Embedded Operating Systems

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Outline

1. Introduction to Embedded Operating Systems
2. Examples of Embedded Operating Systems
3. Multitasking without OS Support

Definition of Embedded OS

❐ OSes used in embedded systems

- Past embedded systems did not use operating systems, but implemented in firmware
- Modern embedded systems are adopting operating systems

❐ Main requirements on embedded OS

- Small size requirement for limited resources
- Real-time services
- Predictability

Why OS in Embedded Systems?

❑ Technical aspects

- Multitasking
- Networking and communications
- Storage and memory management
- Protection and security
- GUI

❑ Economic aspects

- Time-to-market
- Low NRE (non-recurring engineering) cost
- Maintenance cost
  - 40% - 80% in the software lifecycle

Typical Embedded Operating Systems

- RTOS
  - VxWorks, QNX, pSOS, VRTX, Nucleus, WinCE
- Mobile OS
  - iOS, Android, Tizen, WinCE, Symbian, PalmOS
- Open general purpose OS
  - Linux, Solaris 10, FreeBSD, eCOS
- DSP OS
  - ARC/MQX, DSP/BIOS
- Others
  - TinyOS (smart sensor), Nachos (education), Xinu (education),
  - IOS (Internetwork OS, Cisco routers)
  - ThreadX (pripherals)

Commercial RTOSes

❒ Commercial RTOSes

- **QNX, VxWorks, pSOS, VRTX, Nucleus**

❒ Features

- **Multithreading, real-time synchronization and POSIX APIs**
- **Lightweight kernel**
  - Even scaled down to fit in the ROM of the system
- **Modularized structure**
  - Minimum kernel + service components
- **Responsiveness**
  - Minimal interrupt and switching latency

RTOS does not mean “fast”

- RTOS adds runtime overheads
- Slightly slower performance than OS-less systems

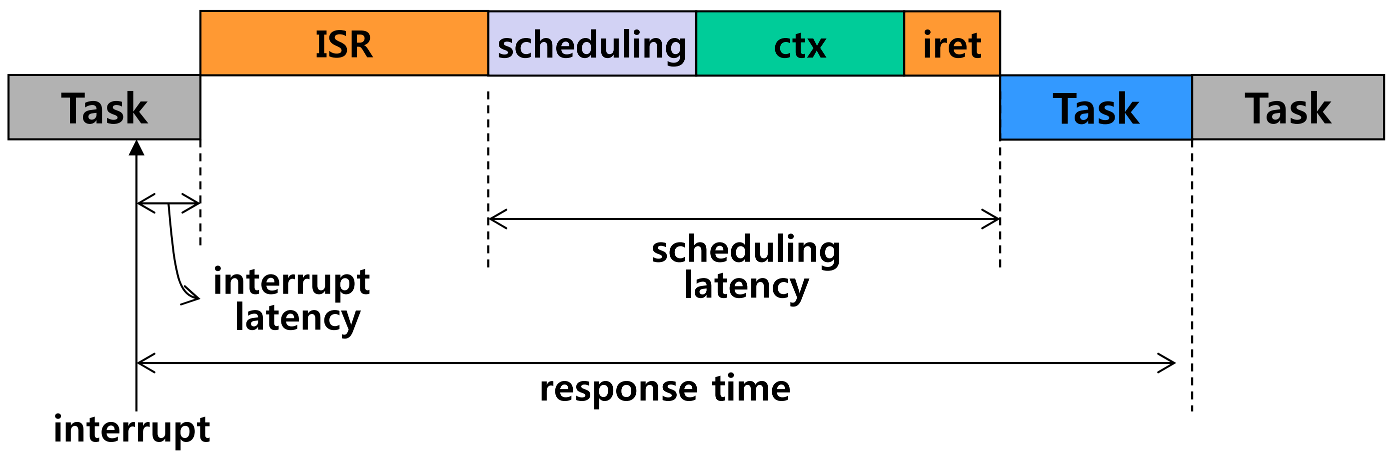
RTOS does mean “deterministic”

- Guarantees “worst case” times
- Better performance than GPOS

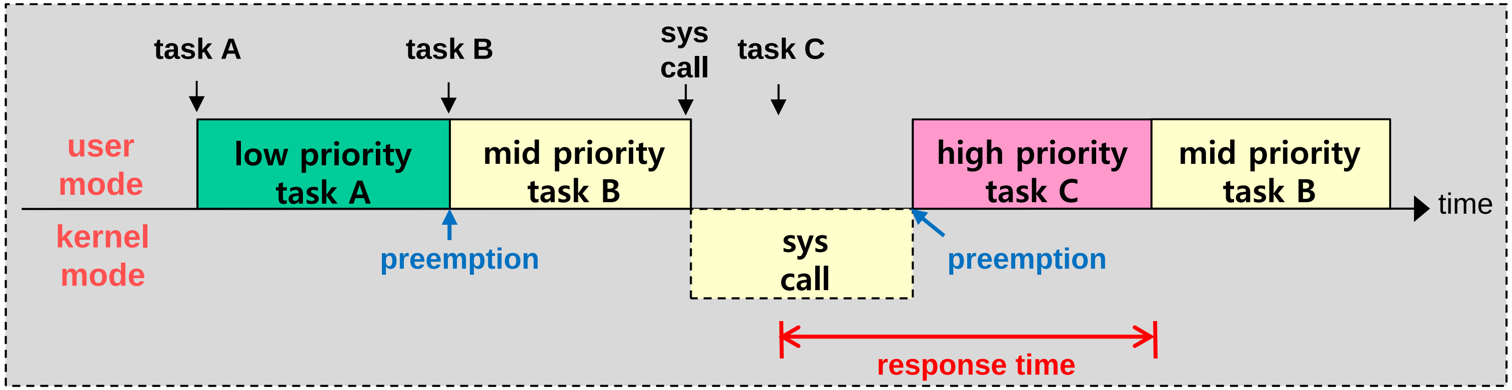
Timing Guarantees from RTOS

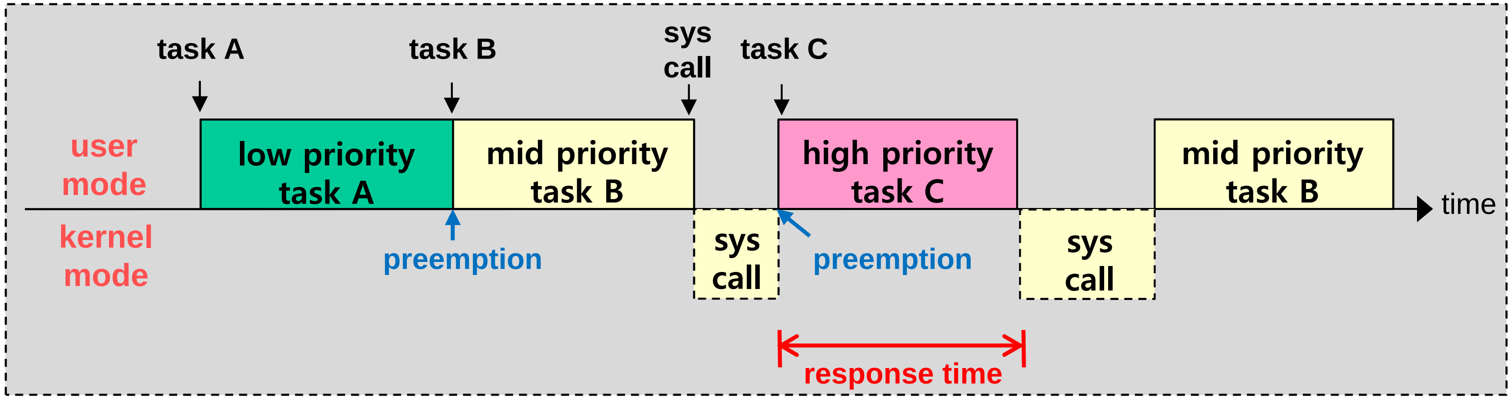
❒ Key requirements

- **Fully preemptive priority-based scheduling**
  - High priority tasks preempt low ones
- **Bounded latency**
  - eg.) interrupt off time < α and scheduling latency < β



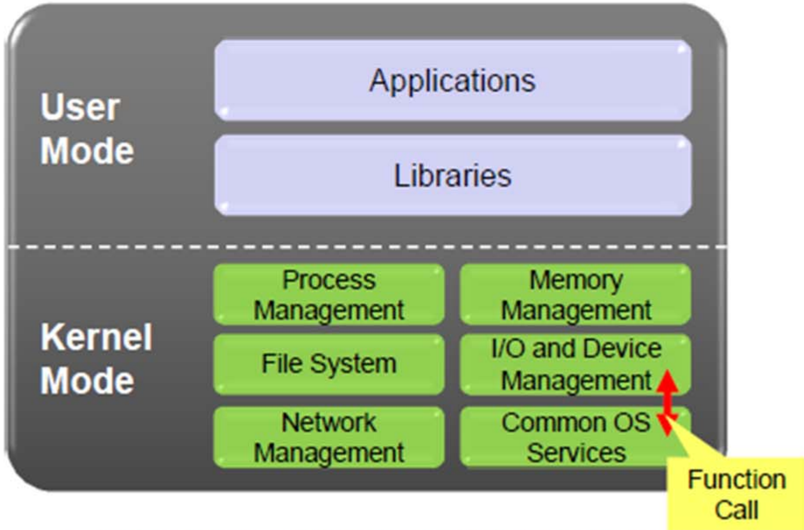
Partially Preemptive vs. Fully Preemptive





