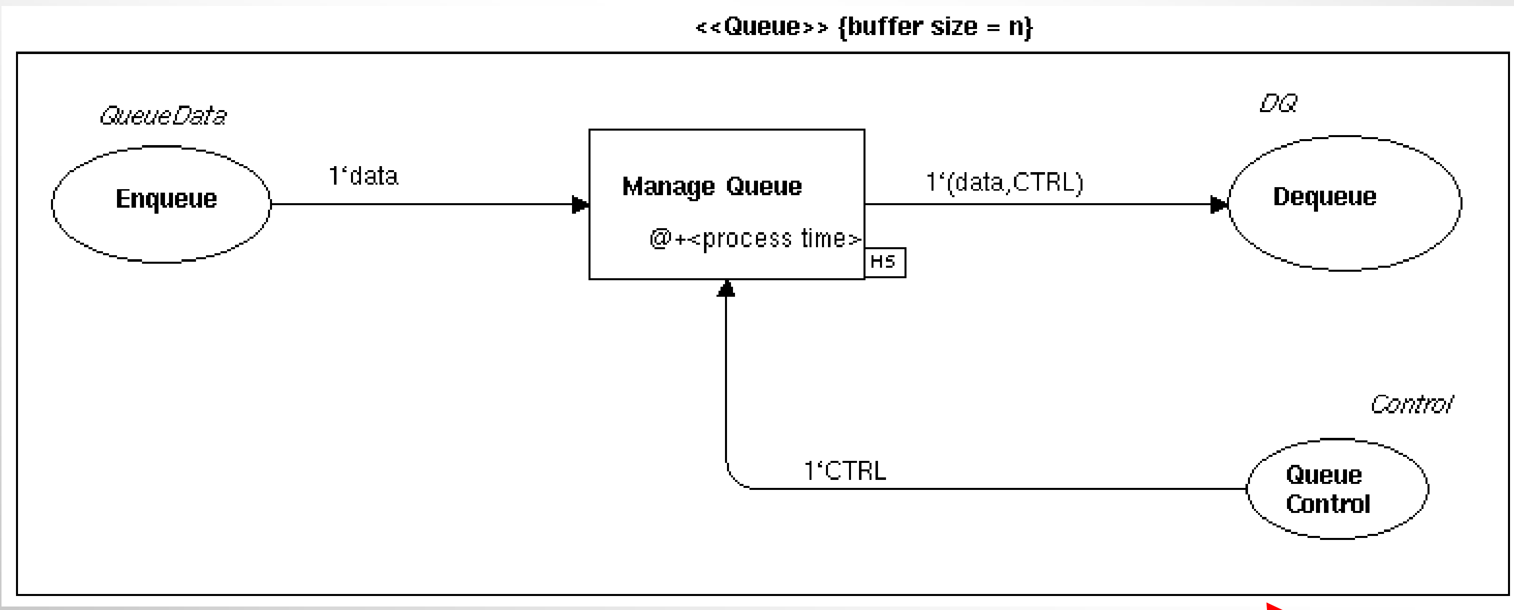
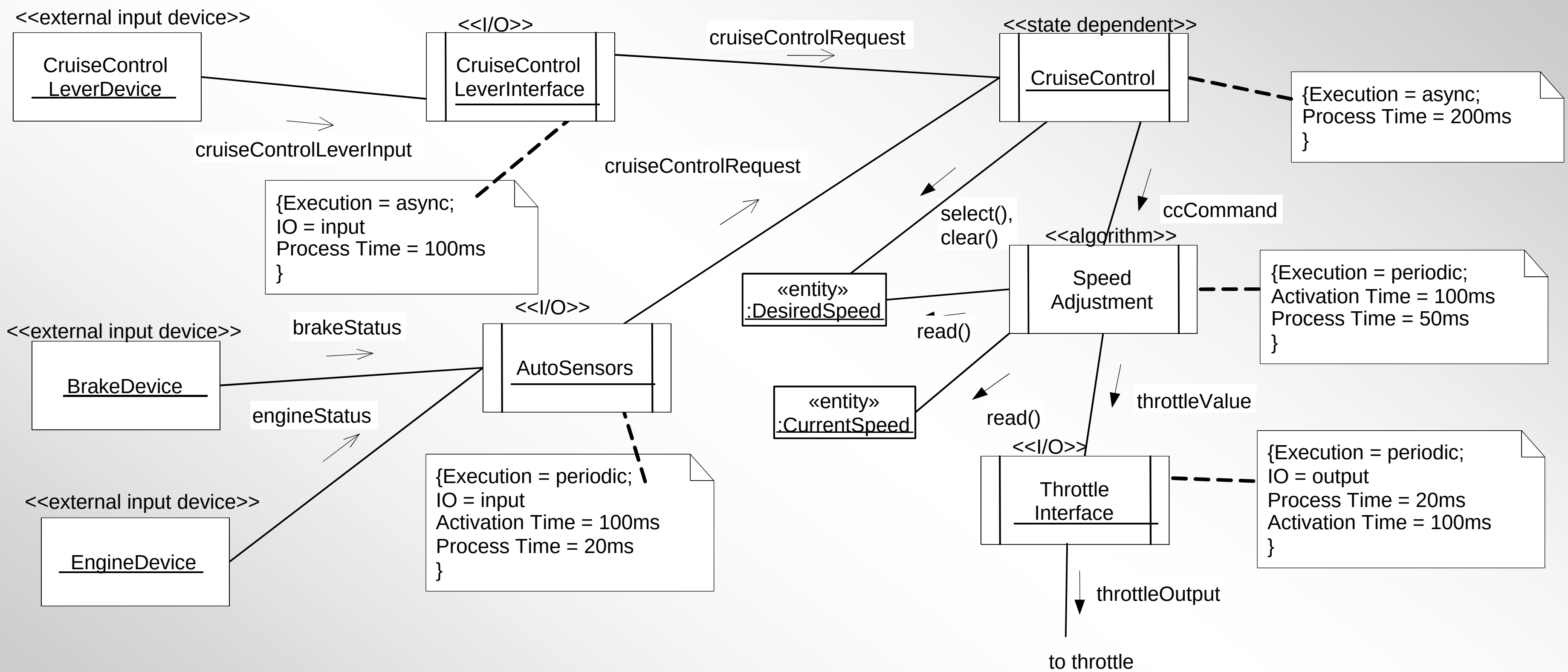


