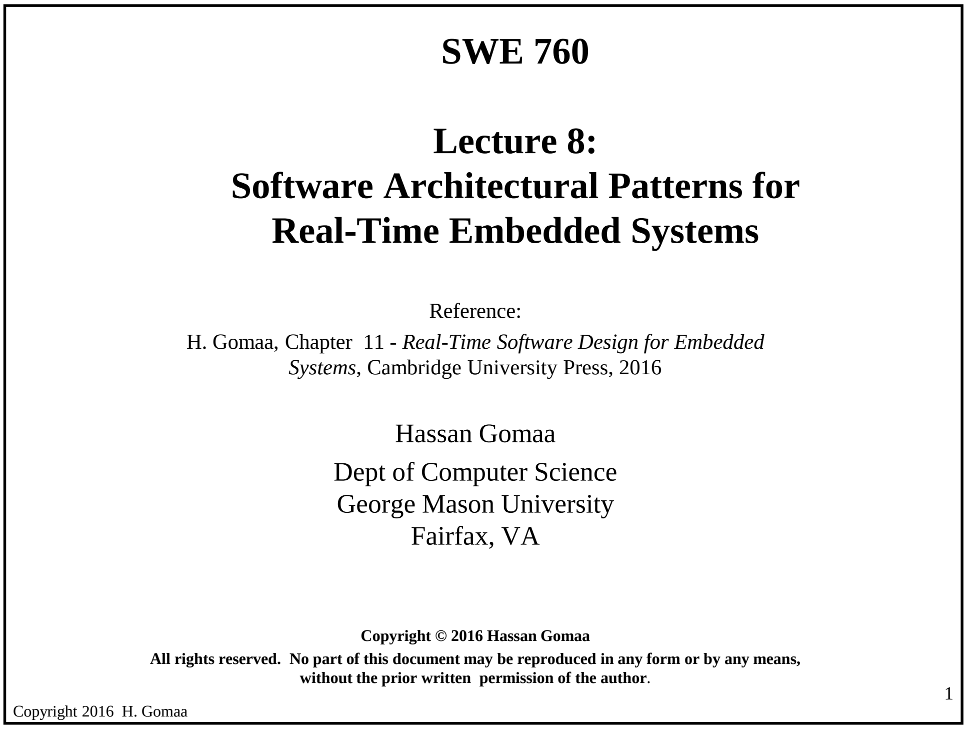

SWE 760

Lecture 8:
Software Architectural Patterns for Real-Time Embedded Systems

Reference:
H. Gomaa, Chapter 11 - *Real-Time Software Design for Embedded Systems*, Cambridge University Press, 2016

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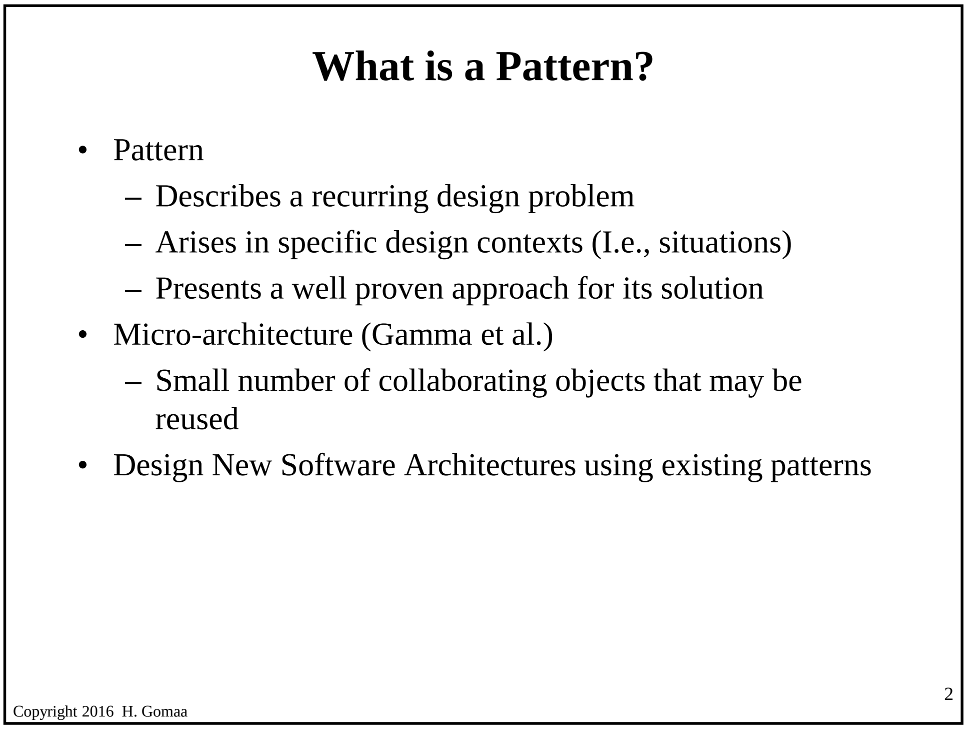


What is a Pattern?

- Pattern
  - Describes a recurring design problem
  - Arises in specific design contexts (I.e., situations)
  - Presents a well proven approach for its solution
- Micro-architecture (Gamma et al.)
  - Small number of collaborating objects that may be reused
- Design New Software Architectures using existing patterns

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

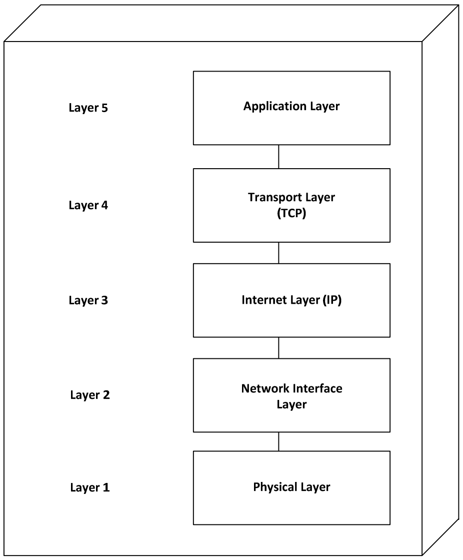
Architectural Structure Patterns

- Layered patterns
  - Layers of Abstraction
- Client/Service patterns
  - Multiple Client / Single Service
  - Multiple Client / Multiple Service
  - Multi-tier Client / Service
- Control Patterns
  - Centralized Control
  - Distributed Control
  - Hierarchical Control

