

✧ Computers control a wide range of systems

- E.g. simple domestic machines, games controllers, manufacturing plants...

✧ They all have software which...

- Is embedded in system hardware, often in read-only memory (ROM)
- Reacts to events generated by the hardware
- Issues control signals in response to these events
- Usually responds in *real-time* to events from the system's environment

Real-time Software Engineering

CS3023 – Software Engineering

Topics covered

- ✧ Embedded system design
- ✧ Architectural patterns for real-time software
- ✧ Timing analysis
- ✧ Real-time operating systems

Responsiveness

- ✧ Responsiveness **in real-time** is the critical difference between embedded systems and other software systems such as information systems, web-based systems or personal software systems.
- ✧ Correctness
 - In non-real-time systems, is defined by specifying how system inputs map to corresponding outputs
 - In a real-time system, depends both on the response to an input and the **time taken to generate that response**. If the system takes too long to respond, then the required response may be ineffective.

Definition

- ✧ A **real-time system** is a software system where the correct functioning of the system depends on the results produced by the system and the time at which these results are produced.
- ✧ A **soft real-time system** is a system whose *operation is degraded* if results are not produced according to the specified timing requirements.
- ✧ A **hard real-time system** is a system whose *operation is incorrect* if results are not produced according to the timing specification.

Examples of hard and soft real-time systems

Vehicle braking system	Hard
Insulin monitoring and delivery system	Soft
Wilderness weather station	Soft
Microwave oven	Hard
Missile guidance system	Hard

Characteristics of embedded systems

1. Embedded systems generally run continuously and do not terminate.
2. Unpredictable interactions with the system's environment.
3. There may be physical limitations that affect the design of a system.
4. Direct hardware interaction may be necessary.
5. Issues of safety and reliability may dominate the system design.

Embedded system design

Embedded system design

Design process for embedded systems:

- ✧ Is a systems engineering process that considers, in detail, the design and performance of the system hardware.
- ✧ May involve deciding which system capabilities are to be implemented in software and which in hardware.
- ✧ Low-level decisions on hardware, support software and system timing must be considered early in the process.
- ✧ May have to include additional software functionality, such as battery and power management.

Reactive systems

Real-time systems are often considered to be **reactive systems**.

- ✧ Given a stimulus, the system must produce a reaction or response within a specified time.

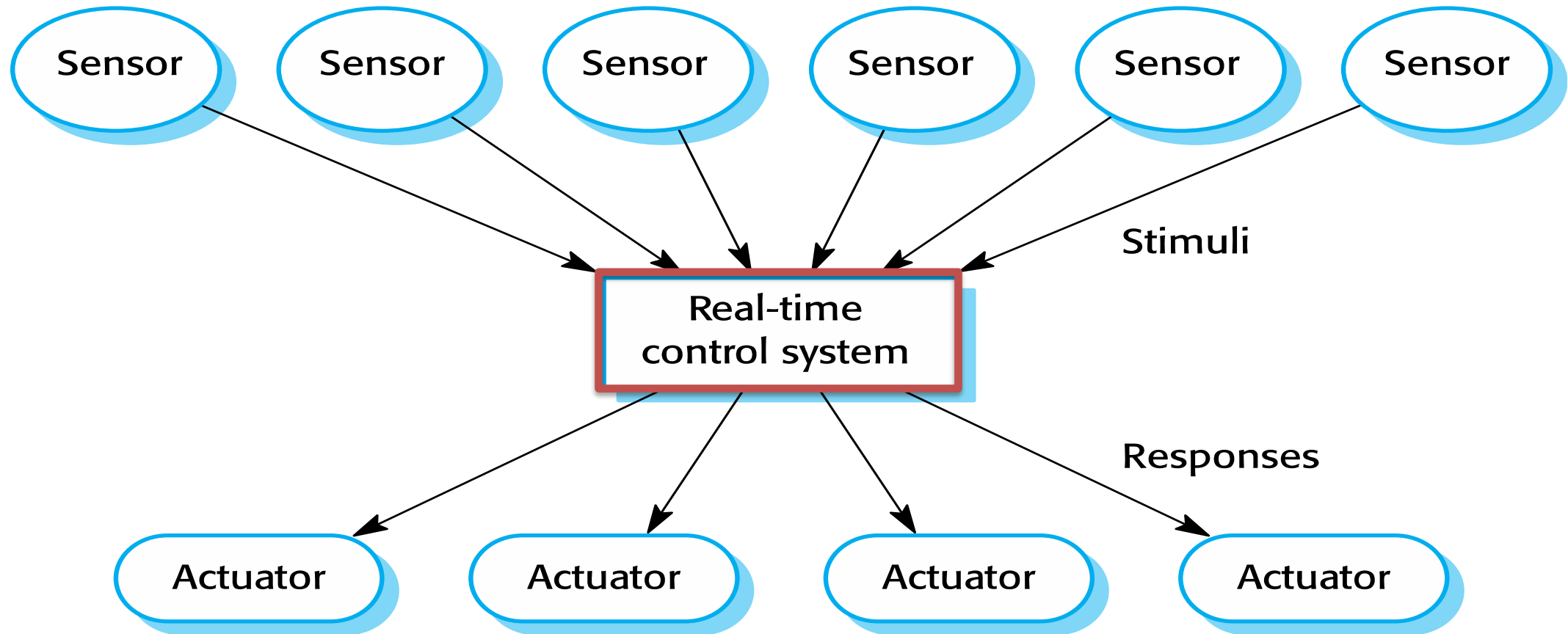
- ✧ **Periodic stimuli.** Stimuli which occur at predictable time intervals
 - E.g., read a temperature sensor every 100 millisecond (and respond depending on sensor value)

- ✧ **Aperiodic stimuli.** Stimuli which occur at unpredictable times
 - E.g., a system power failure may trigger an interrupt which must be processed by the system.