CPN queue template

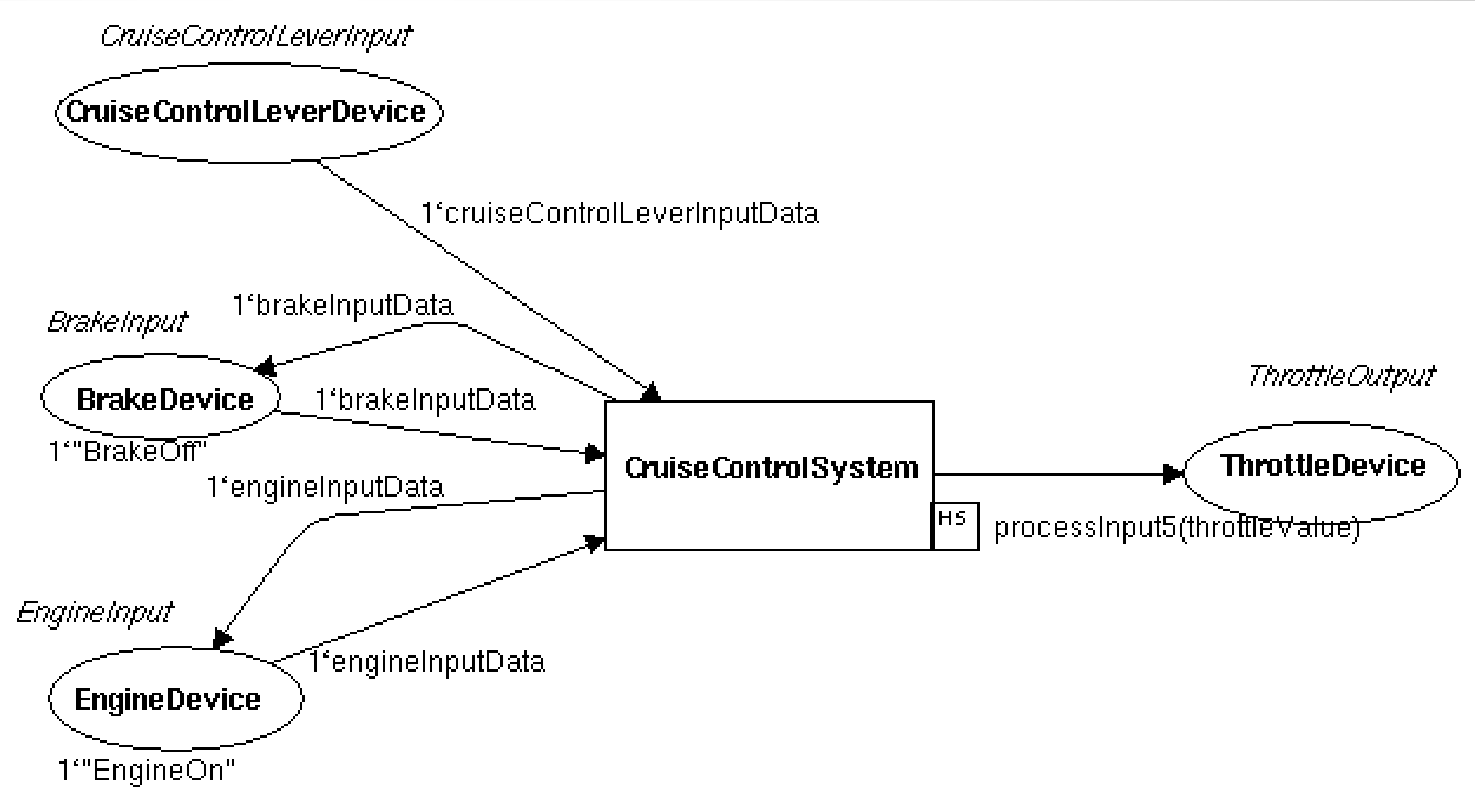
Constructing CPN Model from Concurrent Design Model

1. Develop COMET 