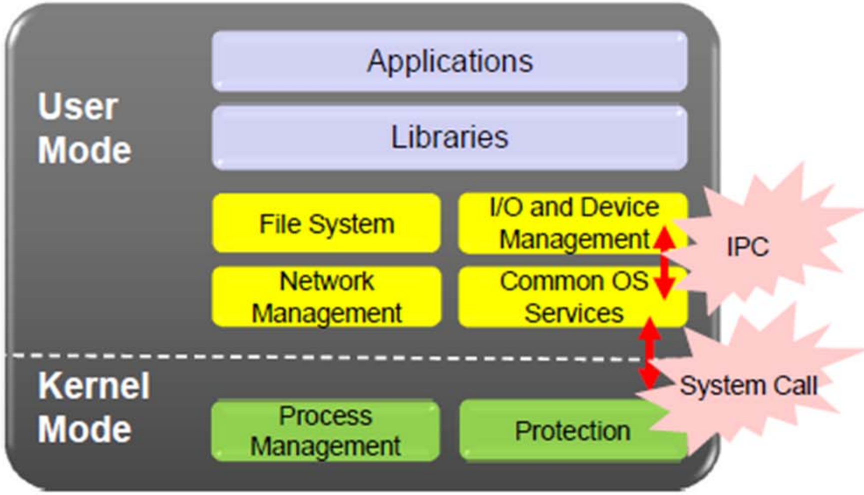
Monolithic Kernel vs. Microkernel

Monolithic Kernel



- Every kernel functionality runs in kernel mode
- Better Performance
- E.g., UNIX, Linux, MS Windows 9x

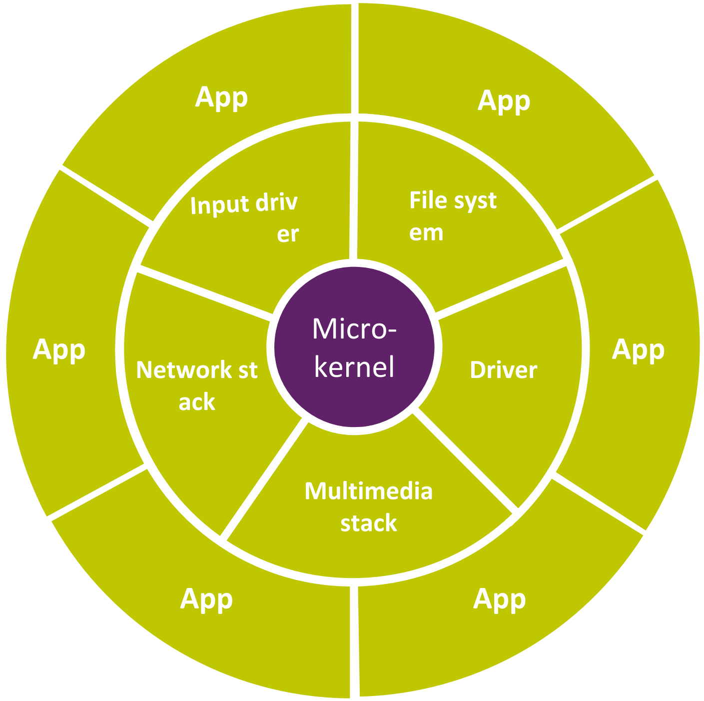
Microkernel



- Most kernel functionality runs in user mode except only the elementary functions
- Better extensibility and modularity
- E.g., MINIX, L4, QNX

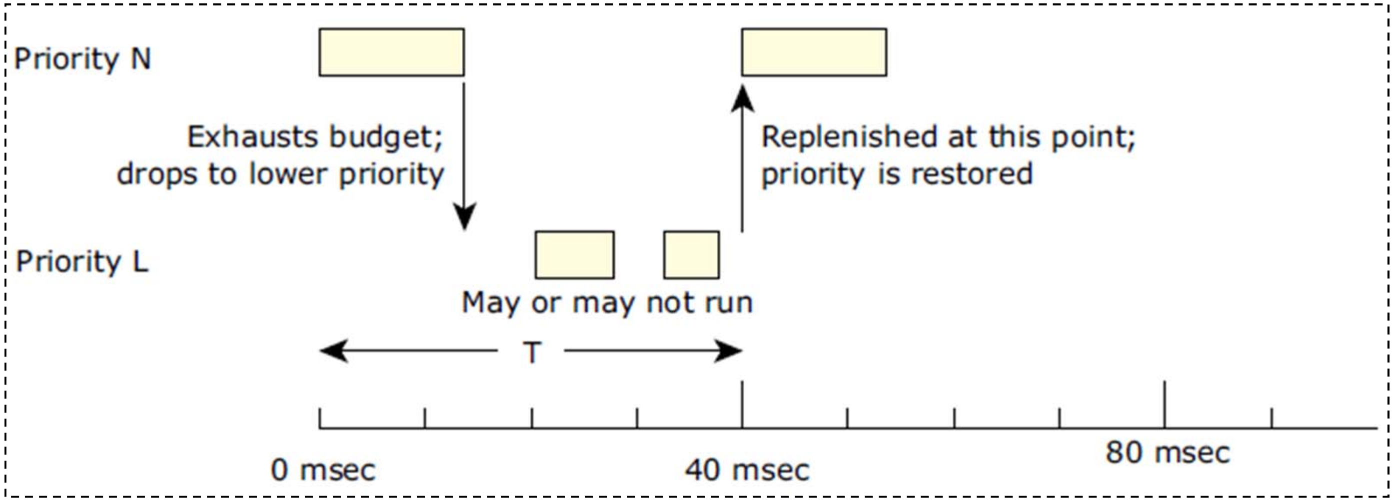
QNX Neutrino RTOS

- ❒ **Microkernel structure**
  - **Moves as much from the kernel into "*user*" space**
- ❒ **Rich features**
  - **Momentics C/C++ IDEs**
  - **Photon microGUI**
  - **HMIs such as HTML5 and Qt**
  - **Multimedia and acoustics support**
  - **Mobile connectivity framework and navigation**



QNX Support for Sporadic Scheduling

- Scheduling of real-time periodic tasks
  - Initial budget: the amount of time a task is allowed to run
  - Replenishment period: the period of task execution



QNX High Availability Manager

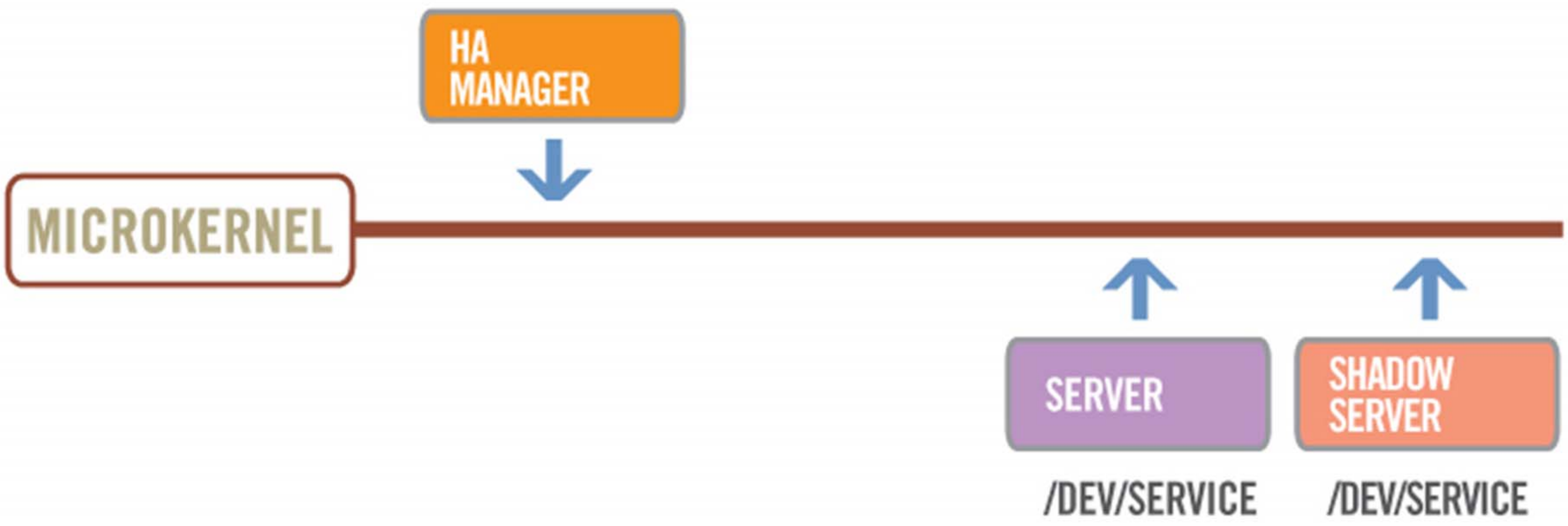
❐ HAM (High Availability Manager)