Example: stimuli and responses for a burglar alarm system

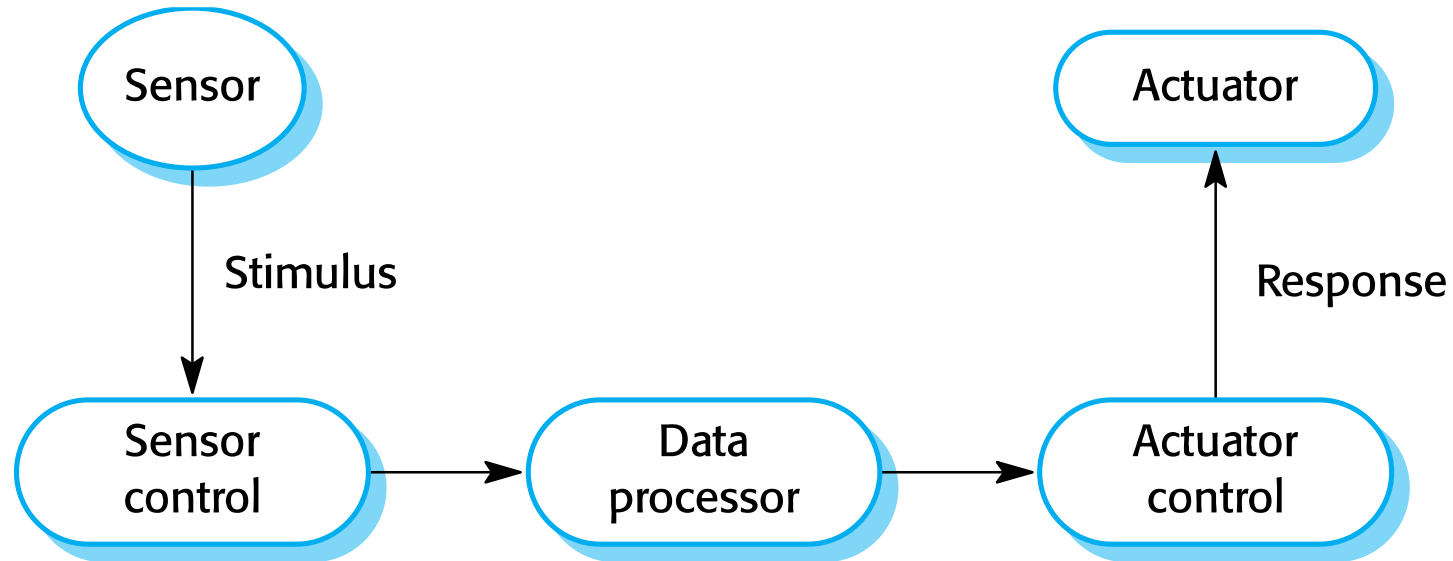
Stimulus	Response
Clear alarms	Switch off all active alarms; switch off all lights that have been switched on.
Console panic button positive	Initiate alarm; turn on lights around console; call police.
Power supply failure	Call service technician.
Sensor failure	Call service technician.
Single sensor positive	Initiate alarm; turn on lights around site of positive sensor.
Two or more sensors positive	Initiate alarm; turn on lights around sites of positive sensors; call police with location of suspected break-in.
Voltage drop of between 10% and 20%	Switch to battery backup; run power supply test.
Voltage drop of more than 20%	Switch to battery backup; initiate alarm; call police; run power supply test.

A general model of an embedded real-time system



Sensor and actuator processes

A separate process for each type of sensor and actuator



A general design guideline

System elements

✧ Sensor control processes

- Collect information from sensors. May buffer information collected in response to a sensor stimulus.

✧ Data processor

- Carries out processing of collected information and computes the system response.

✧ Actuator control processes

- Generates control signals for the actuators.

Architectural considerations

- ✧ Because of the need to respond to timing demands made by different stimuli/responses, the system architecture **must allow for fast switching** between stimulus handlers.
- ✧ Timing demands of different stimuli are different, so a simple sequential loop is not usually adequate.
- ✧ Real-time systems are therefore usually designed as **cooperating processes** with a *real-time executive* controlling these processes.

Design process activities

1. Platform selection
2. Stimuli/response identification
3. Timing analysis
4. Process design
5. Algorithm design
6. Data design
7. Process scheduling

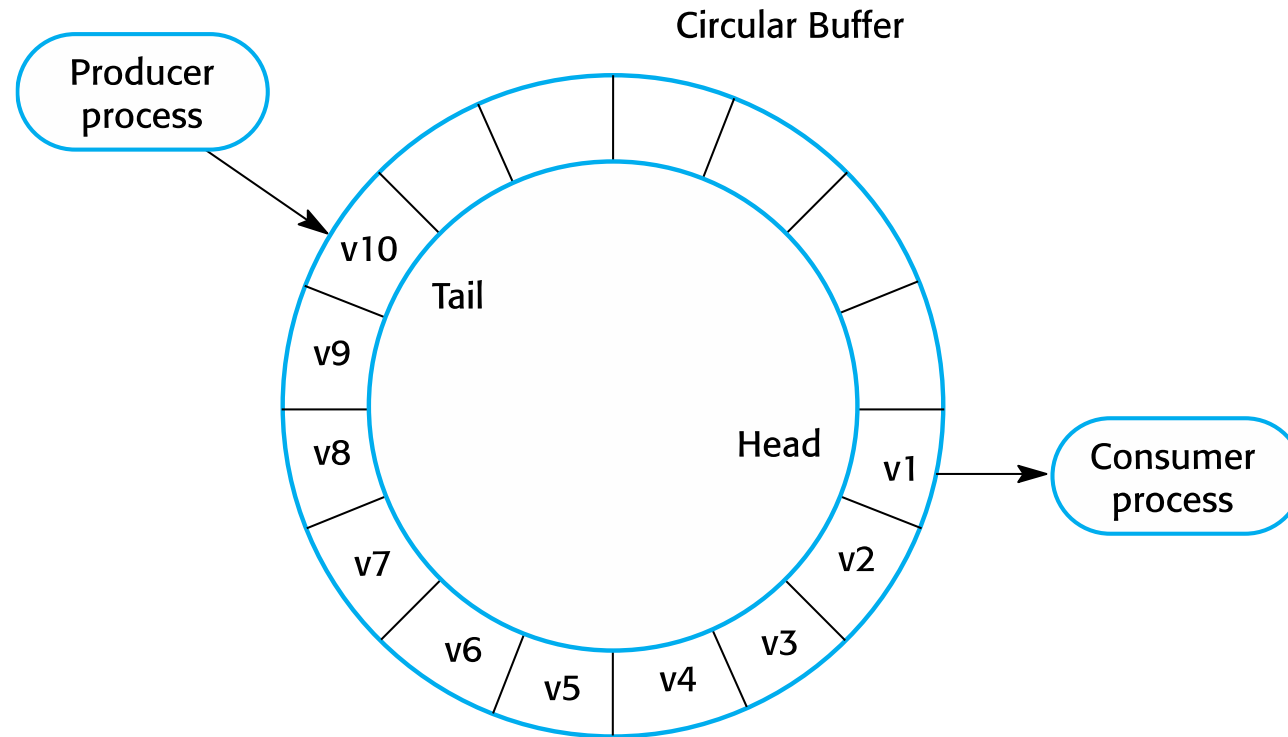
Process coordination

- ✧ Real-time system processes must be coordinated and share information.
- ✧ Process coordination mechanisms ensure mutual exclusion to **shared resources**.
 - When one process is modifying a shared resource, other processes should not be able to change that resource.
- ✧ When designing the information exchange between processes, need to consider that these processes may be running at different speeds.

Mutual exclusion

- ✧ Producer processes collect data and add it to the buffer. Consumer processes take data from the buffer and make elements available.
- ✧ Producer and consumer processes must be mutually excluded from accessing the same element.
- ✧ The buffer must stop producer processes adding information to a full buffer and consumer processes trying to take information from an empty buffer.

Producer/consumer processes sharing a circular buffer



Real-time system modelling

- ✧ The effect of a stimulus in a real-time system may trigger a transition from one state to another.
- ✧ State models are often used to describe embedded real-time systems.
- ✧ UML state diagrams may be used to show the states and state transitions in a real-time system.