Layers of Abstraction Pattern

- Structure system into hierarchical levels
- Each layer provides services for higher layers
- Layers of Abstraction in RT systems (Figs. 11.1, 11.2, 11.3)
  - Allows use of subsets and extensions
  - Lower layers do not depend on upper layers
  - Higher layers depend on lower layers
- Variations in Layers of Abstraction
  - Strict Hierarchy (Fig. 11.1)
  - Flexible Hierarchy (Fig. 11.3)
- Incorporate other patterns into Layered Pattern
  - Client/Service pattern
  - Control Patterns

Figure 11.1 Five layers of Internet (TCP/IP) reference model



Layer 5 Application Layer

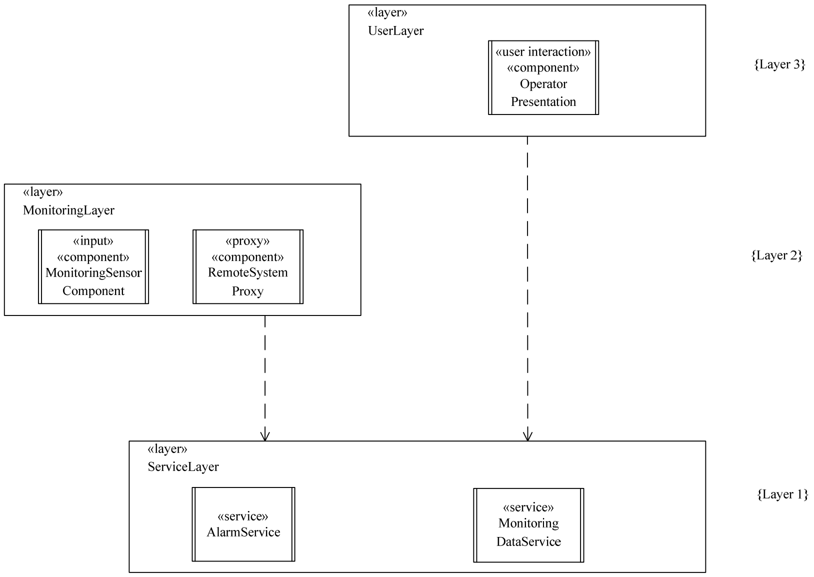
Layer 4 Transport Layer (TCP)

Layer 3 Internet Layer (IP)

Layer 2 Network Interface Layer

Layer 1 Physical Layer

Figure 11.3 Applying layered architecture pattern to Emergency Monitoring System

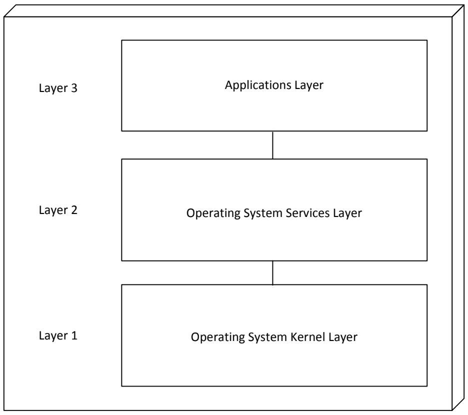


Architectural Structure Patterns

- Kernel or Microkernel (Fig. 11.4)
  - Separates minimal functional core from extended functionality and customer specific parts
  - Most commonly used in operating systems
  - Can be used as lowest layer in layered architecture pattern
- Kernel Pattern with Layered Architecture
  - Kernel of system is determined
    - Always at lowest layer of hierarchy
  - Used in many operating systems

Kernel Pattern

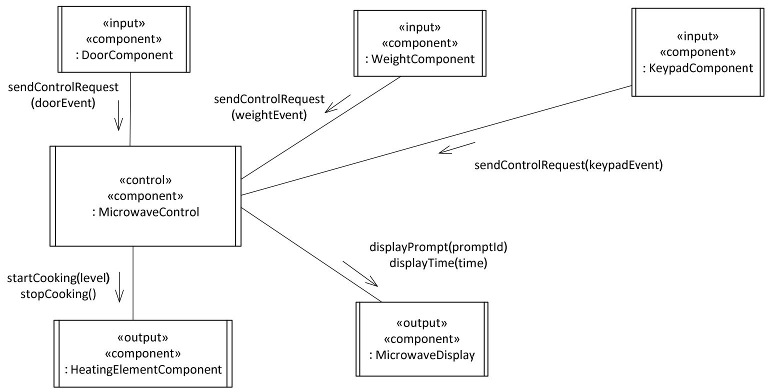
Figure 11.4 Example of kernel pattern within layered architecture


Layer 3
Applications Layer
Layer 2
Operating System Services Layer
Layer 1
Operating System Kernel Layer

Control Patterns for RT Software Architectures

- Centralized Control Pattern
  - One control component
    - Executes state machine
  - Receives sensor input from input device interface components
  - Controls external environment via output device interface components that output to actuators
  - Can use entity objects to store data that needs to be stored
- Examples
  - Cruise Control System
  - Microwave Oven Control System (Fig. 11.5)

Fig. 11.5: Centralized Control Pattern



«input»
«component»
: DoorComponent

«input»
«component»
: WeightComponent

«input»
«component»
: KeypadComponent

sendControlRequest
(doorEvent)

sendControlRequest
(weightEvent)

sendControlRequest(keypadEvent)

«control»
«component»
: MicrowaveControl

startCooking(level)
stopCooking()

displayPrompt(promptId)
displayTime(time)

«output»
«component»
: HeatingElementComponent

«output»
«component»
: MicrowaveDisplay

Variations on Centralized Control Pattern

- Centralized control with single state machine
- Centralized control with interacting state machines
- Distributed independent control with unidirectional communication to service (Fig. 11.7)

Figure 11.7 Example of the Distributed Independent Control architectural pattern with unidirectional communication to a service