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?

Example – Cruise Control Architecture



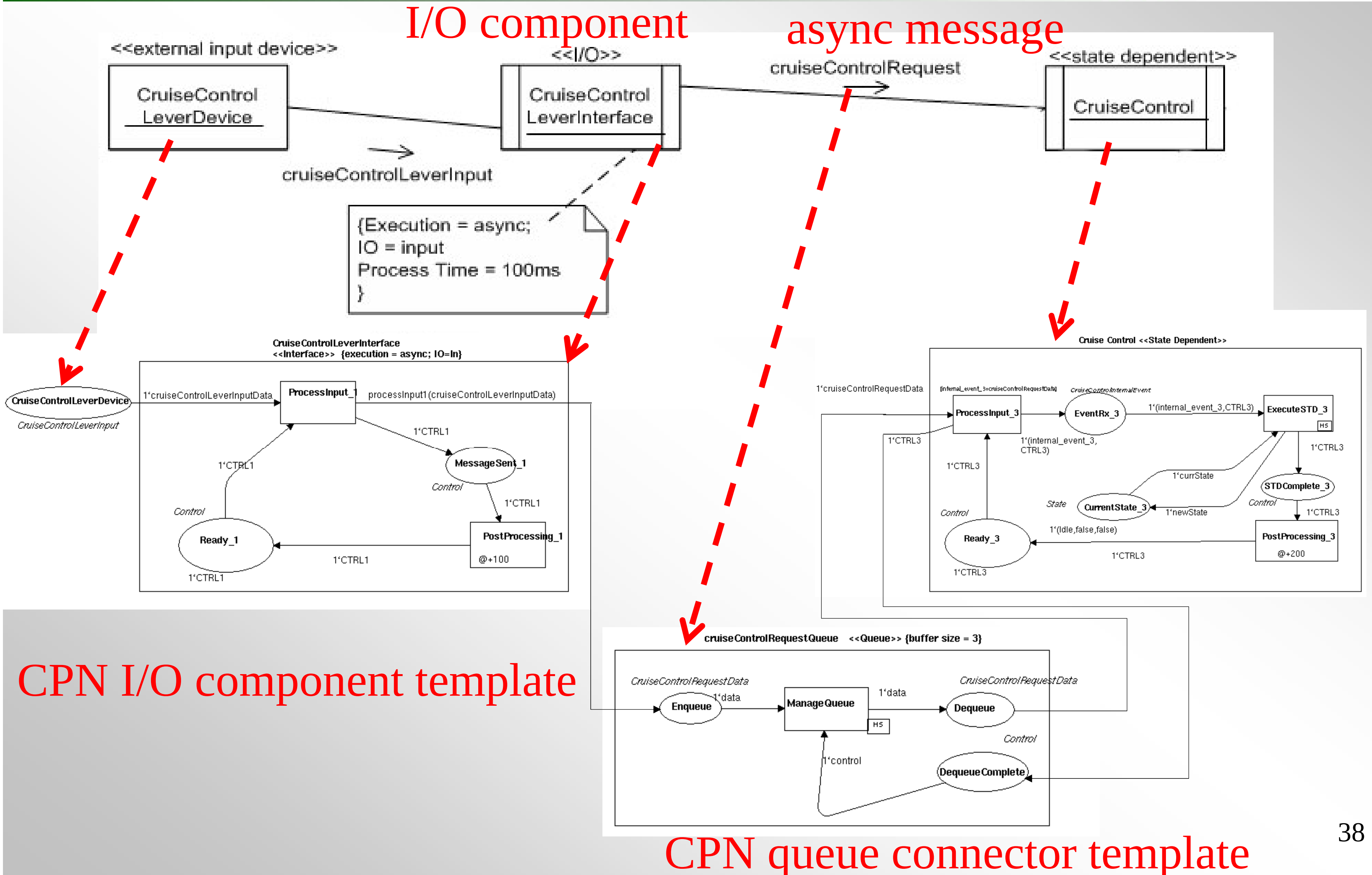
1. Applying CPN Templates – Context Model