State machine model of a petrol pump

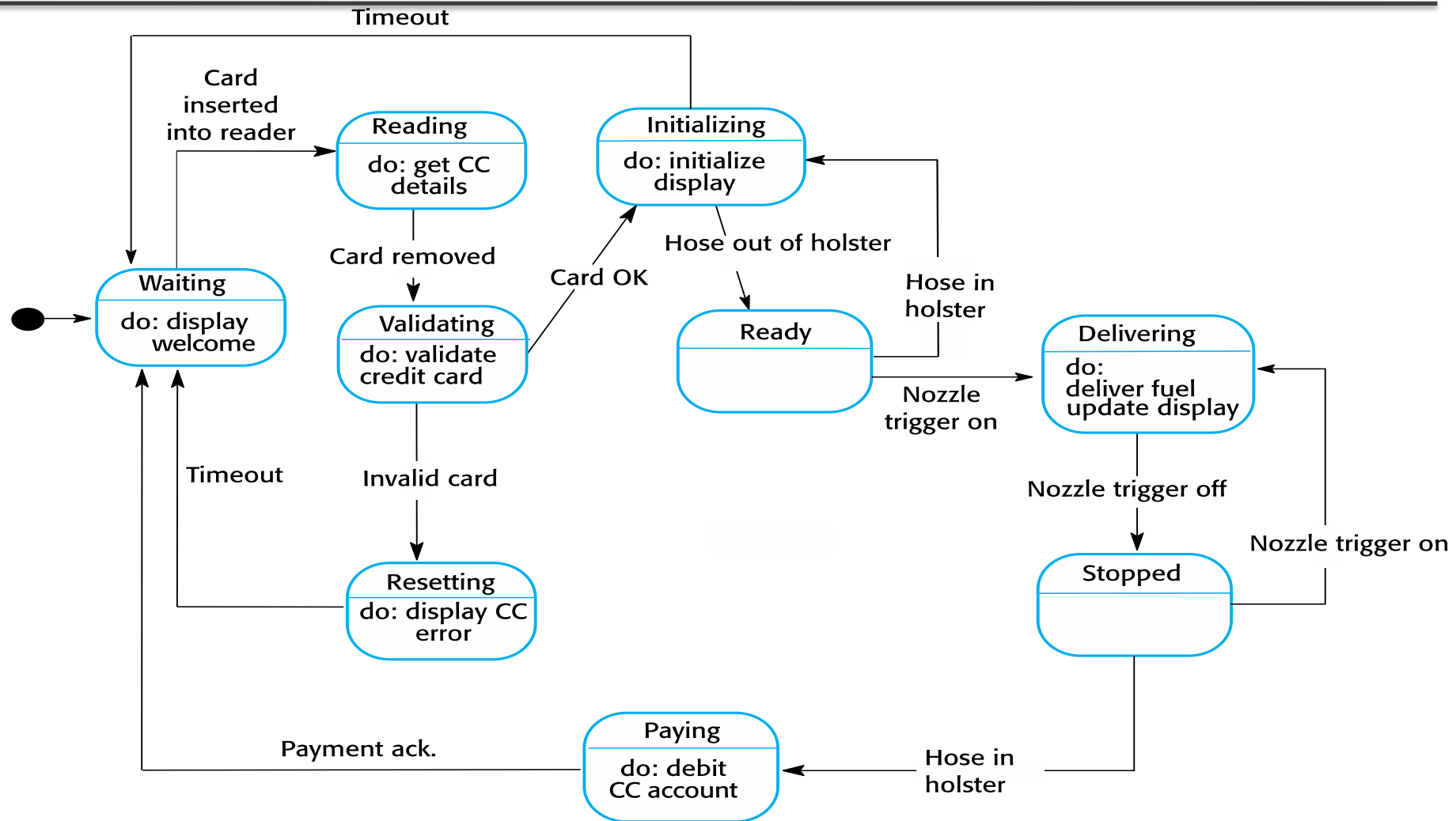


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Sequence of actions in real-time pump control system

- ✧ The buyer inserts a credit card into a card reader built into the pump.
- ✧ Removal of the card triggers a transition to a Validating state where the card is validated.
- ✧ If the card is valid, the system initializes the pump and, when the fuel hose is removed from its holster, transitions to the Delivering state.
- ✧ After the fuel delivery is complete and the hose replaced in its holster, the system moves to a Paying state.
- ✧ After payment, the pump software returns to the Waiting state

State machine model of a petrol pump



Real-time programming

✧ Programming languages for real-time systems development

- facilities to access system hardware
- possible to predict the timing of operations
- C, Assembly, Java
- ~~Object-oriented languages~~

Performance overhead due to extra code to mediate access to attributes and handle calls to operations -> maybe impossible to meet real-time deadlines.

Architectural patterns for real-time software

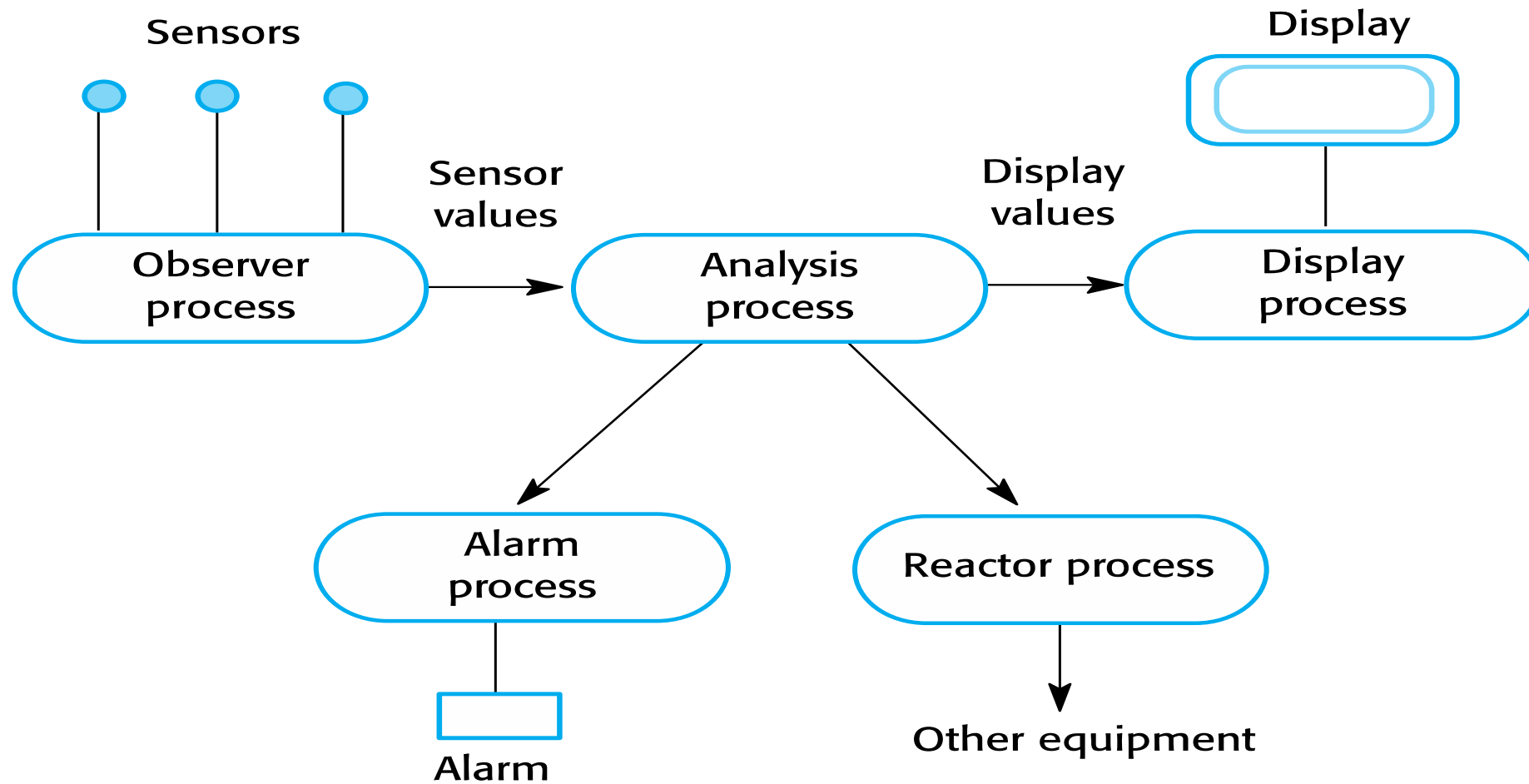
Architectural patterns for embedded systems

1. *Observe and React* - Used when a set of sensors are routinely monitored and displayed.
2. *Environmental Control* - Used when a system includes sensors, which provide information about the environment and actuators that can change the environment
3. *Process Pipeline* - Used when data has to be transformed from one representation to another before it can be processed.