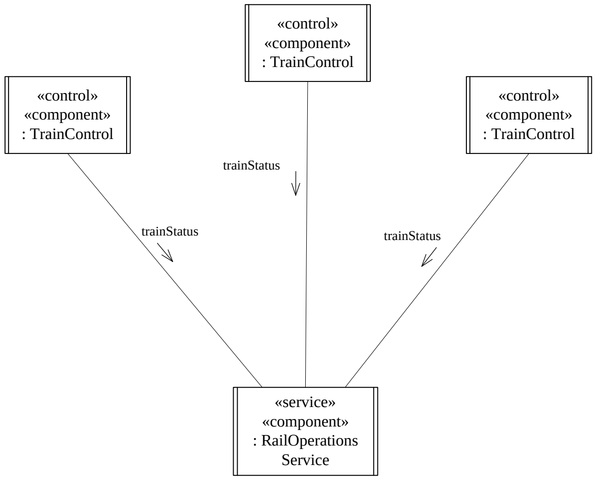


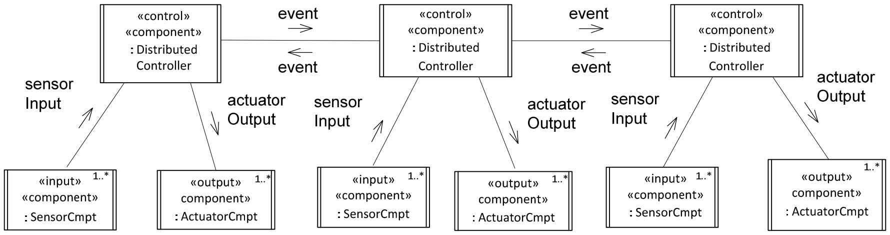
Figure 11.7 Example of the Distributed Independent Control architectural pattern with unidirectional communication to a service

Distributed Collaborative Control Pattern for RT Software Architectures

- Several control components
- Each component
  - Controls part of system
  - Executes state machine
- Control is distributed among the components
  - Components communicate with each other to provide overall control
  - Peer-to-peer asynchronous message communication
    - Communicating state machines
- Example
  - High Volume Manufacturing System

Distributed Collaborative Control Pattern

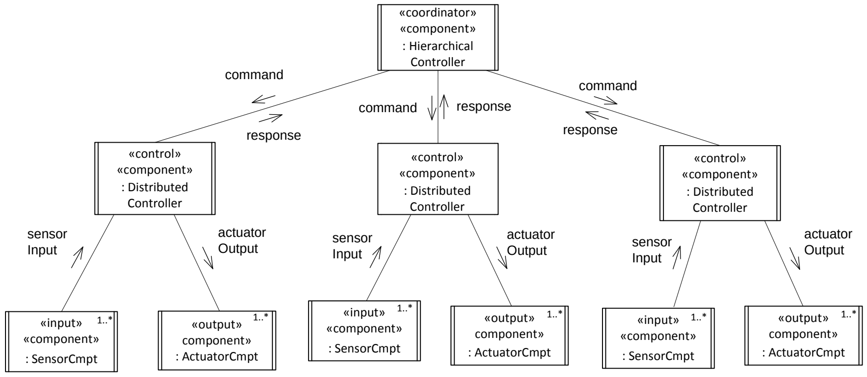
Figure 11.6 Distributed Collaborative Control Pattern



Hierarchical Control Pattern for RT Software Architectures

- Several distributed control components
- Each control component
  - Controls part of system
  - Executes state machine
- Coordinator (Hierarchical Controller) component
  - Coordinates several distributed controller components
    - Provides high level control
    - Sends commands to each control component
    - Determines next job for each control component
- Example - Figure 11.8
- Frequently used in factory automation systems

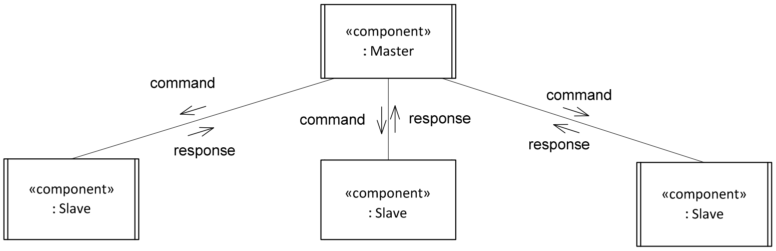
Figure 11.8 Hierarchical Control Pattern



Master-Slave Pattern

- Master sends command to Slave
- Slave sends completion acknowledgement to Master
- Master can divide a computational problem into parts
- Sends each part to a slave
- Receives responses
- Integrates responses
- Example of Master-Slave Pattern (Fig. 11.9)

Figure 11.9 Master-Slave Pattern



Client/Service Patterns

- **Client** requests services
- **Service** is provider of services for clients
- Client depends on service
- Client at higher layer than service in layered architecture
- Real-time clients can use service
  - During initialization
  - Update real-time status
- Variations:
  - Single Client / Multiple Service (Fig. 11.11)
  - Multiple Client / Multiple Service (Fig. 11.13)
    - Clients communicate with multiple services

Figure 11.11 Example of Multiple Client / Single Service Pattern

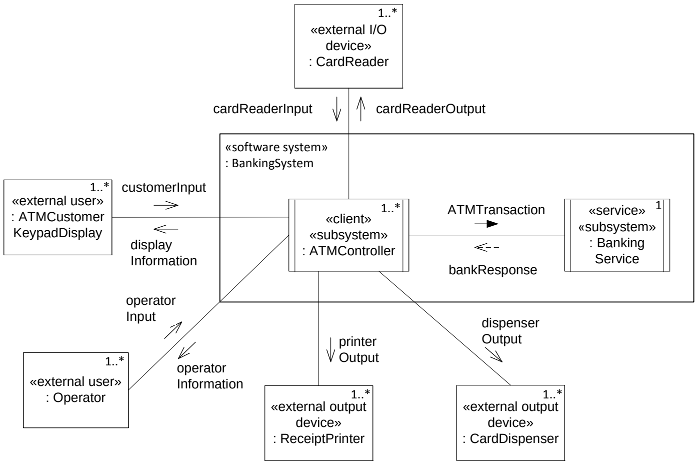
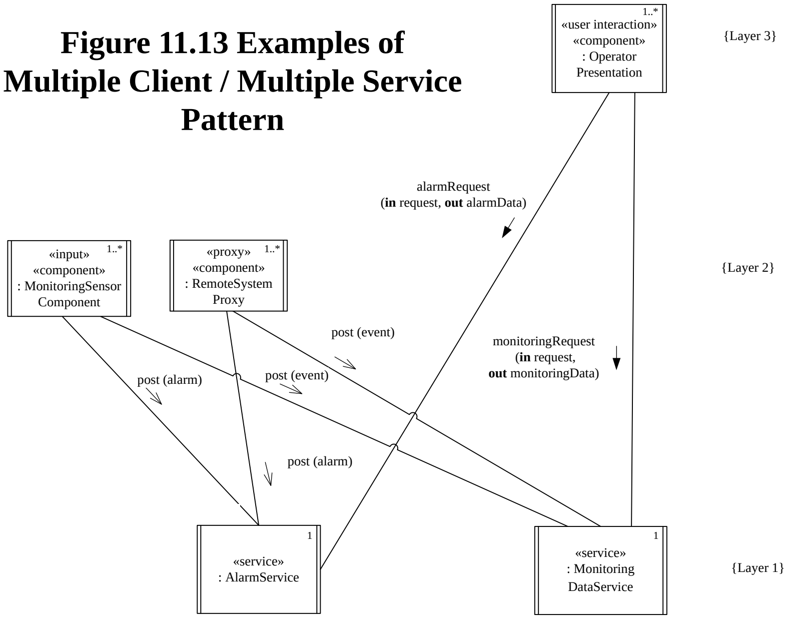