2. Construct CPN Architecture Model

- Interconnect CPN templates
  – Decompose context-level CPN model into architecture-level model
  – Each component and connector mapped to CPN template
- CPN Interfaces for components and connectors
  – Concurrent object CPN templates use transitions
  – Passive & connector object templates use places
  – Concurrent object templates are connected to passive / connector object templates
    - Maintains CPN place-transition connection rules

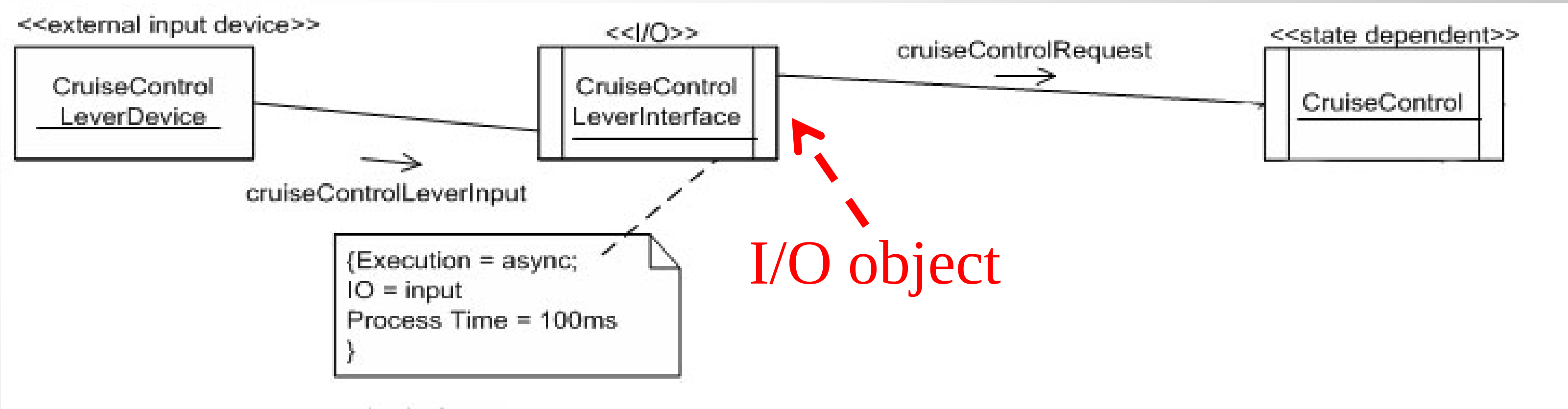
Connecting CPN Templates to form CPN Architecture