- **Monitor tasks and services (smart watchdog)**
- **Perform multistage recovery**

❐ HAM Hierarchy

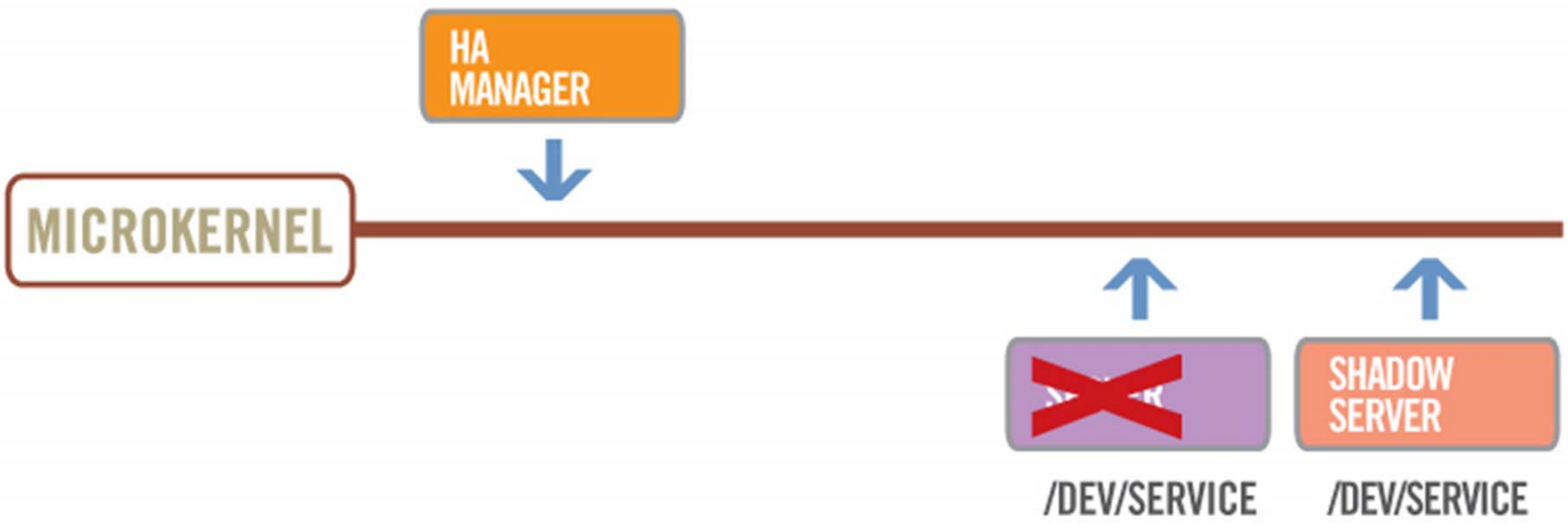
- **Entities**
  - Units of observation and monitoring
- **Conditions**
  - Represent entity states
- **Actions**
  - Executed when the appropriate conditions are true with respect to a specific entity

HAM Example



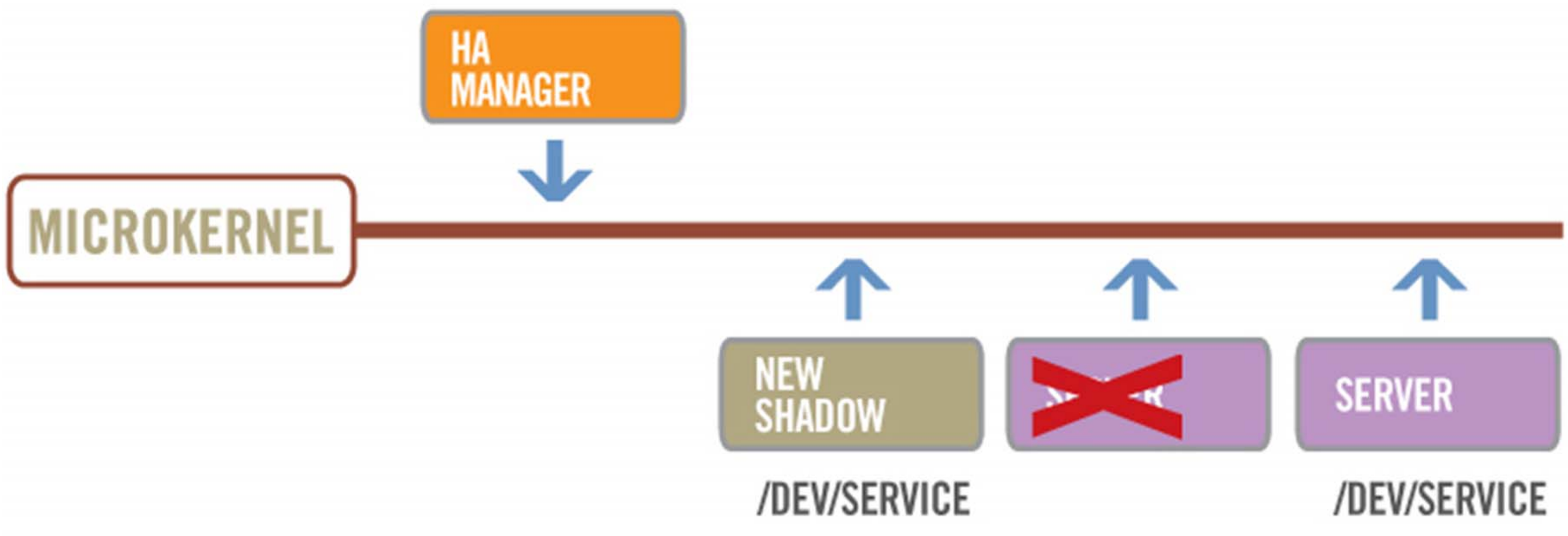
- A second “shadow” server runs

HAM Example



- ❒ A second “shadow” server runs
- ❒ If a fault occurs, new clients use the shadow server

HAM Example



❒ **Start a new "shadow" server**

QNX Certification

- Several certified variants for use in products with high criticality and low tolerance for failure

Operating System	Certification/Compliance
QNX OS for Automotive	ISO 26262 ASIL D
QNX OS for Medical	IEC 62304
QNX OS for Safety and Se curity	Common Criteria ISO/IEC 15408 Evaluation Assurance Level (EAL) 4+ and IEC 61508 Safety Integrity Level 3 (SIL 3)
QNX OS for Security	Common Criteria ISO/IEC 15408 Evaluation Assurance Level (EAL) 4+
QNX OS for Safety	IEC 61508 Safety Integrity Level 3 (SIL 3)

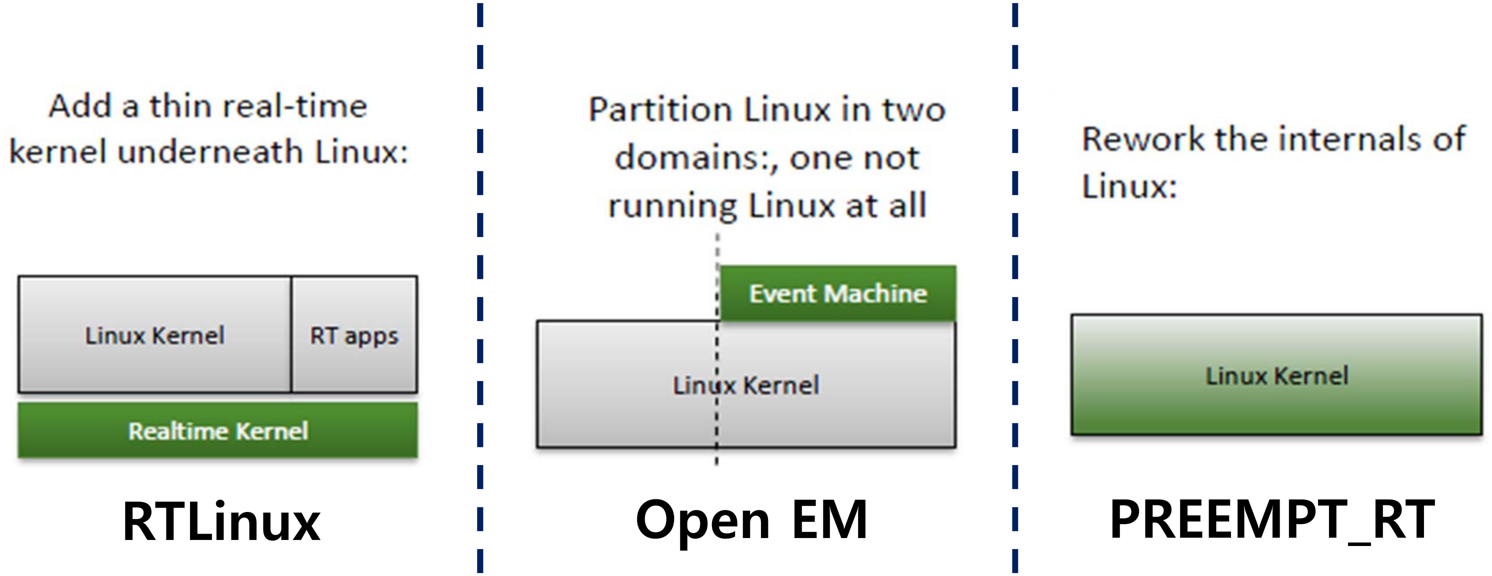
Linux for Real-Time?