Figure 10.12 Example of client and service subsystems in Emergency Monitoring System

Figure 11.13 Examples of Multiple Client / Multiple Service Pattern



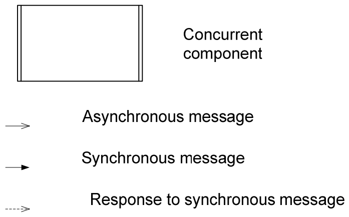
Architectural Communication Patterns

- Asynchronous communication patterns
- Synchronous communication patterns

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

- Group Communication Patterns
  - Broadcast
  - Subscription/notification

- Broker and group communication patterns
  - Facilitate software evolution and adaptation

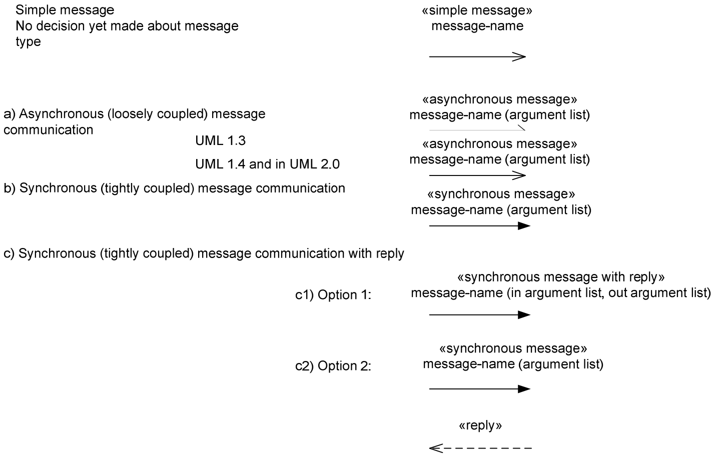

Concurrent component

Asynchronous message

Synchronous message

Response to synchronous message

UML notation for messages


Simple message
No decision yet made about message type

«simple message»
message-name

a) Asynchronous (loosely coupled) message communication

UML 1.3

«asynchronous message»
message-name (argument list)

UML 1.4 and in UML 2.0

«asynchronous message»
message-name (argument list)

b) Synchronous (tightly coupled) message communication

«synchronous message»
message-name (argument list)

c) Synchronous (tightly coupled) message communication with reply

c1) Option 1:

«synchronous message with reply»
message-name (in argument list, out argument list)

c2) Option 2:

«synchronous message»
message-name (argument list)

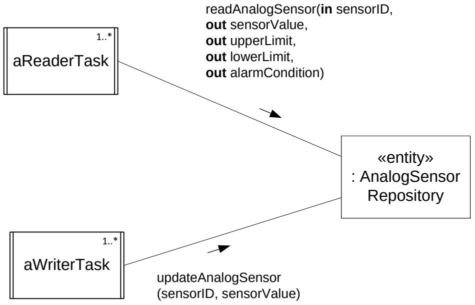
«reply»

Synchronized Call/Return Pattern

- Synchronization of Tasks Interacting via Passive Objects
- Task interaction via shared data
  - Needs synchronization
- Task interaction via passive data abstraction object
  - Hides structure of data repository
  - Hides synchronization from tasks
    - Mutual exclusion
    - Multiple readers / multiple writers

Synchronized Call/Return Pattern

Figure 11.14 Example of Synchronized Call/Return Pattern



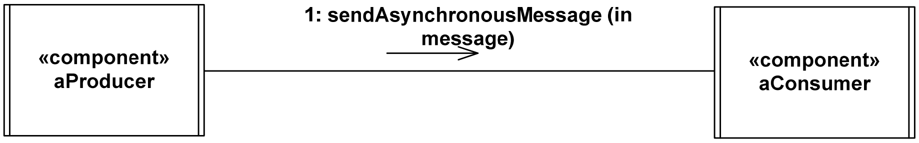
readAnalogSensor(**in** sensorID,
out sensorValue,
out upperLimit,
out lowerLimit,
out alarmCondition)

updateAnalogSensor
(sensorID, sensorValue)

Asynchronous Message Communication Pattern

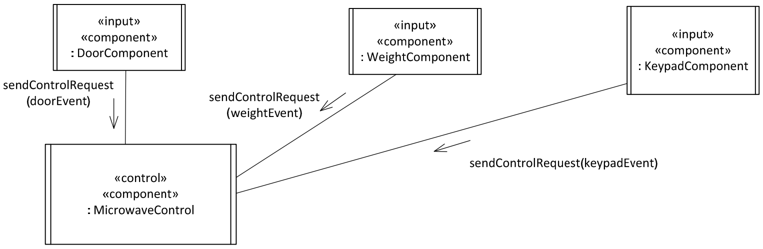
- Producer sends message and continues
  - Consumer receives message
    - Suspended if no message is present
    - Activated when message arrives
  - Message queue may build up at Consumer

Figure 11.15 Asynchronous message communication pattern



Many-to-one Asynchronous Communication (Fig. 11.16)

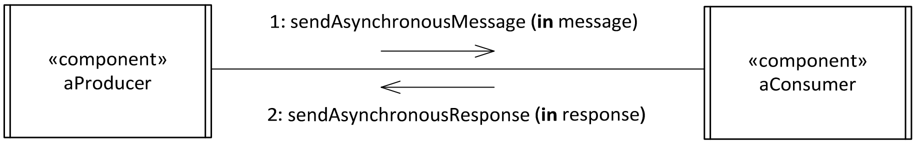
- Several producers send messages to one consumer
- FIFO queue at consumer



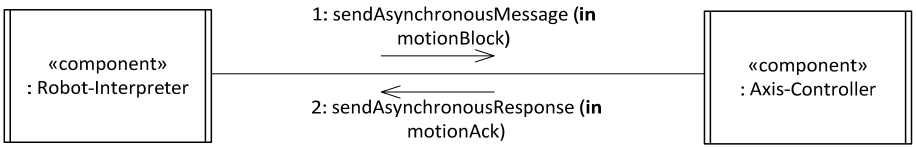
Bi-directional Asynchronous Communication Pattern