1) The Observe and React pattern

Name	Observe and React
Description	The input values of a set of sensors of the same types are collected and analyzed. These values are displayed in some way. If the sensor values indicate that some exceptional condition has arisen, then actions are initiated to draw the operator's attention to that value and, in certain cases, to take actions in response to the exceptional value.
Stimuli	Values from sensors attached to the system.
Responses	Outputs to display, alarm triggers, signals to reacting systems.
Processes	Observer, Analysis, Display, Alarm, Reactor.
Used in	Monitoring systems, alarm systems.

Observe and React process structure

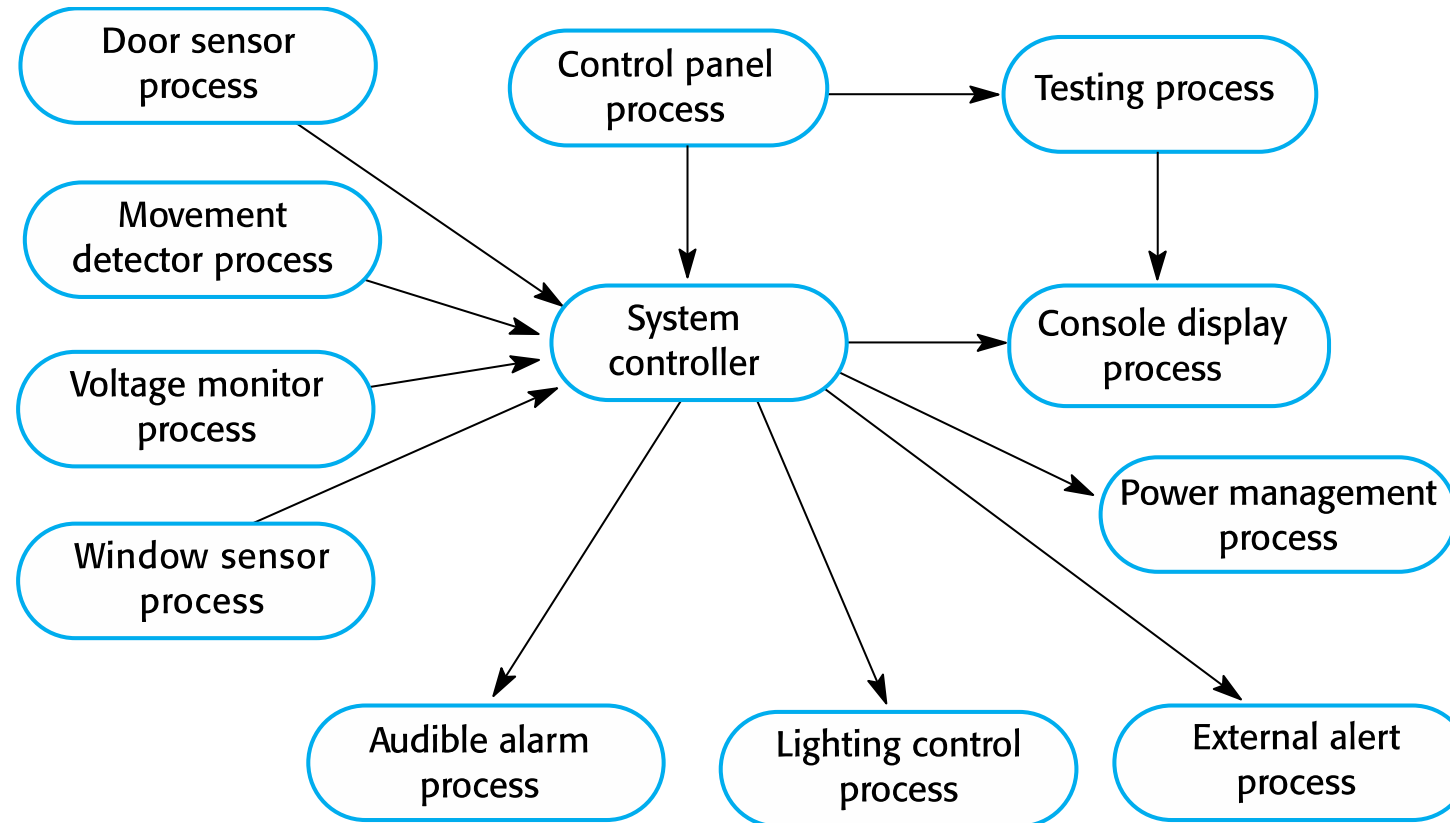


Example: Alarm system description

A software system is to be implemented as part of a burglar alarm system for commercial buildings. This uses several different types of sensor. These include movement detectors in individual rooms, door sensors that detect corridor doors opening, and window sensors on ground-floor windows that detect when a window has been opened.

When a sensor detects the presence of an intruder, the system automatically calls the local police and, using a voice synthesizer, reports the location of the alarm. It switches on lights in the rooms around the active sensor and sets off an audible alarm. The sensor system is normally powered by mains power but is equipped with a battery backup. Power loss is detected using a separate power circuit monitor that monitors the mains voltage. If a voltage drop is detected, the system assumes that intruders have interrupted the power supply, so an alarm is raised.