- ❒ Linux is a general purpose OS
  - Aimed at high performance and stability
- ❒ Old Linux did not support
  - Full preemption and bounded latency
- ❒ Current Linux supports
  - ✓ Deterministic scheduler (SCHED_FIFO and EDF)
  - ✓ Priority inheritance mutexes
  - ✓ Lockable memory (disabling demand paging)
  - ✓ High resolution timers
  - ? Bounded latency inside the kernel
  - ? Boot-up time

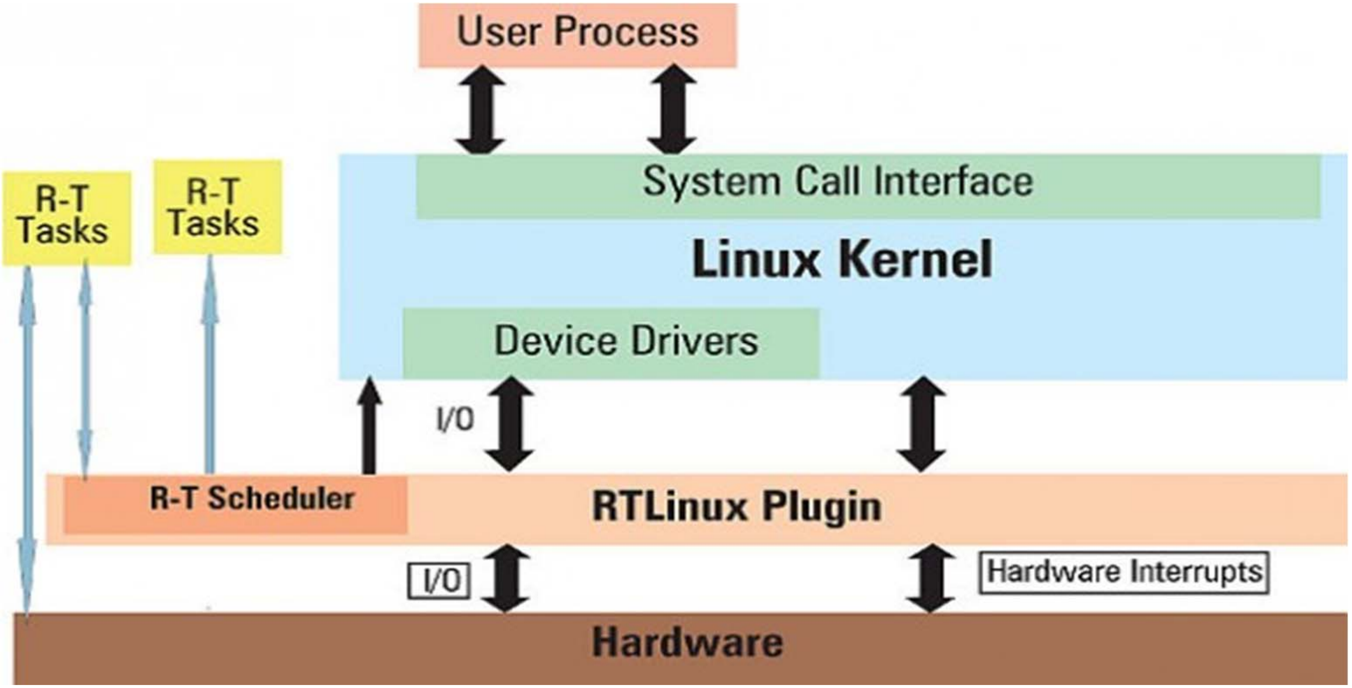
Linux Variants for RT

❒ Extensions for real-time systems

- RTLinux
- Open Event Machine
- PREEMP_RT patch



RTLinux



- Developed by Victor Yodaiken, Michael Barabanov, Cort Dougan as a commercial product at FSMLabs
- Wind River Systems acquired FSMLabs in February 2007, but ended it in 2011

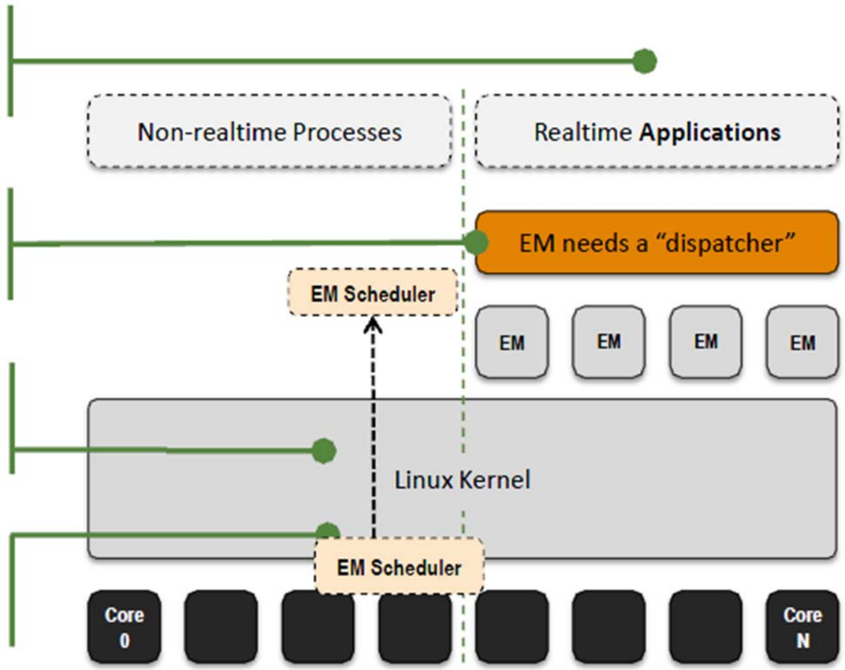
Open Event Machine

EM partitions the system into one RT domain and one non-RT domain

EM uses an event-based model, a run-to-completion model, for individual “context-less” work packages (NO threading or OS model)

Non-essential Linux processes and interrupts are migrated away from the EM cores

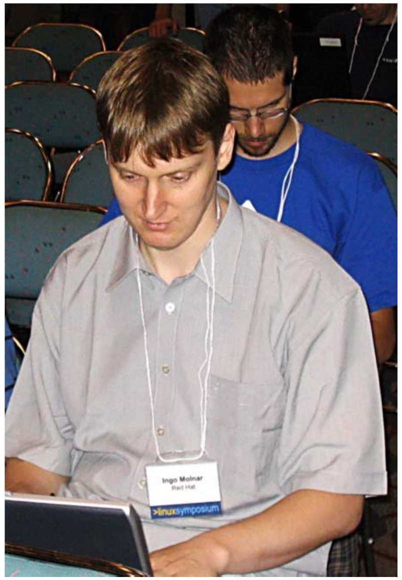
EM does not need a special interrupt handling model. Needs a “scheduler” in either Linux partition OR in HW

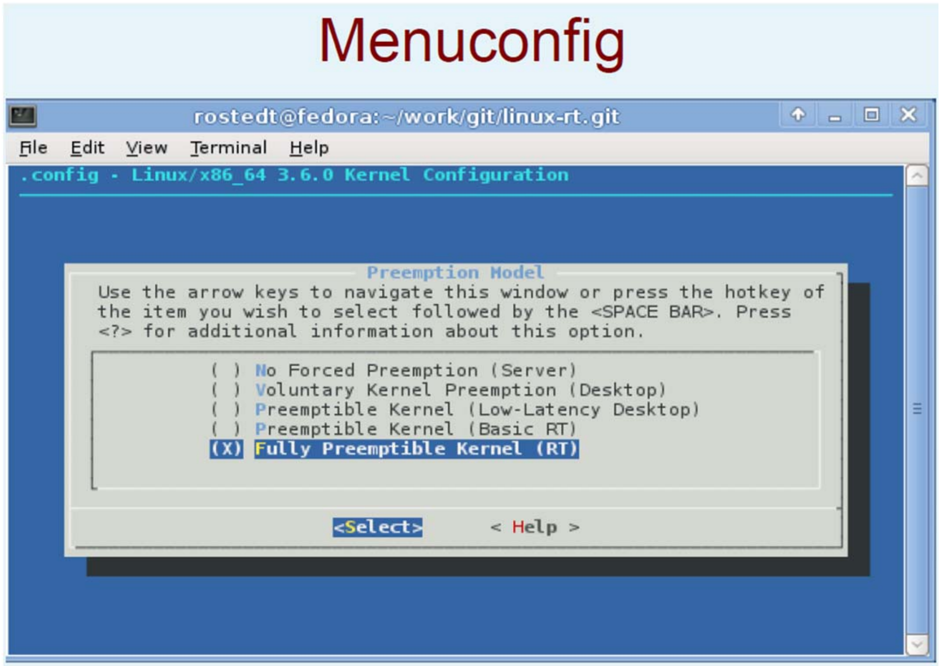


❒ Open EM has been chosen as a starting point for the OpenDataPlaneTM (ODP) initiative by Linaro, the not-for-profit engineering organization developing open source software for the ARM® architecture