- Producer sends asynchronous message and continues
- Consumer receives message
- Consumer generates and sends asynchronous response
- Message queue can build up at Consumer
- Response queue can build up at Producer

Bi-directional Asynchronous message communication pattern (Figure 11.17)


«component»
aProducer
1: sendAsynchronousMessage (**in** message)
2: sendAsynchronousResponse (**in** response)
«component»
aConsumer

Example of Bidirectional asynchronous message communication pattern


«component»
: Robot-Interpreter
1: sendAsynchronousMessage (**in** motionBlock)
2: sendAsynchronousResponse (**in** motionAck)
«component»
: Axis-Controller

Synchronous Message Communication with Reply Pattern (Client/Service Scenario)

- Service
  - Responds to message requests from several clients
- Client
  - Sends message to Service and Waits for response
- Remote Procedure Call
  - Client makes RPC to service on different node
  - Communication details hidden from client & service
- Remote method invocation (RMI)
  - Client object sends message to service object

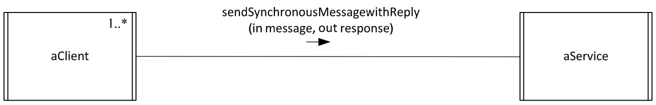
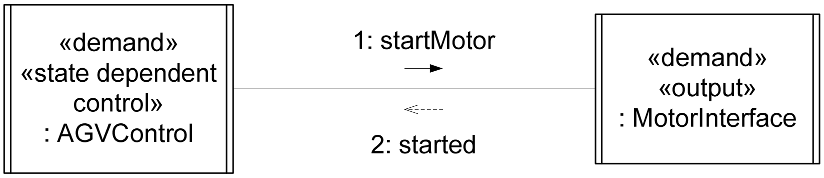


Figure 11.19 Synchronous message communication with reply

Synchronous Message Communication With Reply Pattern (Producer/Consumer Scenario)

- Producer task 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



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Asynchronous communication with Callback Pattern

- RT software architecture
  - Asynchronous message communication often preferred
- Send message and receiver response
  - Without delaying Producer
- Asynchronous communication with Callback
  - Producer
    - Sends message and callback handle (return address) to Consumer
  - Consumer
    - Sends response using callback handle

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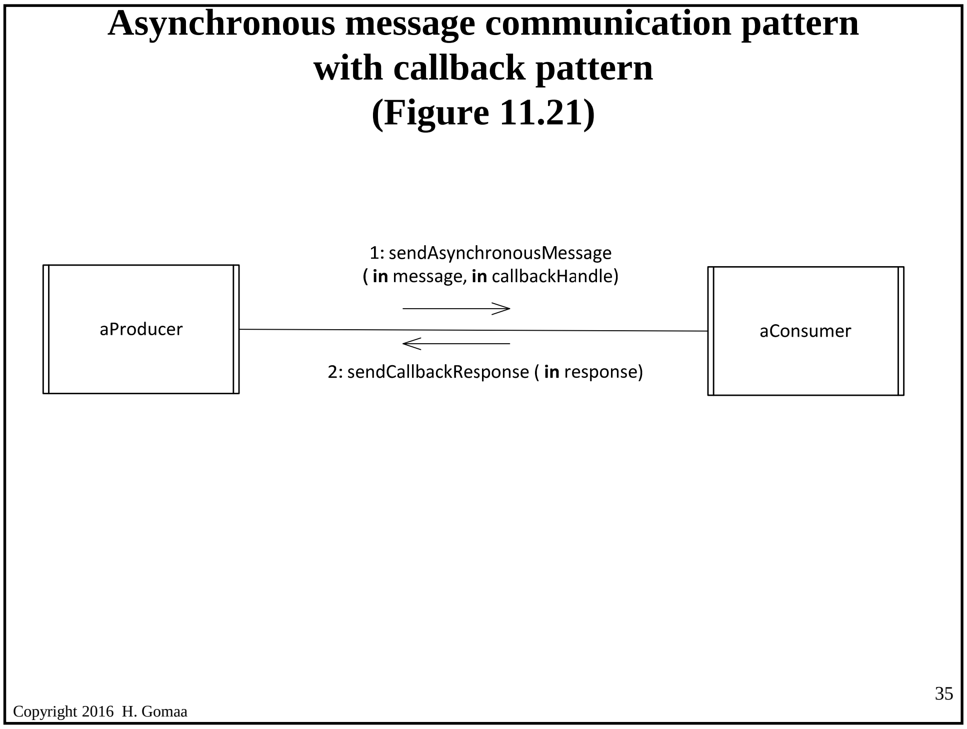


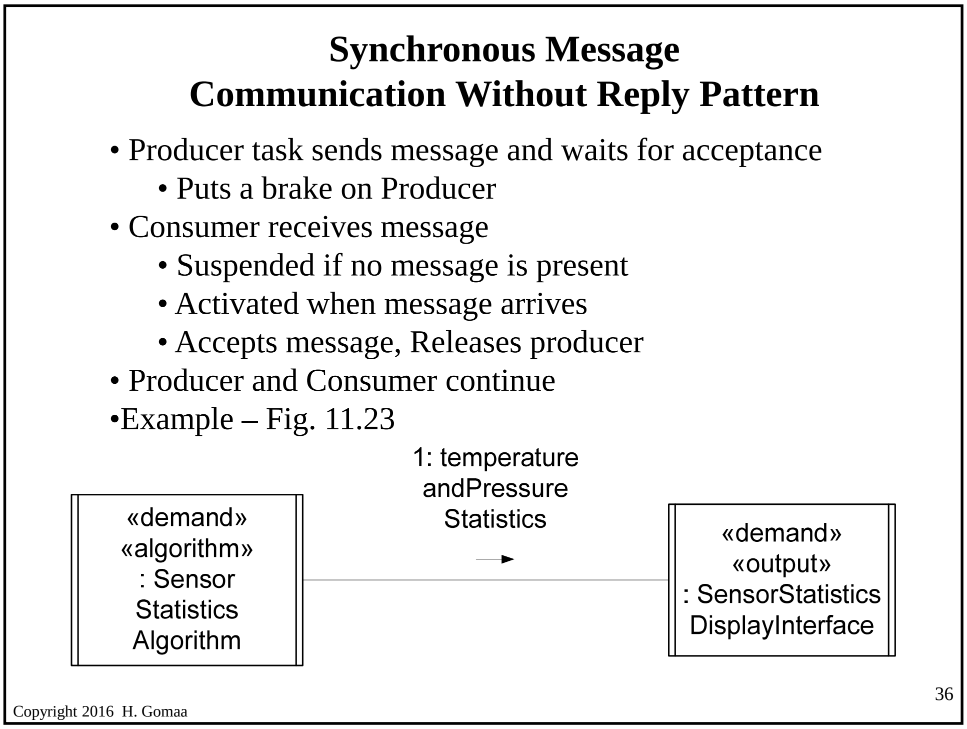
Asynchronous message communication pattern with callback pattern (Figure 11.21)

aProducer

1: sendAsynchronousMessage
(**in** message, **in** callbackHandle)