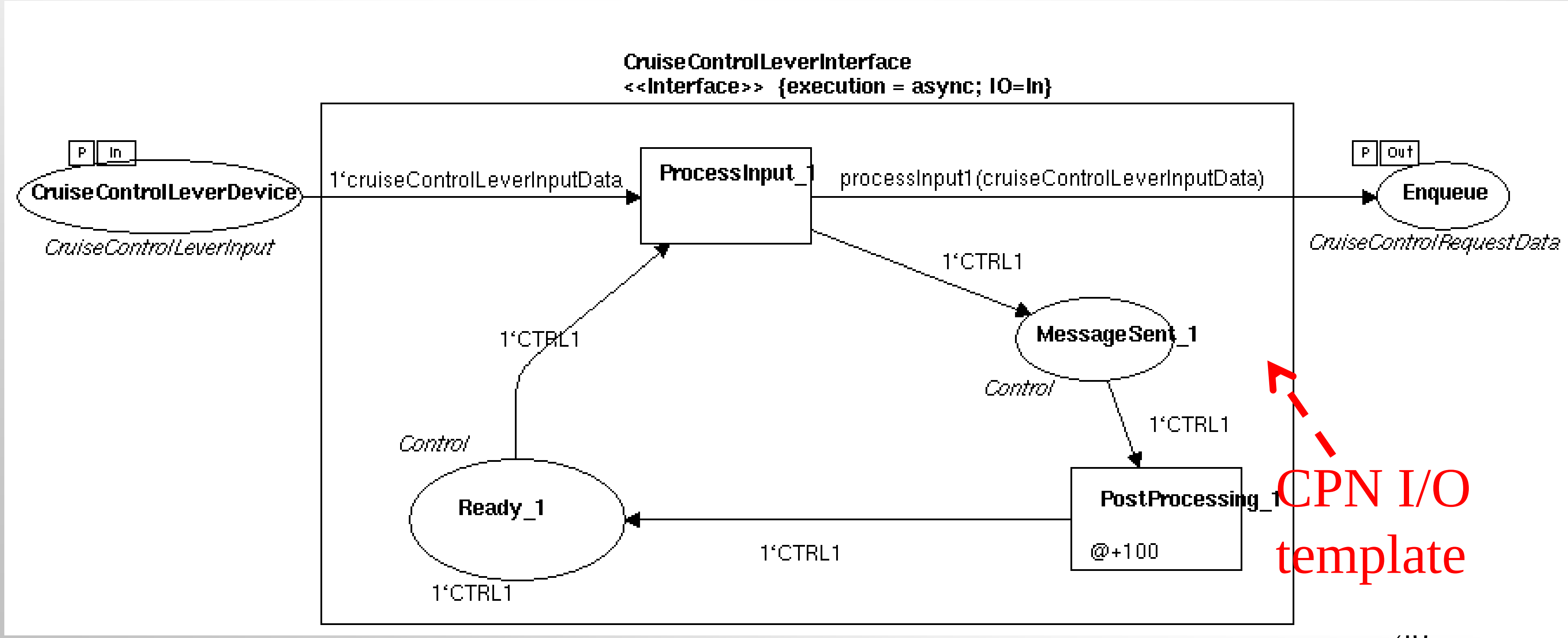


3. Modeling Individual Components

- Each CPN template must be customized to capture specific object behavior
  - Architectural parameters
    - Processing time / sleep time – set CPN timing parameters
    - Buffer size - set queue limits
  - Passive classes
    - Capture attributes and operations to be included in entity objects
    - Exclusion / Access type - capture desired mutual exclusion behavior on entities
  - Message / data specifications
    - Use to define CPN colorsets and token variables