PREEMPT_RT

- PREEMPT_RT has merged into the mainline kernel
  - Since August 2006 by Ingo Molnar *et al*.
  - https://www.kernel.org/pub/linux/kernel/projects/rt/





PREEMPT_RT

❒ Features

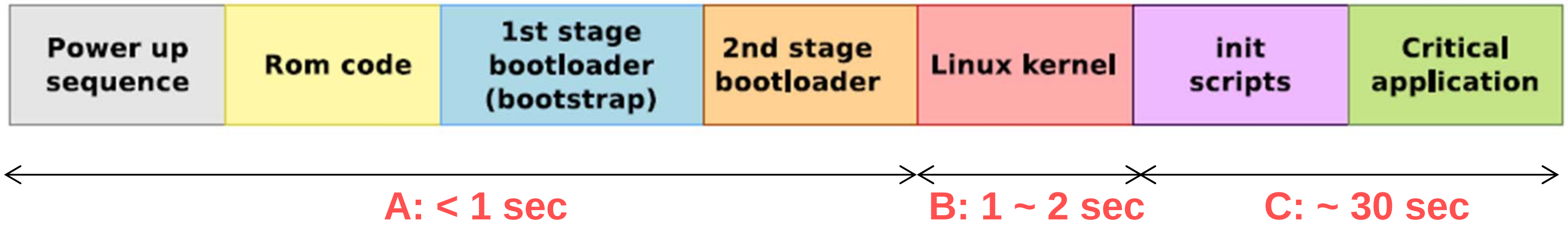
- Preemptible critical sections
- Preemptible interrupt handlers
- Priority inheritance for in-kernel spinlocks and semaphores
- Deferred operations
- Some latency-reduction measures

❒ Work is still going on

Linux Boot-up Time

❐ Generic boot sequence

A. Firmware initialization phase
B. Kernel initialization phase
C. User Space initialization phase



❐ Typical boot time

- < 60 seconds: desktops, set top boxes, GPS devices, …
- < 30 seconds: smartphones
- < 5 seconds: smart TVs

Boot-up Time Reduction

- General techniques for boot-up time reduction
  - Optimize each job of the boot sequence
  - See backup slides for details
- Snapshot-based techniques
  - Save RAM content to nonvolatile storage before power-off
  - Upon power-on, restore RAM state
- Limitations of snapshot approach
  - Stability problem
  - Retake snapshot every time power is turned off
  - Take snapshot only at “stable” state
  - Android adds another SW layer, increasing snapshot size

GPL License Issue

- GPL guarantees end users the freedoms to use, study, share (copy), and modify the software
  - Written by Richard Stallman of the Free Software Foundation (FSF) for the GNU project
- Restriction
  - Modified or derived code must be released under GPL
- LGPL (Lesser GPL)
  - Library linking is allowed without releasing the code
  - Android uses Bionic libc derived from BSD libc to isolate apps from GPL and LGPL

Multitasking without OS Support

Four Approaches to Multitasking

- Four approaches
  - Polling-based approach (PA)
  - Event-based approach (EA)
  - Schedule-based approach (SA)
  - Thread-based approach (TA)

- The first three can be implemented without operating system's support

- The above approaches can be combined
  - PA + EA, PA + SA, EA + SA, PA + TA …

Polling-based Approach

❒ Extremely simple

- No preemption and no context switch

```
void main(void)
{
    while(1) {
        if (check_A) {
            service_A();
        }
        if (check_B) {
            service_B();
        }
        if (check_C) {
            service_C();
        }
    }
}
```

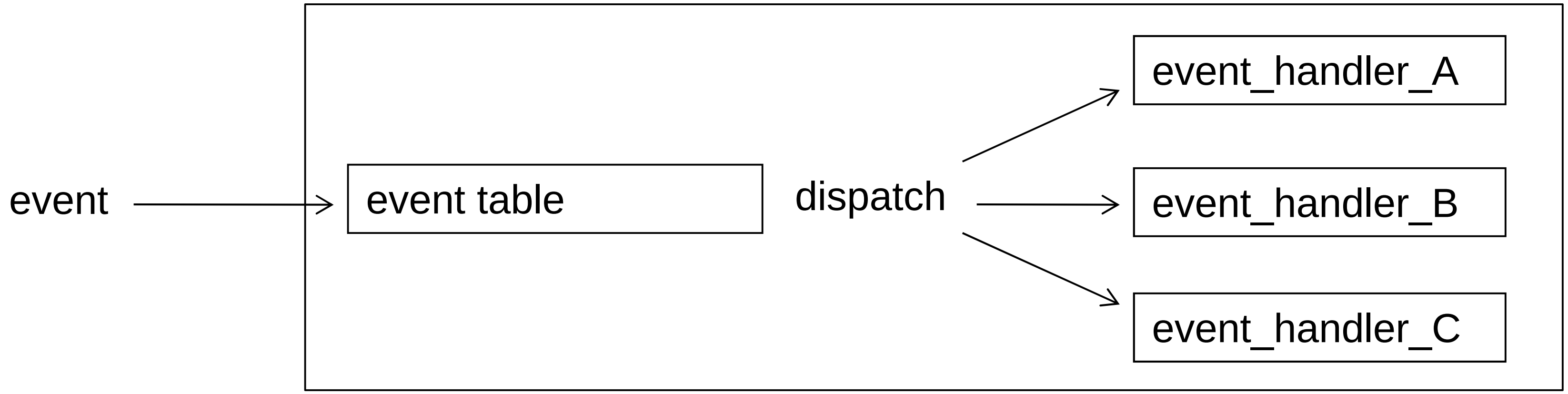
Problems with PA

- PA does not support multi-rate systems
  - Voice recorder samples microphone at 20kHz, samples switches at 15Hz, and updates display at 4Hz
- Polling frequency is limited by the time required to execute the loop
  - We may obtain more performance by testing more often
    - A/B/A/C/A/B/A/C …
- Waiting time may be very long
  - In the worst case, we need to wait for all services to be completed (no preemption)
- The architecture is fragile
  - Adding a new service will affect timing of all other services
  - Changing rates is tedious and difficult

Event-based Approach

❒ A typical approach for interrupt handling

- Possible to execute periodic tasks by using timer events
- Response time is short



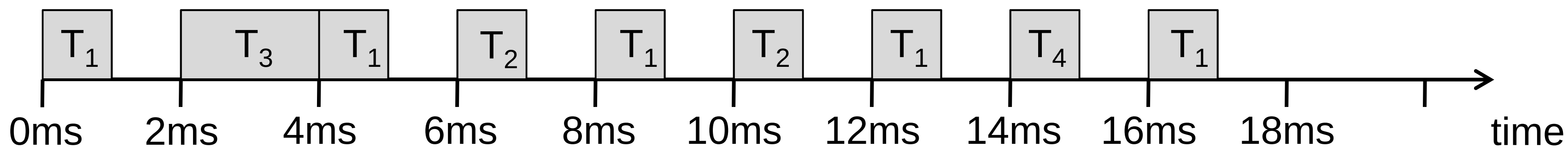
Problems with EA

- ❒ **Waiting time may be long**
  - **We need to wait for the current job to be completed (no preemption)**
- ❒ **It is hard to control the execution rate of each task**
  - **It may depend upon the frequency of event occurring**
- ❒ **Hard to apply a priority scheme**
  - **But some hardware supports priorities**

Schedule-based Approach

- **Basically meant for real-time periodic task scheduling**
  - **Off-line schedule creation**
  - **On-line task dispatching according to the schedule**
  - **Uses periodic timer interrupts (time-triggered)**

- **Four task scheduling: T_i(period, execution time)** =calendar scheduling
  - **$T_1(4, 1)$, $T_2(10, 1)$, $T_3(20, 2)$, $T_4(20, 1)$**



Some Issues with SA

- **Advantages**
  - **Deterministic behavior**
  - **Amenable to timing analysis**
  - **Jitter control**

- **We need an algorithm for off-line schedule creation**
  - **RM (rate monotonic)**
    - Tasks with small periods get high priorities
  - **EDF (earliest deadline first)**
    - Tasks with early deadlines get high priorities

- **We need WCET (worst-case execution time) for each task**
  - **Schedule must be based on WCETs**
  - **If not, tasks may overrun**

Cyclic Executive Example

```
#define MAX 10
int schedule[MAX] = {1,3,1,2,1,2,1,4,1,0};  <- task 번호
int tick = 0;

/* timer interrupt every 2ms */

void Timer_ISR()
{
    switch (schedule[tick]) {
        case 0: break;
        case 1: execute_task_1(); break;
        case 2: execute_task_2(); break;
        case 3: execute_task_3(); break;
        case 4: execute_task_4(); break;
    }

    tick = (tick + 1)%MAX;
}
```

Thread-based Approach

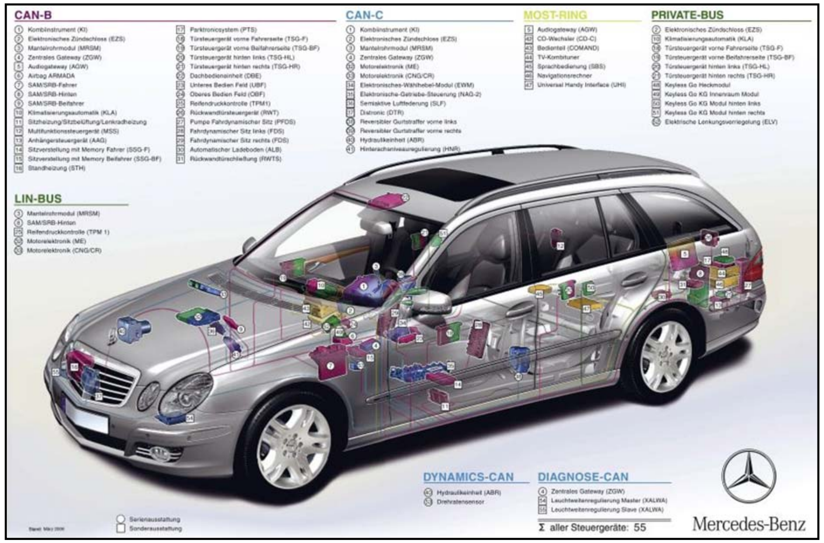
programmer가 직접 context switch timing&code 구현해야한다.