2: sendCallbackResponse (**in** response)

aConsumer



Synchronous Message Communication Without Reply Pattern

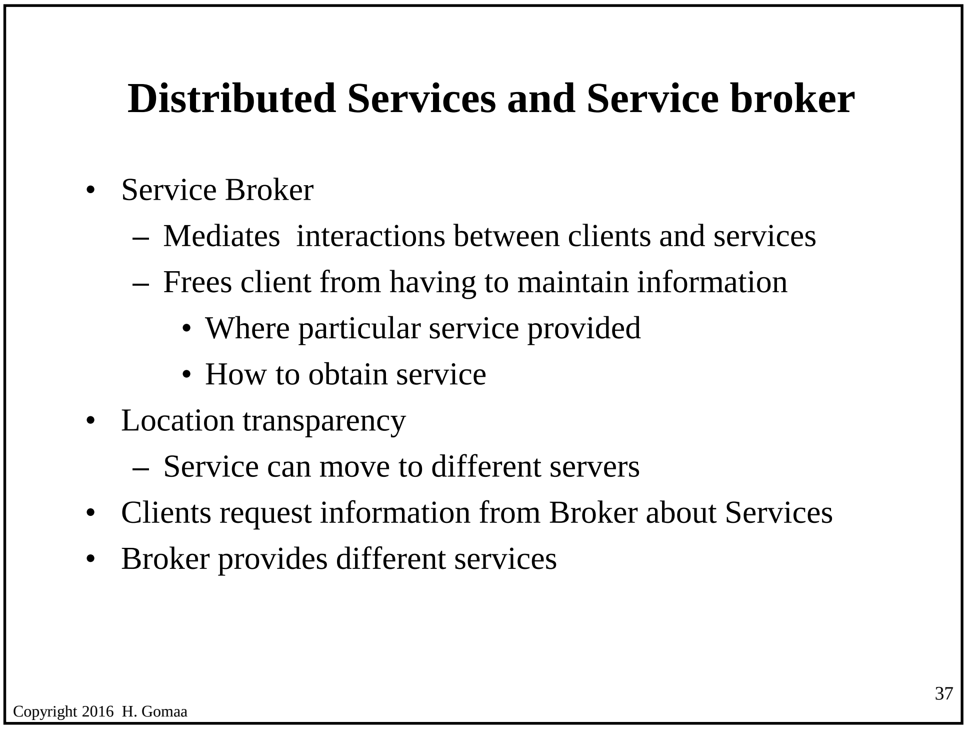
- Producer task sends message and waits for acceptance
  - Puts a brake on Producer
- Consumer receives message
  - Suspended if no message is present
  - Activated when message arrives
  - Accepts message, Releases producer
- Producer and Consumer continue

•Example – Fig. 11.23

«demand»
«algorithm»
: Sensor
Statistics
Algorithm

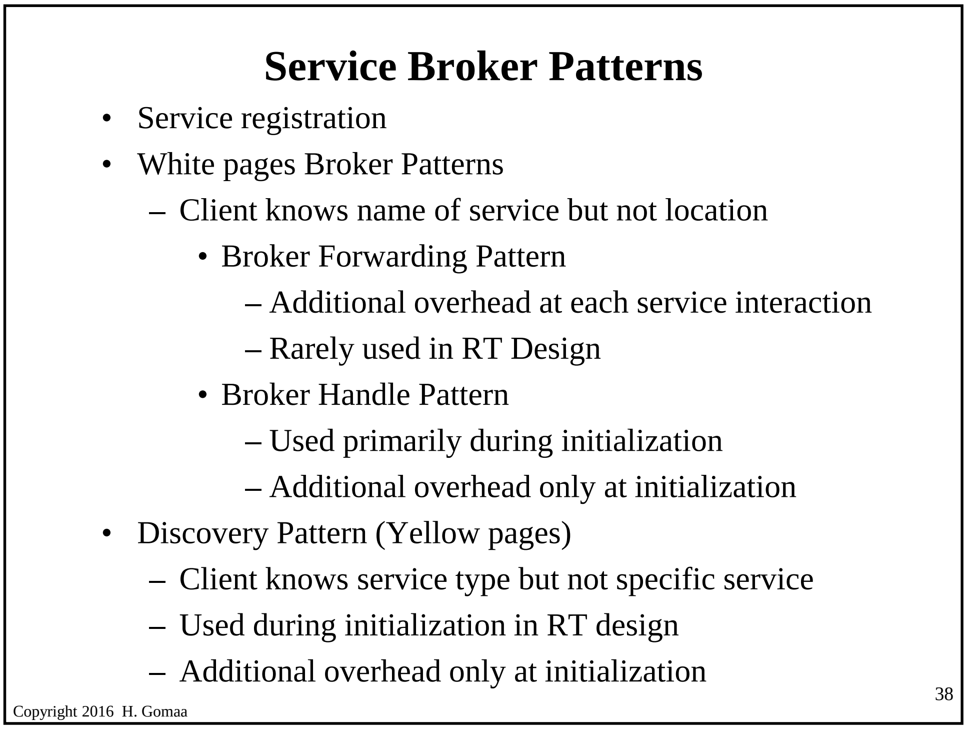
1: temperature
andPressure
Statistics

«demand»
«output»
: SensorStatistics
DisplayInterface



Distributed Services and Service broker

- Service Broker
  - Mediates interactions between clients and services
  - Frees client from having to maintain information
    - Where particular service provided
    - How to obtain service
- Location transparency
  - Service can move to different servers
- Clients request information from Broker about Services
- Broker provides different services