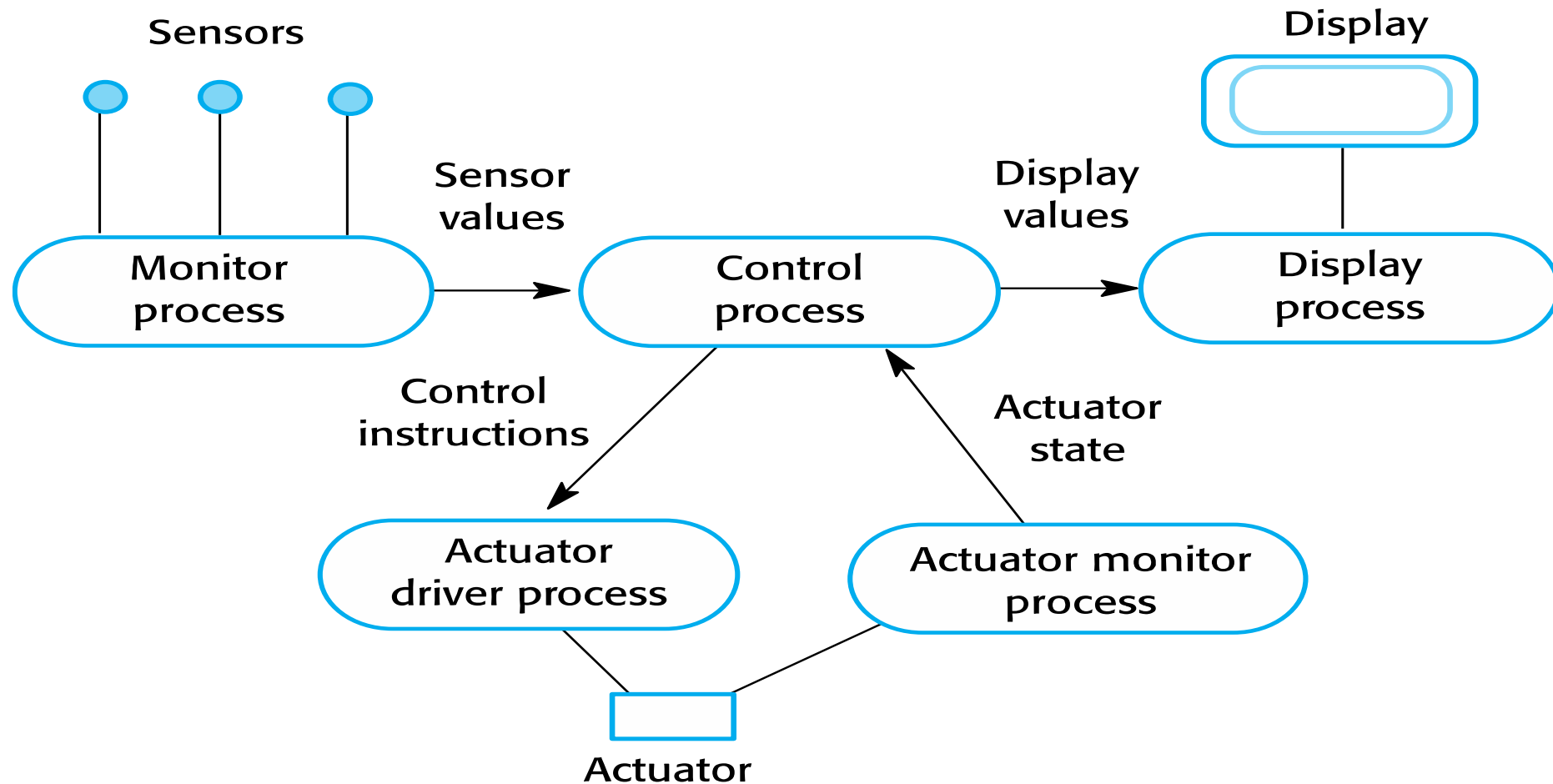
Example: Process structure for a burglar alarm system



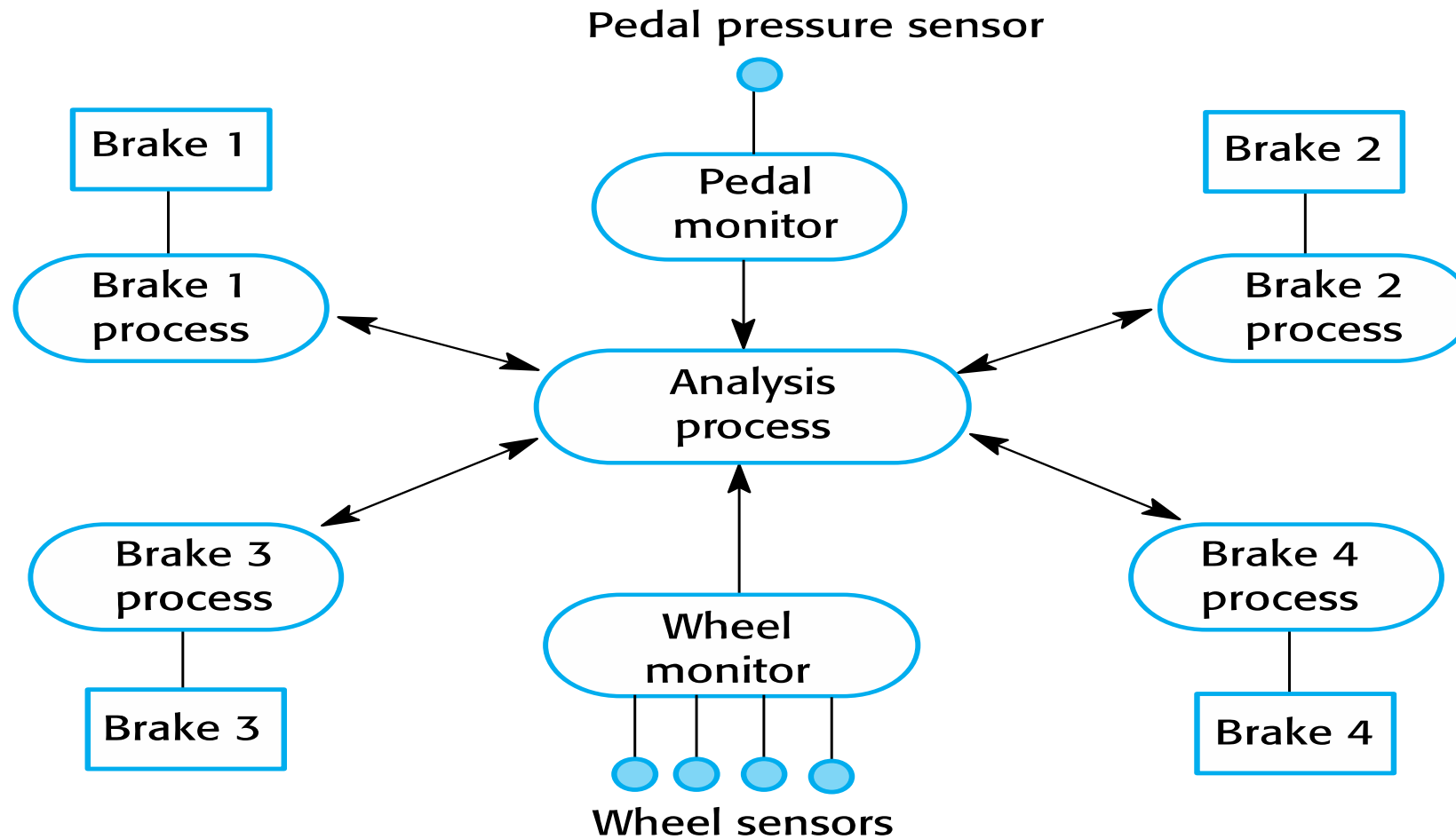
2) The Environmental Control pattern

Name	Environmental Control
Description	The system analyzes information from a set of sensors that collect data from the system's environment. Further information may also be collected on the state of the actuators that are connected to the system. Based on the data from the sensors and actuators, control signals are sent to the actuators that then cause changes to the system's environment. Information about the sensor values and the state of the actuators may be displayed.
Stimuli	Values from sensors attached to the system and the state of the system actuators.
Responses	Control signals to actuators, display information.
Processes	Monitor, Control, Display, Actuator Driver, Actuator monitor.
Used in	Control systems.