- ❒ Good for managing the inherent concurrency of an application
- ❒ Easy to apply a priority scheme or real-time scheduling policy
- ❒ Response time can be short
  - Preemption is supported
  - Blocking can be allowed in a thread, but there is no blocking for the entire application

AUTomotive Open System ARchitecture

Software Crisis?

- ❐ **Complexity: a lot of ECUs, buses, and gateways**
- ❐ **Productivity: poor reusability and composability**
- ❐ **Diversity: diverse OEMs and their suppliers**



- **55 ECUs**
- **7 Buses of 4 types**
- **4 Gateways**
- **More than 10 million LOC**

AUTomotive Open System ARchitecture

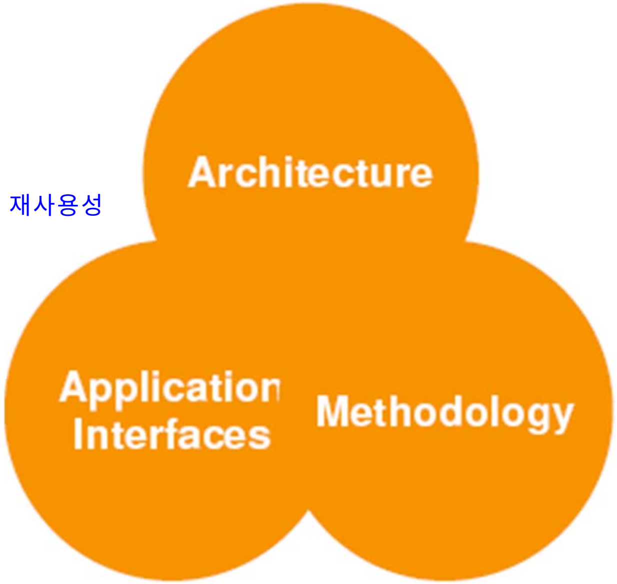
AUTOSAR - 자동차 S/W convention

❒ Standardized system S/W architecture

- OSEK kernel
- OS services and H/W abstractions

❒ Component-based application S/W 재사용성

- Standard component interfaces
- Communication middleware

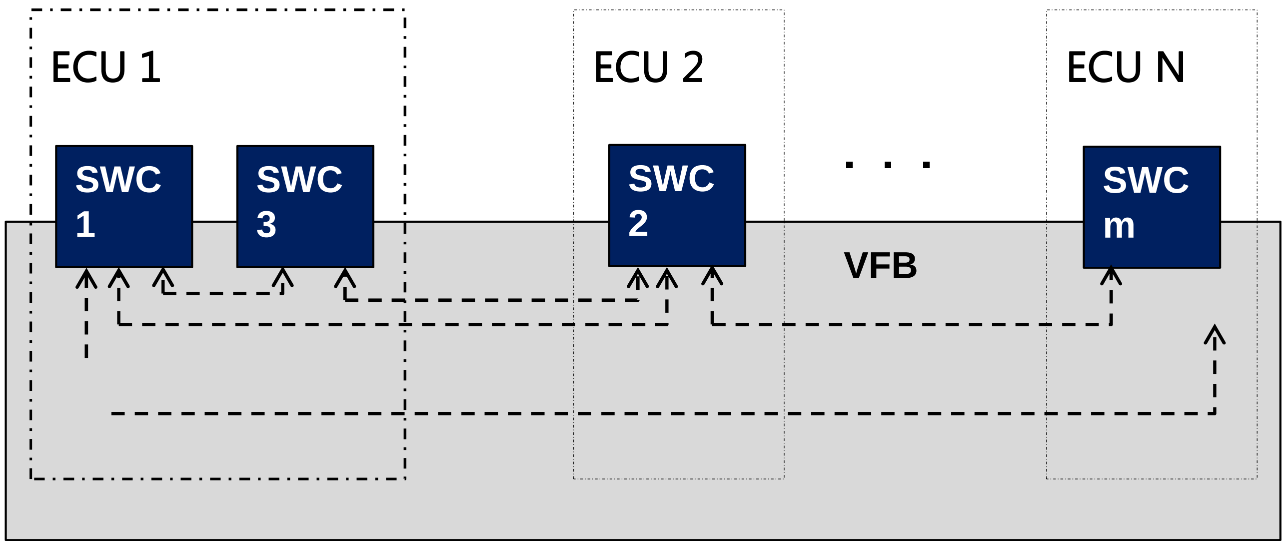


❒ Model-based development

- Authoring tools and XML formats
- Automatic code generation

SW Components and Virtual Functional Bus

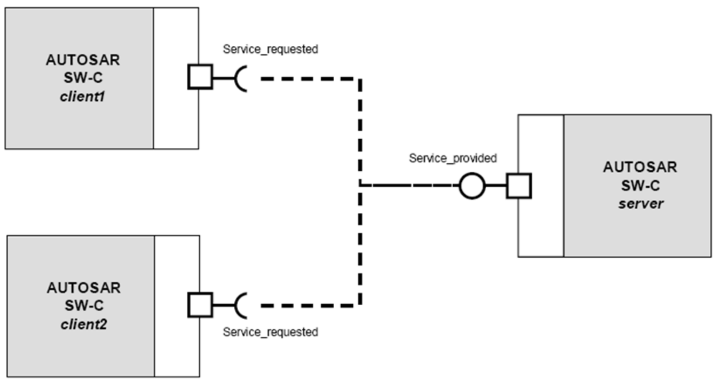
- ❒ **SWC (Software Components)**
  - Standardized interfaces
  - Reusability and composability
- ❒ **VFB (Virtual Functional Bus)**
  - Separation between software components and infrastructure