Service Broker Patterns

- Service registration
- White pages Broker Patterns
  - Client knows name of service but not location
    - Broker Forwarding Pattern
      - Additional overhead at each service interaction
      - Rarely used in RT Design
    - Broker Handle Pattern
      - Used primarily during initialization
      - Additional overhead only at initialization
- Discovery Pattern (Yellow pages)
  - Client knows service type but not specific service
  - Used during initialization in RT design
  - Additional overhead only at initialization

Figure 11.24 Service registration with Broker

- Services registers service information with Broker
  - Service name
  - Service interface
  - Service description
  - Location
- Service re-registers after moving to different location

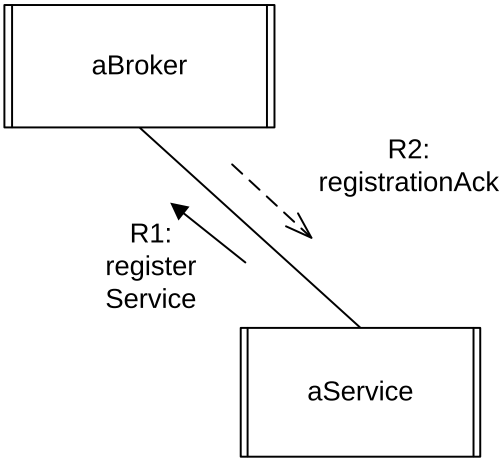


Figure 11.25: Broker Handle (White pages) pattern

- Broker Handle Pattern
  - Broker returns handle (remote reference) to Client
  - Client uses handle to communicate with Service

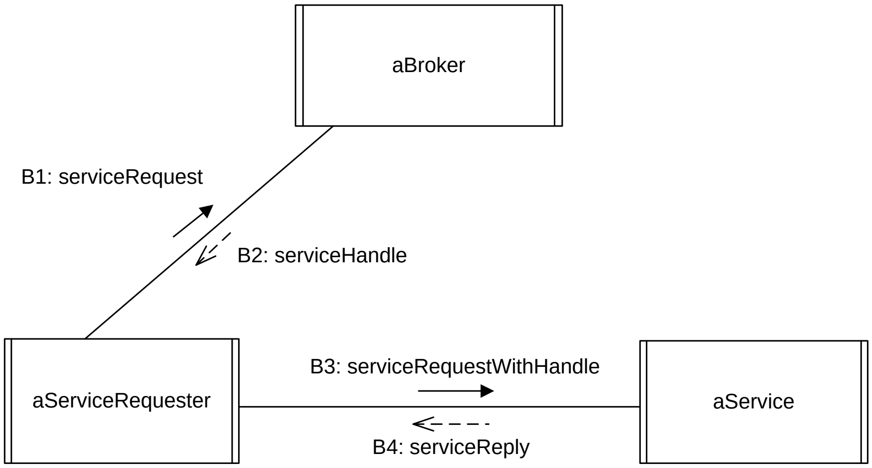
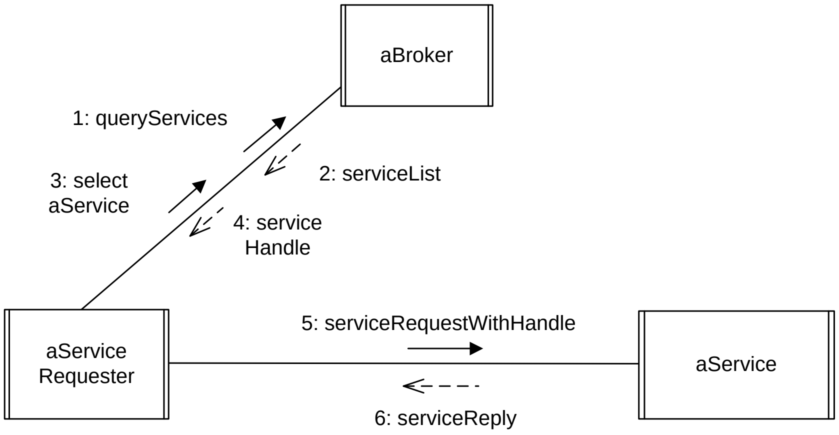


Figure 11.26: Discovery (Yellow pages) pattern

- Discovery Pattern
  - Client knows service type but not specific service
  - Client makes yellow pages query
    - Request all services of a given type
  - Client selects service
  - Client makes white pages query



aBroker

1: queryServices

2: serviceList

3: select aService

4: service Handle

aService Requester

5: serviceRequestWithHandle

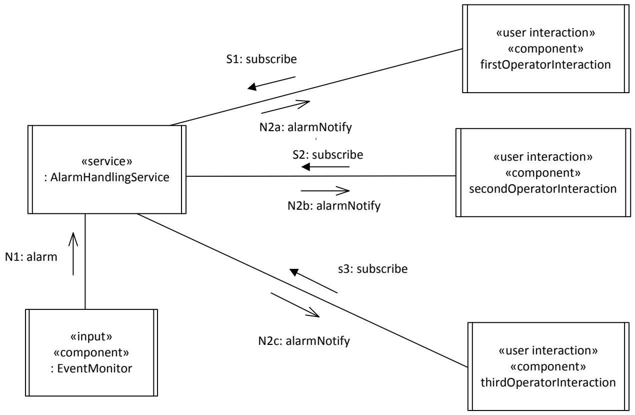
aService

6: serviceReply

Group Message Communication

- One-to-many message communication
  - Same message sent to several recipients
- Broadcast message communication
  - Message sent to all recipients
- Multicast message communication
  - Same message sent to all members of group
- Subscription/Notification communication (Fig. 11.28)
  - Client subscribes to group
  - Receives messages sent to all members of group
  - Sender sends message to group
    - Does not need to know recipients

Figure 11.28 Example of subscription/notification (message multicast) communication



Documenting a Design Pattern

- Pattern describes
  - Pattern Name
  - Aliases
  - Context
    - When should pattern be used
  - Problem
  - Summary of solution
  - Strengths of solution
  - Weaknesses of solution
  - Applicability
    - When can you use the pattern
  - Related Patterns
  - Reference