Environmental Control process structure



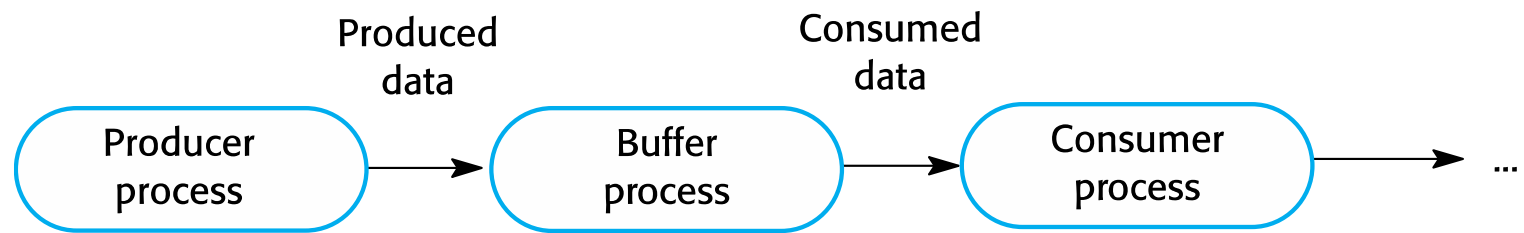
Example: Control system architecture for an anti-skid braking system



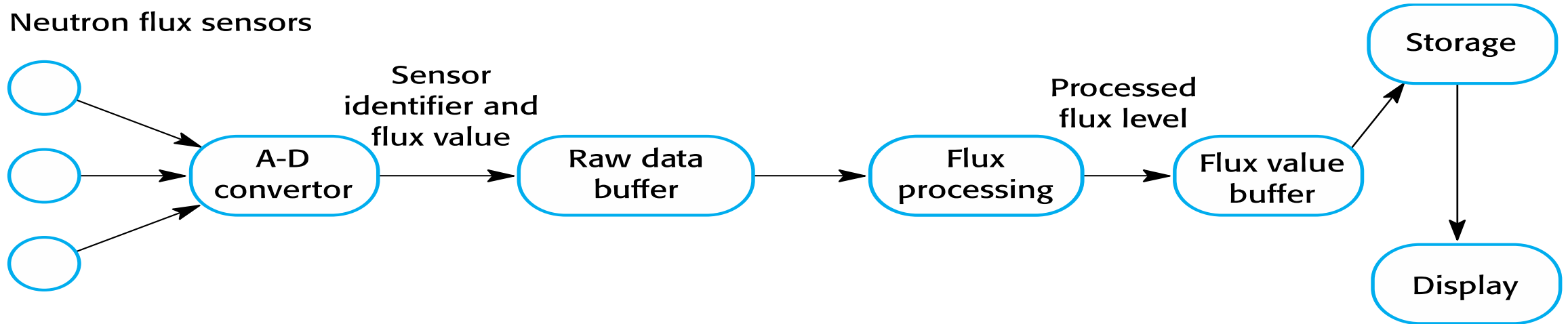
3) The Process Pipeline pattern

Name	Process Pipeline
Description	A pipeline of processes is set up with data moving in sequence from one end of the pipeline to another. The processes are often linked by synchronized buffers to allow the producer and consumer processes to run at different speeds. The culmination of a pipeline may be display or data storage or the pipeline may terminate in an actuator.
Stimuli	Input values from the environment or some other process
Responses	Output values to the environment or a shared buffer
Processes	Producer, Buffer, Consumer
Used in	Data acquisition systems, multimedia systems

Process Pipeline process structure



Example: Neutron flux data acquisition



Part of control software for a
nuclear reactor

Timing analysis

Timing analysis

Correctness of a real-time system depends on the correctness of its outputs AND on the time at which these outputs were produced.

Calculate how often each process in the system must be executed to ensure that all inputs are processed, and all system responses produced in a timely way.

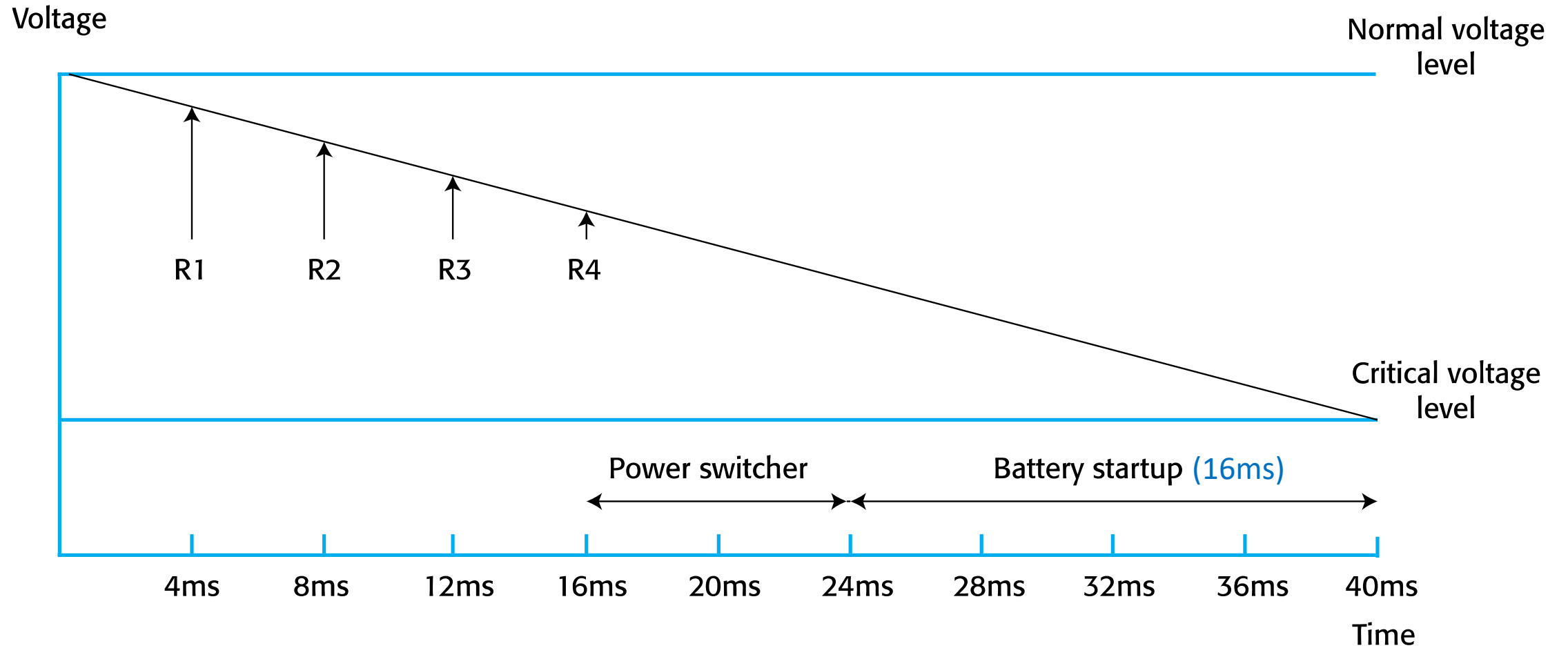
✧ Results of timing analysis are used to decide:

- How frequently each process should execute and
- How these processes should be scheduled by the RTOS.

Factors in timing analysis

1. *Deadlines* - The times by which stimuli must be processed and some response produced by the system.
2. *Frequency* - Number of times per second that a process must execute (to be confident that it can always meet its deadlines).
3. *Execution time* - Time required to process a stimulus and produce a response.

Example: Power failure timing analysis



Example: Power failure timings

- ✧ It takes 50 milliseconds (ms) for the supplied voltage to drop to a level where the equipment may be damaged. The battery backup must therefore be activated and in operation within 50ms.
- ✧ It takes 16ms from starting the backup power supply to the supply being fully operational.
- ✧ There is a checking process that is scheduled to run 250 times per second (i.e. every 4ms).
 - This process assumes that there is a power supply problem if there is a significant drop in voltage between readings and this is sustained for 3 readings.