3 Applying CPN Templates – Customizing Individual Object

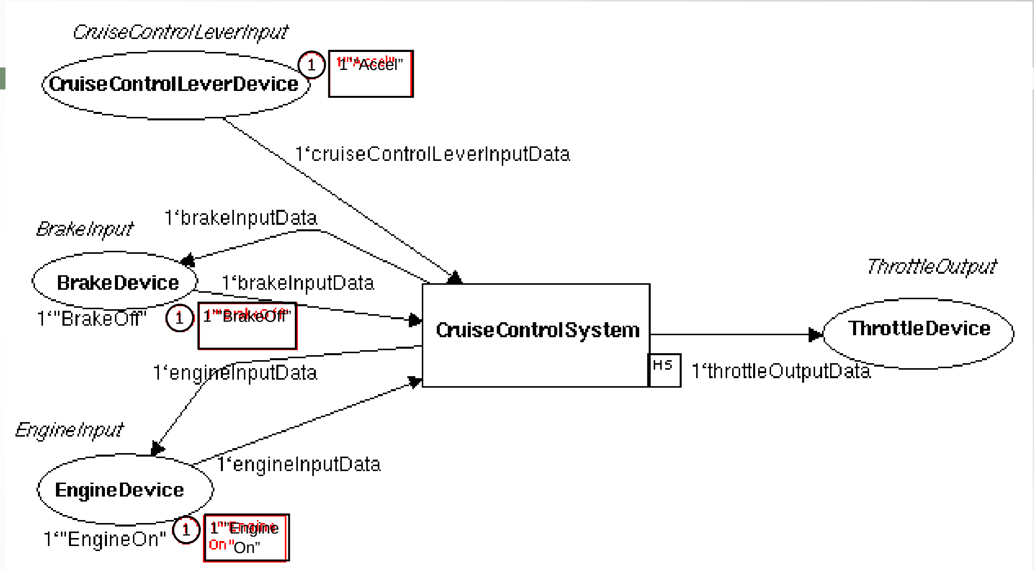




4. Analyzing Software Architecture with CPN Model

- CPN model used to execute architectural design
- Validation
  - Two detailed case studies
  - Exercised using Design CPN simulator
- Functional analysis
  - Execute test scenarios to determine if architecture outputs expected / desired results
  - Can examine architecture at varying levels of detail
- Performance analysis
  - Throughput analysis
  - Timing analysis
  - Queuing backlogs