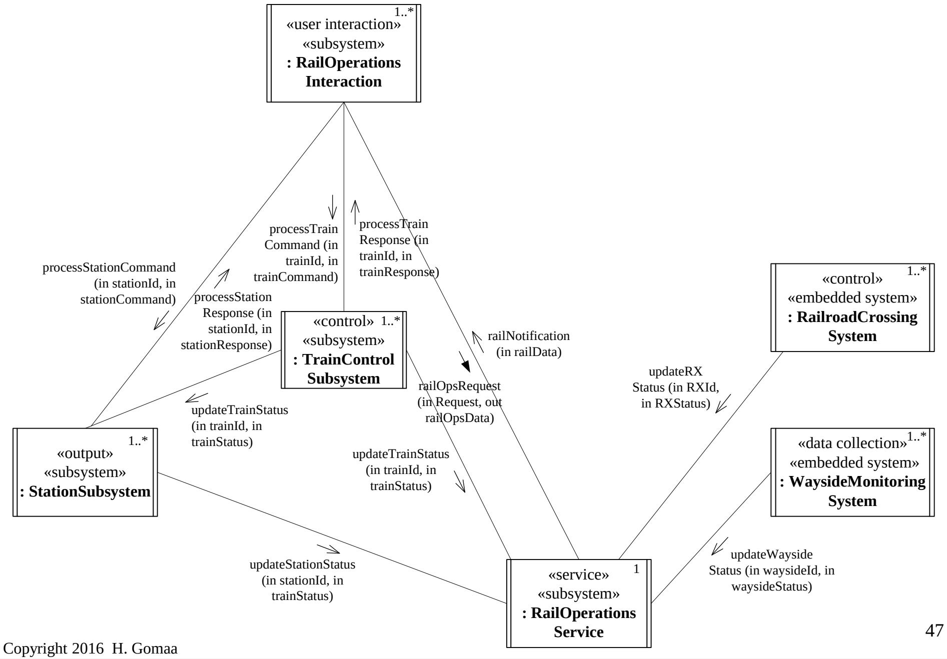
Subscription/Notification Pattern

Pattern name	Subscription/Notification.
Aliases	Multicast.
Context	Distributed systems.
Problem	Distributed application with multiple clients and services. Clients want to receive messages of a given type.
Summary of solution	Selective form of group communication. Clients subscribe to receive messages of a given type. When service receives message of this type, it notifies all clients who have subscribed to it.
Strengths of solution	Selective form of group communication. Widely used on the Internet and in World Wide Web applications.
Weaknesses of solution	If client subscribes to too many services, it may unexpectedly receive a large number of messages.
Applicability	Distributed environments: client/service and distribution applications with multiple services.
Related patterns	Similar to Broadcast, except that it is more selective.
Reference	Chapter 17, Section 17.6.2.

Building Software Applications from Software Architectural Patterns

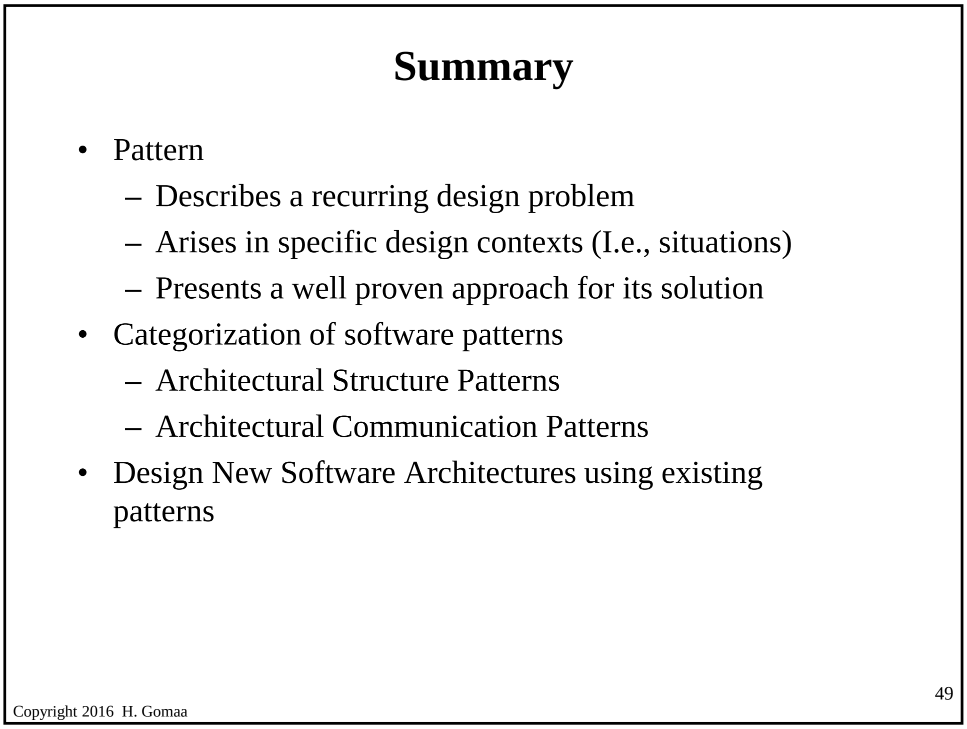
- Consider architectural structure patterns
  - Different patterns can be combined
- Start with layers of abstractions pattern
  - Incorporate client/service patterns
  - Incorporate control patterns
- Apply architectural communication patterns
  - Decouple sender components from receiver components
    - Broker patterns
    - Group communication patterns

Figure 21.32 Distributed software architecture for Light Rail System


«user interaction»
«subsystem»
: RailOperations Interaction
1..*
processTrain Command (in trainId, in trainCommand)
processTrain Response (in trainId, in trainResponse)
processStationCommand (in stationId, in stationCommand)
processStation Response (in stationId, in stationResponse)
«control»
«subsystem»
: TrainControl Subsystem
1..*
railNotification (in railData)
railOpsRequest (in Request, out railOpsData)
«control»
«embedded system»
: RailroadCrossing System
1..*
updateRX Status (in RXId, in RXStatus)
updateTrainStatus (in trainId, in trainStatus)
«output»
«subsystem»
: StationSubsystem
1..*
updateTrainStatus (in trainId, in trainStatus)
«data collection»
«embedded system»
: WaysideMonitoring System
1..*
updateWayside Status (in waysideId, in waysideStatus)
updateStationStatus (in stationId, in trainStatus)
«service»
«subsystem»
: RailOperations Service
1

Building Light Rail System From Software Architectural Patterns

- Architectural Structure Patterns
  - Layered pattern
  - Client/Service pattern
  - Distributed Control
- Architectural Communication Patterns
  - Asynchronous
  - Synchronous
  - Broker
  - Subscription/Notification



Summary

- Pattern
  - – Describes a recurring design problem
  - – Arises in specific design contexts (I.e., situations)
  - – Presents a well proven approach for its solution
- Categorization of software patterns
  - – Architectural Structure Patterns
  - – Architectural Communication Patterns
- Design New Software Architectures using existing patterns