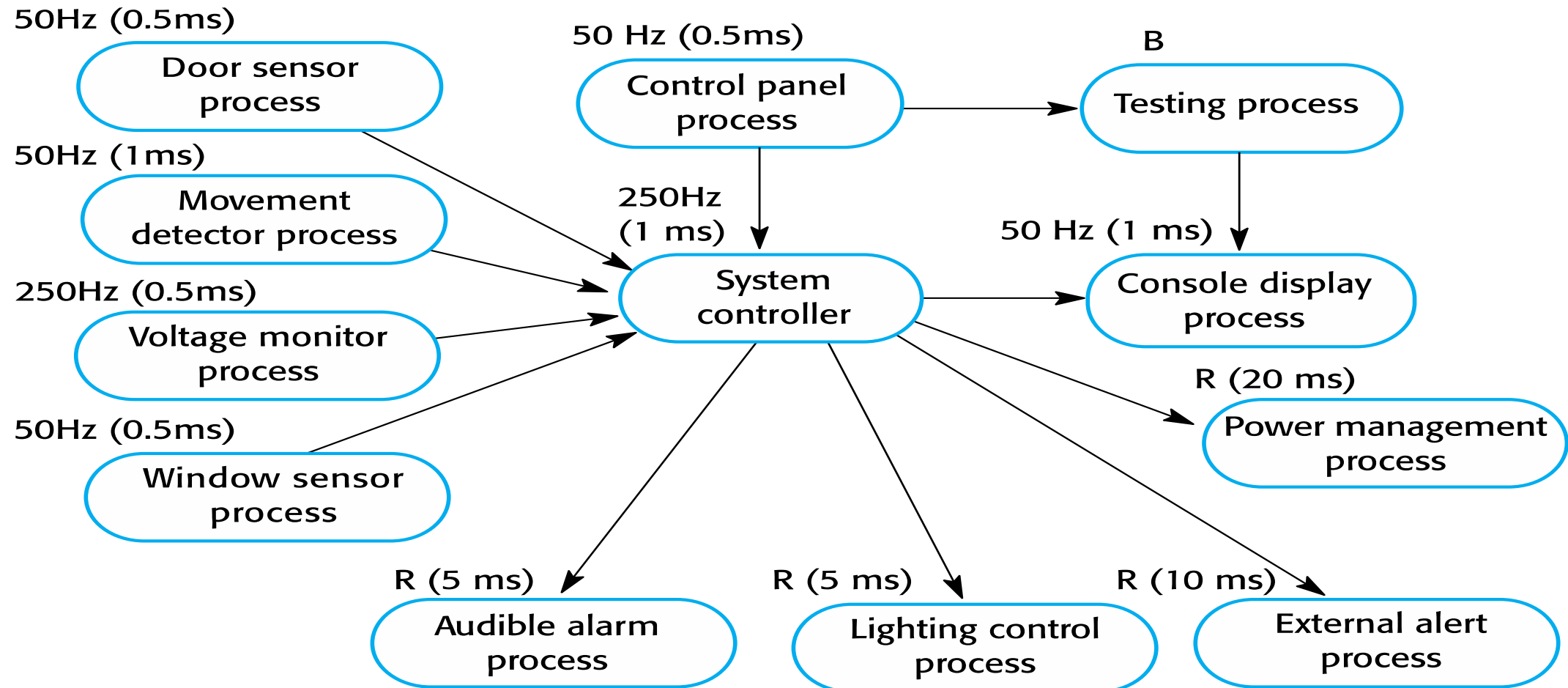
Example: Power failure timings

- ✧ Assume the power fails immediately after a reading has been taken. Therefore reading R1 is the start reading for the power fail check.
- ✧ Voltage continues to drop for readings R2–R4, so a power failure is assumed. (This is the worst possible case)
- ✧ At this stage, the process to switch to the battery backup is started. Because the battery backup takes 16ms to become operational, this means that the worst-case execution time for this process is **8ms**.

Example: Timing requirements for the burglar alarm system

Stimulus/Response	Timing requirements
Audible alarm	The audible alarm should be switched on within <u>half a second</u> of an alarm being raised by a sensor.
Communications	The call to the police should be started within <u>2 seconds</u> of an alarm being raised by a sensor.
Door alarm	Each door alarm should be <u>polled twice per second</u> .
Lights switch	The lights should be switched on within <u>half a second</u> of an alarm being raised by a sensor.
Movement detector	Each movement detector should be <u>polled twice per second</u> .
Power failure	The switch to backup power must be completed within a <u>deadline of 50 ms</u> .
Voice synthesizer	A synthesized message should be available within <u>2 seconds</u> of an alarm being raised by a sensor.
Window alarm	Each window alarm should be <u>polled twice per second</u> .

Example: Alarm process timing



Stimuli to be processed

- ✧ Power failure is detected by observing a voltage drop of more than 20%.
 - The required response is to switch the circuit to backup power by signalling an electronic power-switching device that switches the mains power to battery backup.
- ✧ Intruder alarm is a stimulus generated by one of the system sensors.
 - The response to this stimulus is to compute the room number of the active sensor, set up a call to the police, initiate the voice synthesizer to manage the call, and switch on the audible intruder alarm and building lights in the area.

Frequency and execution time

- ✧ The deadline for detecting a change of state is 0.25 seconds, which means that each sensor has to be checked 4 times per second. If you examine 1 sensor during each process execution, then if there are N sensors of a particular type, you must schedule the process $4N$ times per second to ensure that all sensors are checked within the deadline.
- ✧ If you examine 4 sensors, say, during each process execution, then the execution time is increased to about 4 ms, but you need only run the process N times/second to meet the timing requirement.

Real-time operating systems



 **Apache NuttX**

Community

Doc

Apache NuttX

Apache NuttX is a mature, real-time embedded operating system (RTOS).

Get NuttX



Real-time operating systems

- ✧ Are specialised operating systems which manage the processes in the RTS.
- ✧ Responsible for process management and resource (processor and memory) allocation.
- ✧ May be based on a standard kernel which is used unchanged or modified for a particular application.
- ✧ Do not normally include facilities such as file management.

Operating system components

1. *Real-time clock* - Provides information for process scheduling.
2. *Interrupt handler* - Manages aperiodic requests for service.
3. *Scheduler* - Chooses the next process to be run.
4. *Resource manager* - Allocates memory and processor resources.
5. *Dispatcher* - Starts process execution.