Analyzing Software Architecture with CPN Model



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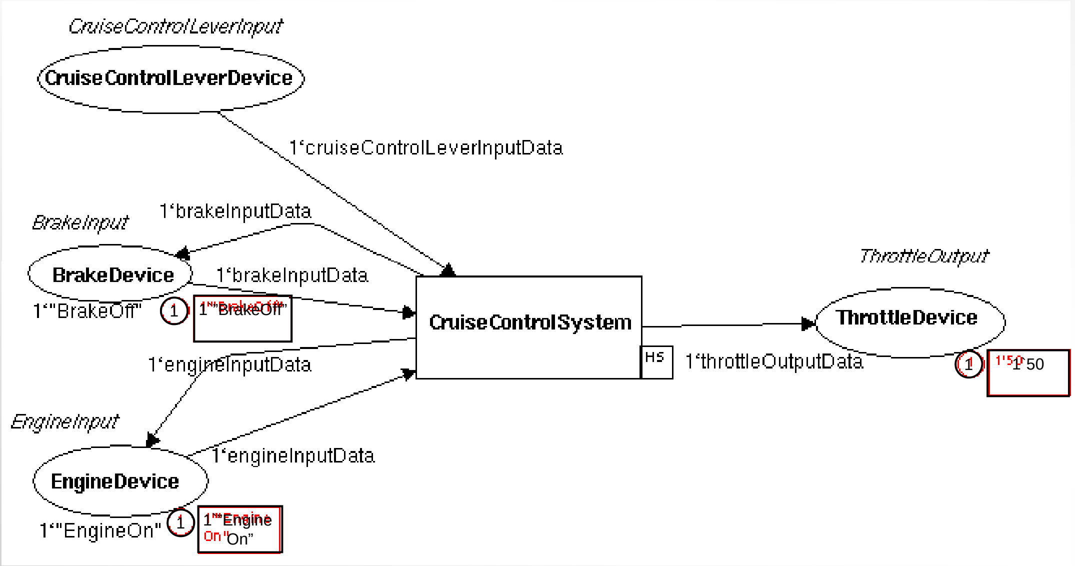
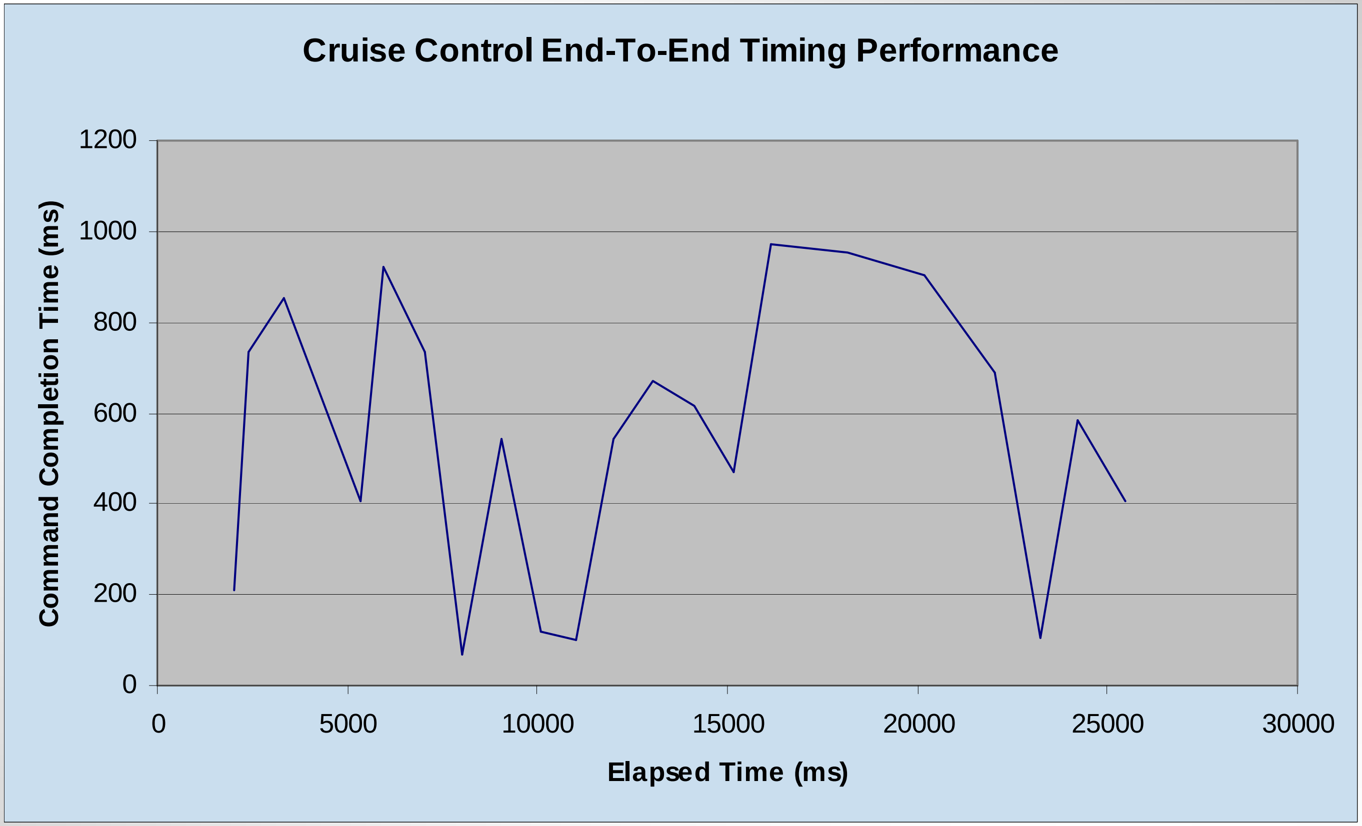


(b)

Example of Timing Analysis



Conclusions and Future Research

- Dynamic behavior of concurrent system represented using
  - CPN templates
    - Allow systematic, repeatable modeling of object behavioral patterns
    - Maintain structure and integrity of software architecture
- CPN analysis
  - Analyze concurrent behavior at design stage
  - Allows correction of fundamental design problems
- Areas for future work
  - Extend to support distributed environments
  - Investigate scalability to larger models
  - Automate translation to CPN model