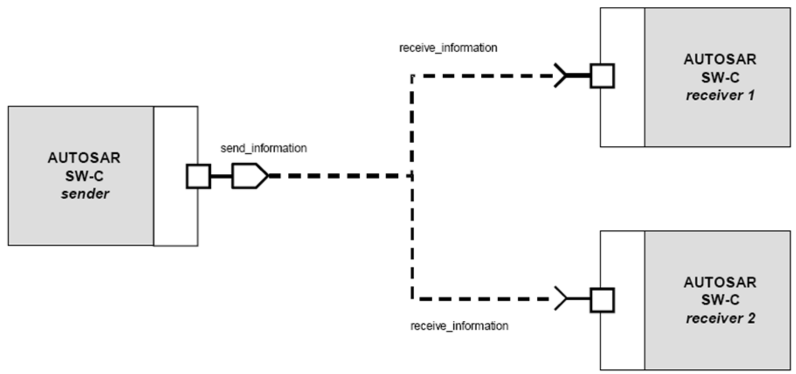
SWC and VFB

❒ Two types of communication

- Client-Server Communication
- Sender-Receiver Communication



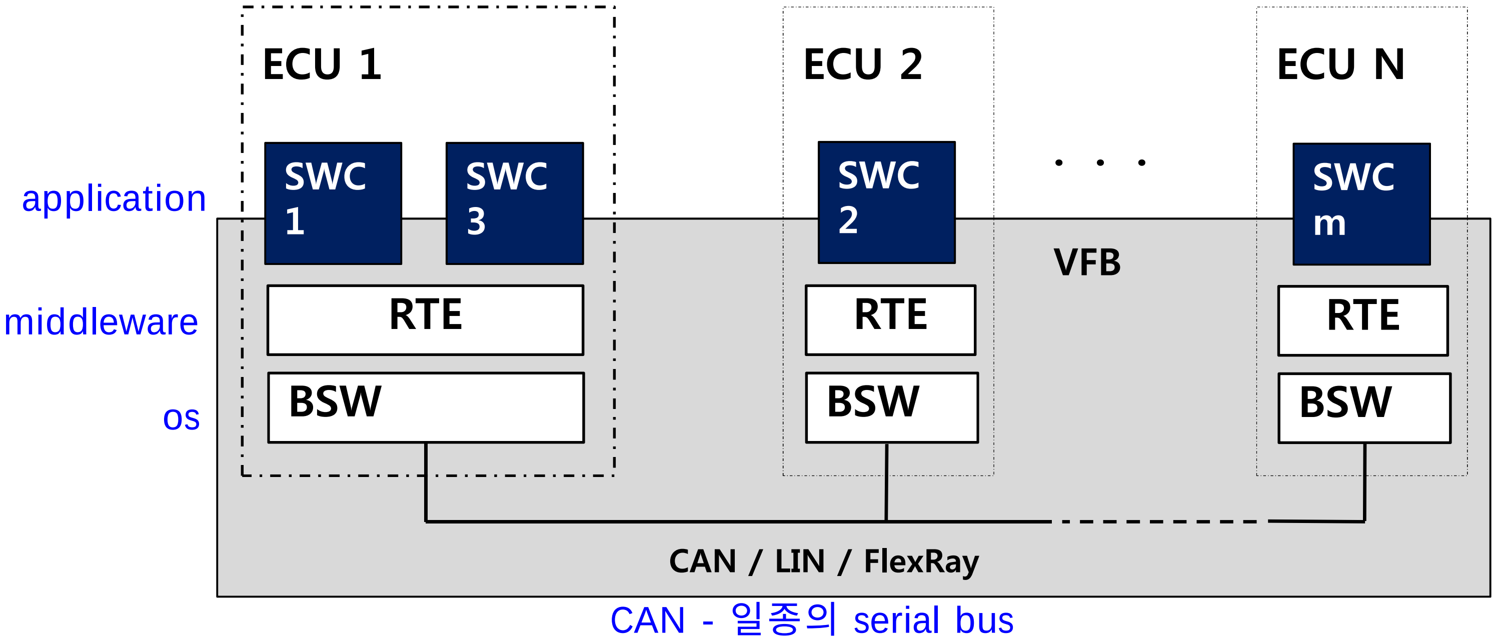
Client-Server Communication



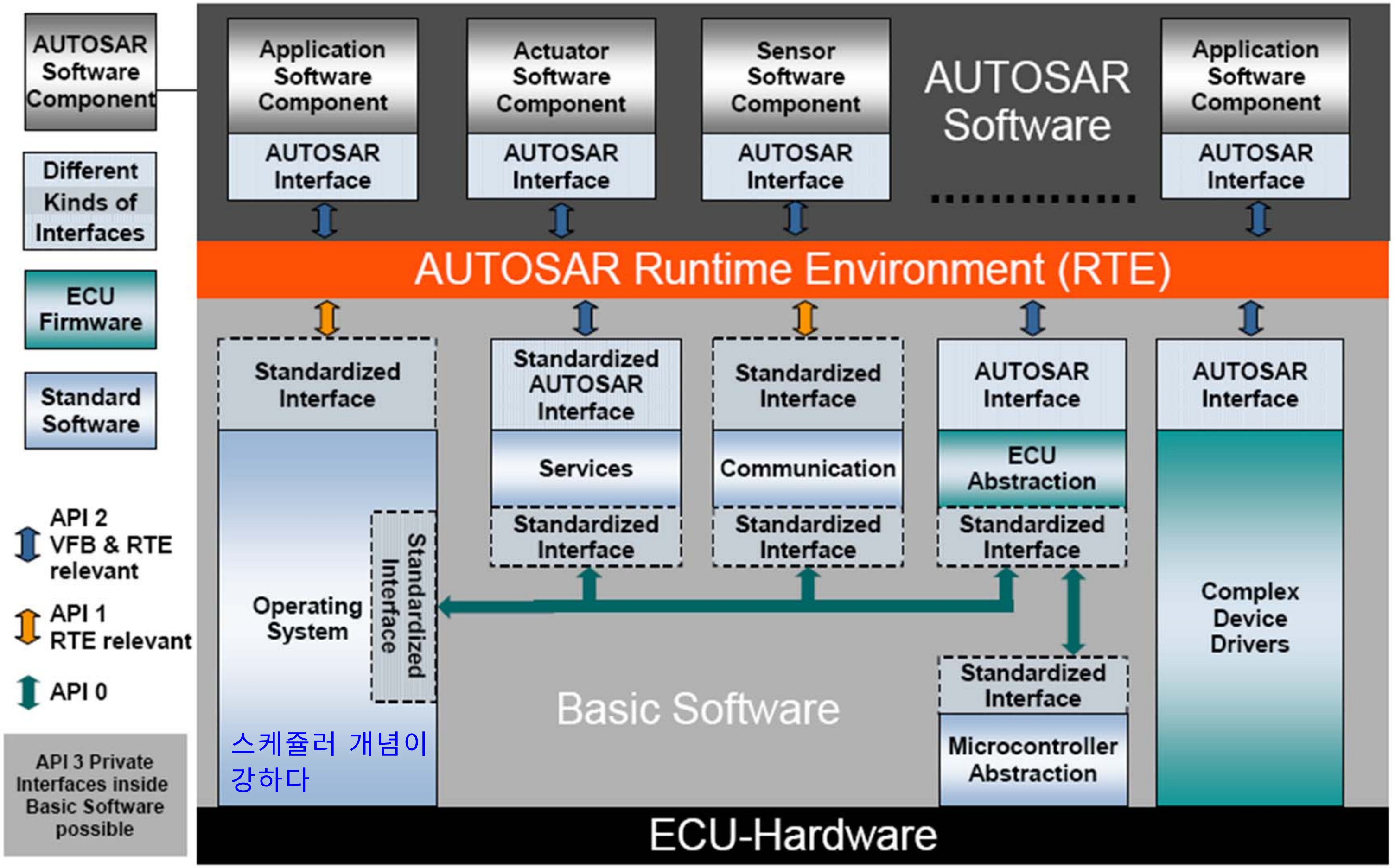
Sender-Receiver Communication

Runtime Environment and Basic SW

- **RTE (Runtime Environment)**
  - Middleware for inter- and intra-ECU communication
- **BSW (Basic Software)**
  - Traditional OS services