Non-stop system components

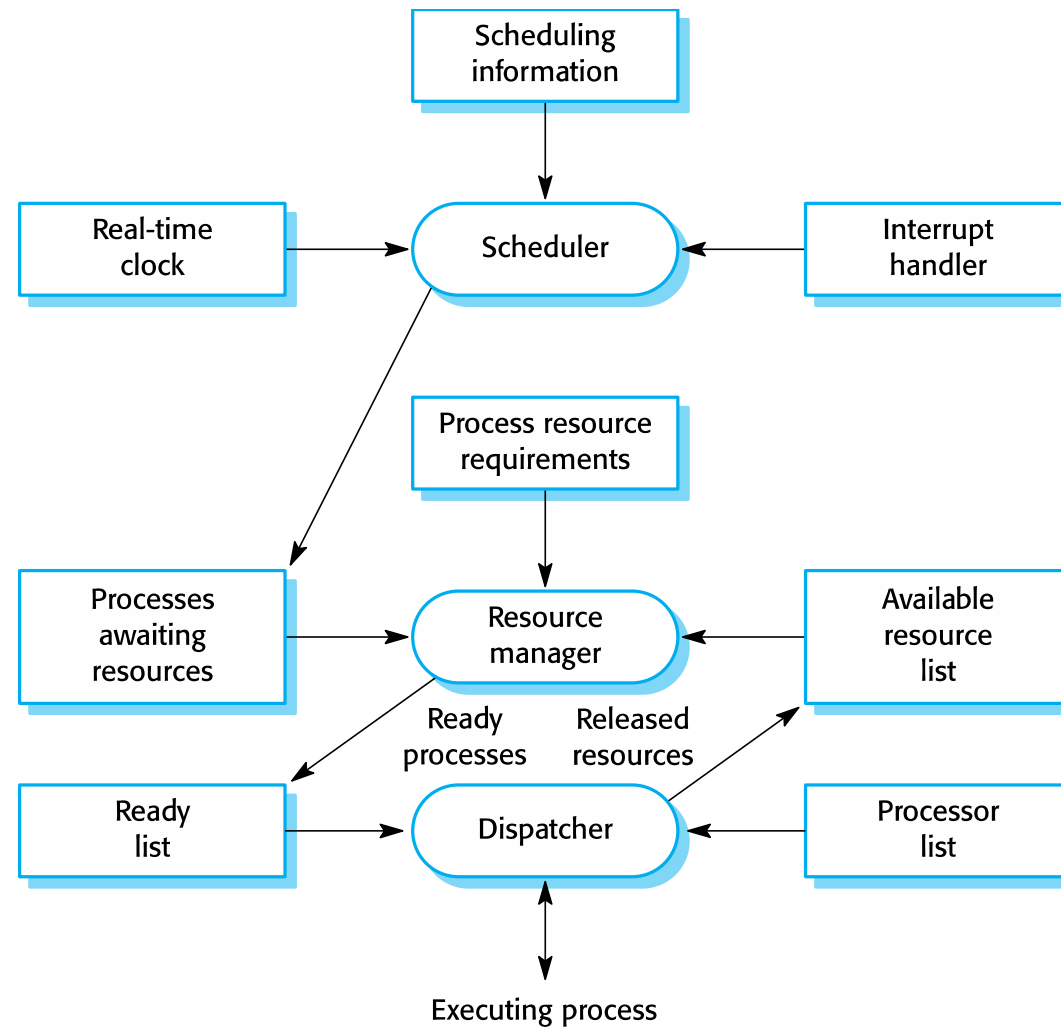
✧ Configuration manager

- Responsible for the dynamic reconfiguration of the system software and hardware. Hardware modules may be replaced and software upgraded without stopping the systems.

✧ Fault manager

- Responsible for detecting software and hardware faults and taking appropriate actions (e.g. switching to backup disks) to ensure that the system continues in operation.

Components of a real-time operating system



Process management

- ✧ Concerned with managing the set of concurrent processes.
- ✧ Periodic processes are executed at pre-specified time intervals.
- ✧ The RTOS uses the real-time clock to determine when to execute a process taking into account:
 - Process period - time between executions.
 - Process deadline - the time by which processing must be complete.

Process management

The processing of some types of stimuli must sometimes take priority.

1. *Interrupt level priority*. Highest priority which is allocated to processes requiring a very fast response.
2. *Clock level priority*. Allocated to periodic processes.

Within these, further levels of priority may be assigned. (E.g. background processes)

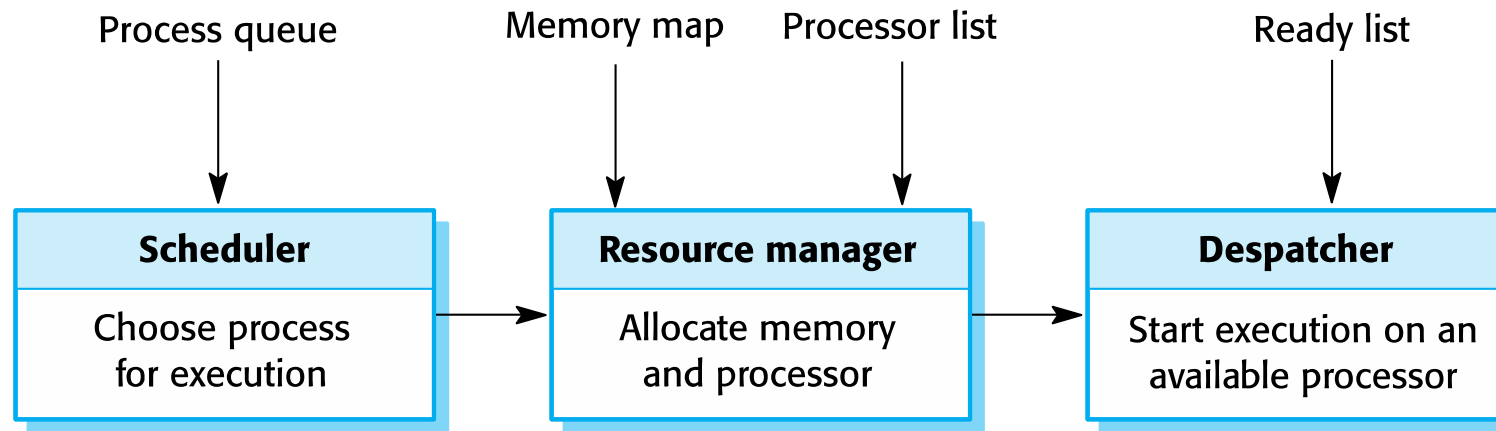
Interrupt servicing

- ✧ Control is transferred automatically to a pre-determined memory location.
- ✧ This location contains an instruction to jump to an interrupt service routine.
- ✧ Further interrupts are disabled, the interrupt serviced and control returned to the interrupted process.
- ✧ Interrupt service routines **MUST** be short, simple and fast.

Periodic process servicing

- ✧ In most real-time systems, there will be several classes of periodic process, each with different periods (the time between executions), execution times and deadlines (the time by which processing must be completed).
- ✧ The real-time clock ticks periodically and each tick causes an interrupt which schedules the process manager for periodic processes.
- ✧ The process manager selects a process which is ready for execution.

RTOS actions required to start a process



Process switching

- ✧ The scheduler chooses the next process to be executed by the processor. This depends on a scheduling strategy which may take the process priority into account.
- ✧ The resource manager allocates memory and a processor for the process to be executed.
- ✧ The dispatcher takes the process from ready list, loads it onto a processor and starts execution.

Scheduling strategies

✧ Non pre-emptive scheduling

- Once a process has been scheduled for execution, it runs to completion or until it is blocked for some reason (e.g. waiting for I/O).

✧ Pre-emptive scheduling

- The execution of an executing processes may be stopped if a higher priority process requires service.

✧ Scheduling algorithms

- Round-robin;
- Rate monotonic;
- Shortest deadline first.

Key points

- ✧ An embedded software system is part of a hardware/software system that reacts to events in its environment. The software is 'embedded' in the hardware. Embedded systems are normally real-time systems.
- ✧ A real-time system is a software system that must respond to events in real time. System correctness does not just depend on the results it produces, but also on the time when these results are produced.
- ✧ Real-time systems are usually implemented as a set of communicating processes that react to stimuli to produce responses.
- ✧ State models are an important design representation for embedded real-time systems. They are used to show how the system reacts to its environment as events trigger changes of state in the system.

Key points

- ✧ There are several standard patterns that can be observed in different types of embedded system. These include a pattern for monitoring the system's environment for adverse events, a pattern for actuator control and a data-processing pattern.
- ✧ Designers of real-time systems have to do a timing analysis, which is driven by the deadlines for processing and responding to stimuli. They have to decide how often each process in the system should run and the expected and worst-case execution time for processes.
- ✧ A real-time operating system is responsible for process and resource management. It always includes a scheduler, which is the component responsible for deciding which process should be scheduled for execution.