Layered Architecture

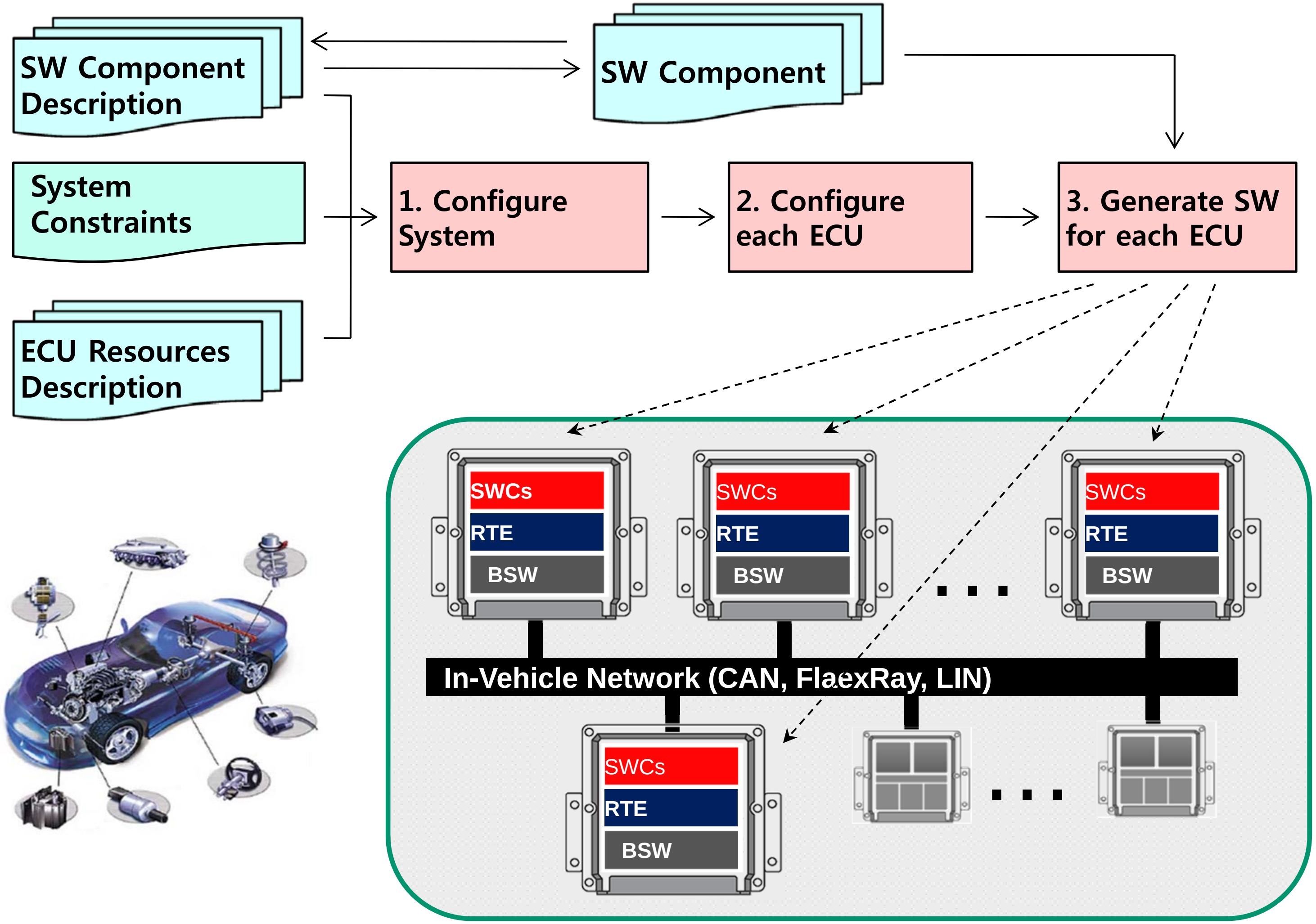


microprocessor
- cpu
microcontroller ~ SOC
- cpu+ram+통신

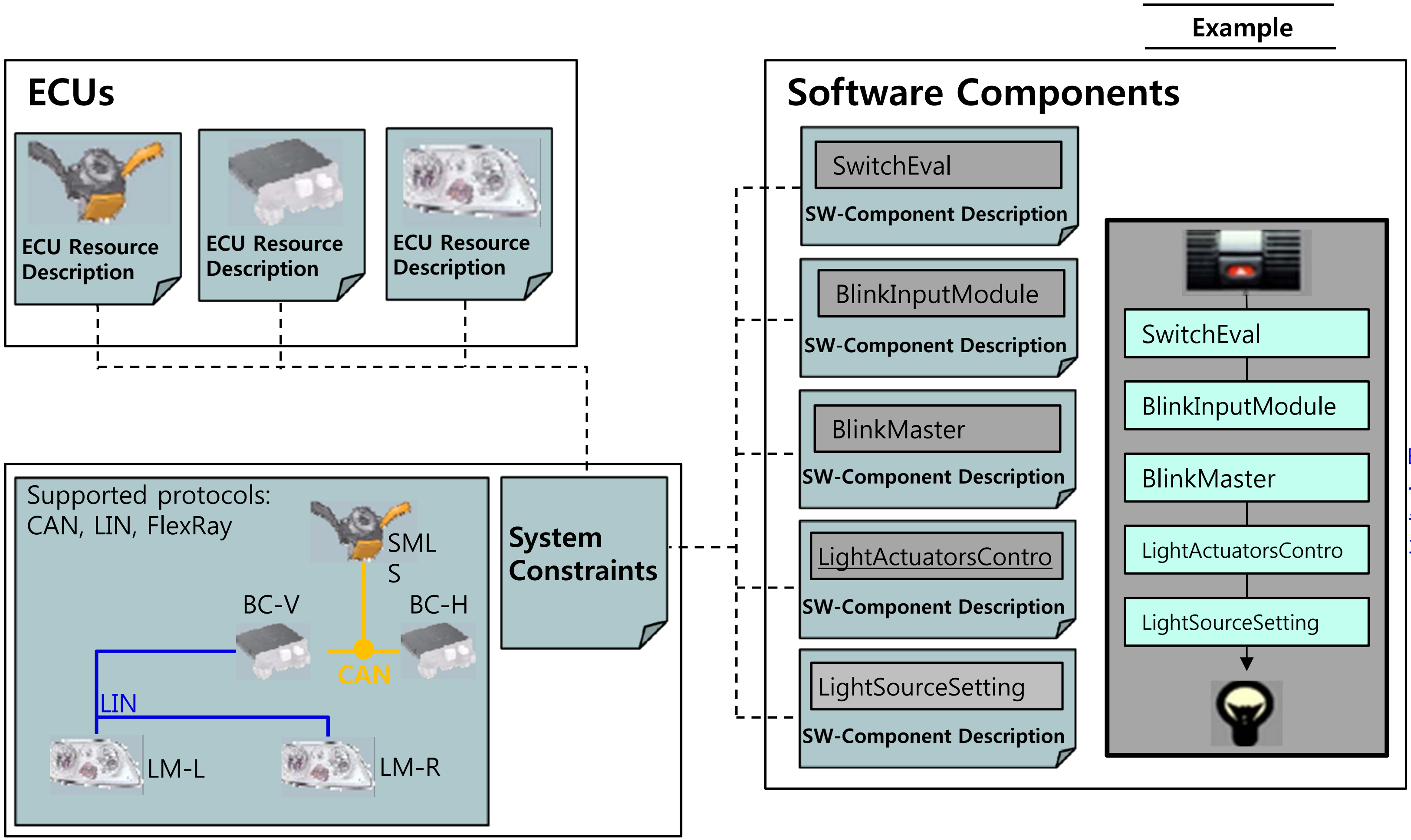
Methodology

대표 자동차 s/w 회사
1. vector tool
component <- 프로그래머가 s/w 작성
BSW RTE
2. eb tool

=> BSW/RTE가 자동으로 정해져서 compile 후 binrary executable 만듬



Input Descriptions



자동차 회사 hierarchy
조립업체
ex) 현대차
|
부품업체
티어 1 현대 모비스,만도
|
티어 2 SW,POWER 생산
| 등등등..

BMW,폭스바겐
- AUTOSAR 표준을 맞춰서 수출해야 가능 ! S/W 자체 개발이 현실적으로 어렵다.

Input Descriptions

SW Component Description

- General characteristics (name, manufacturer, etc.)
- Communication properties:
  - p_ports
  - r_ports
  - interfaces
- Inner structure (composition)
  - sub-components
  - connections
- Required HW resources:
  - processing time
  - scheduling
  - memory (size, type, etc.)

ECU Resource Description

- General characteristics (name, manufacturer, etc.)
- Temperature (own, environment, cooling/heating)
- Available signal processing methods
- Available programming capabilities
- Available HW:
  - uC, architecture
  - Memory
  - Interfaces (CAN, LIN, MOST, FlexRay)
  - Periphery (sensor/actuator)
- SW below RTE for microcontroller
- Signal path from Pin to ECU-abstraction

System Description

- Network topology
  - bus systems: CAN, LIN, FlexRay
  - connected ECUs, Gateways
  - power supply, system activation
- Communication (for each channel)
  - K-matrix
  - gateway table
- Mapping / Clustering of SW components

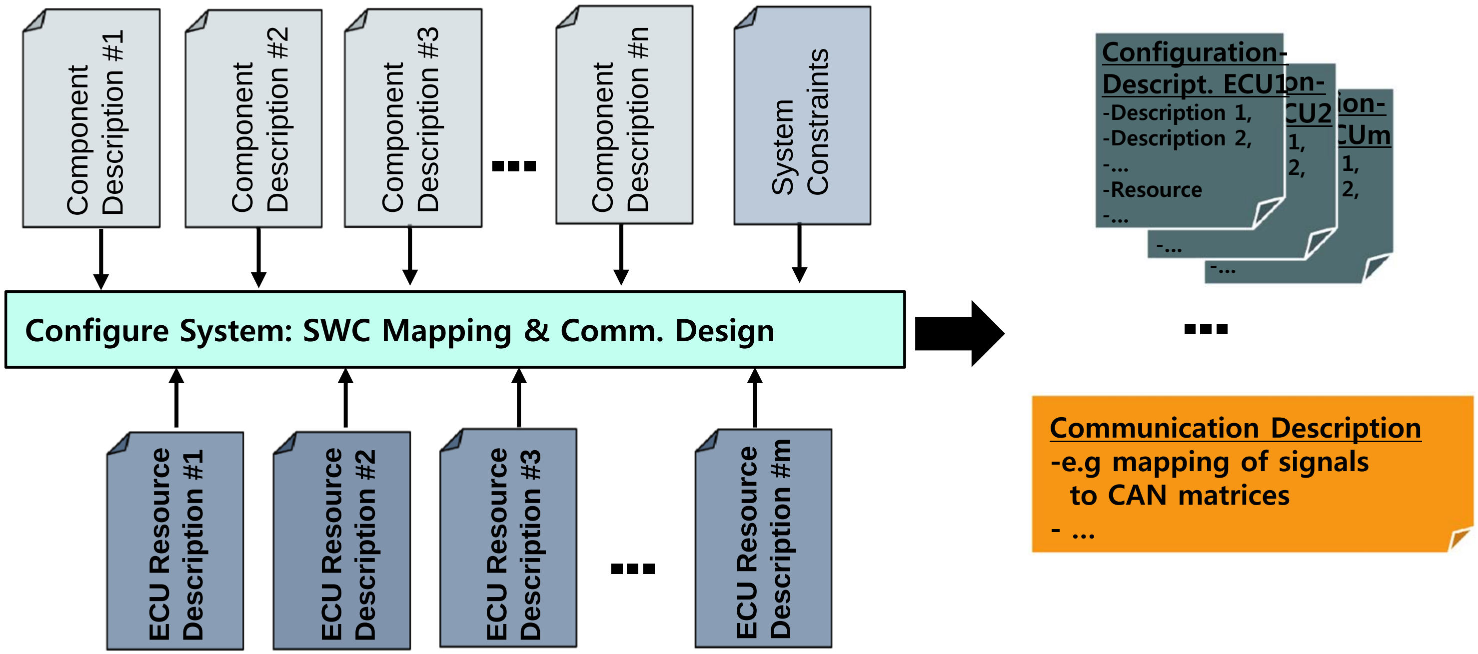
System Configuration

❒ SWC mapping

- Maps the software components to the ECUs

❒ Communication design

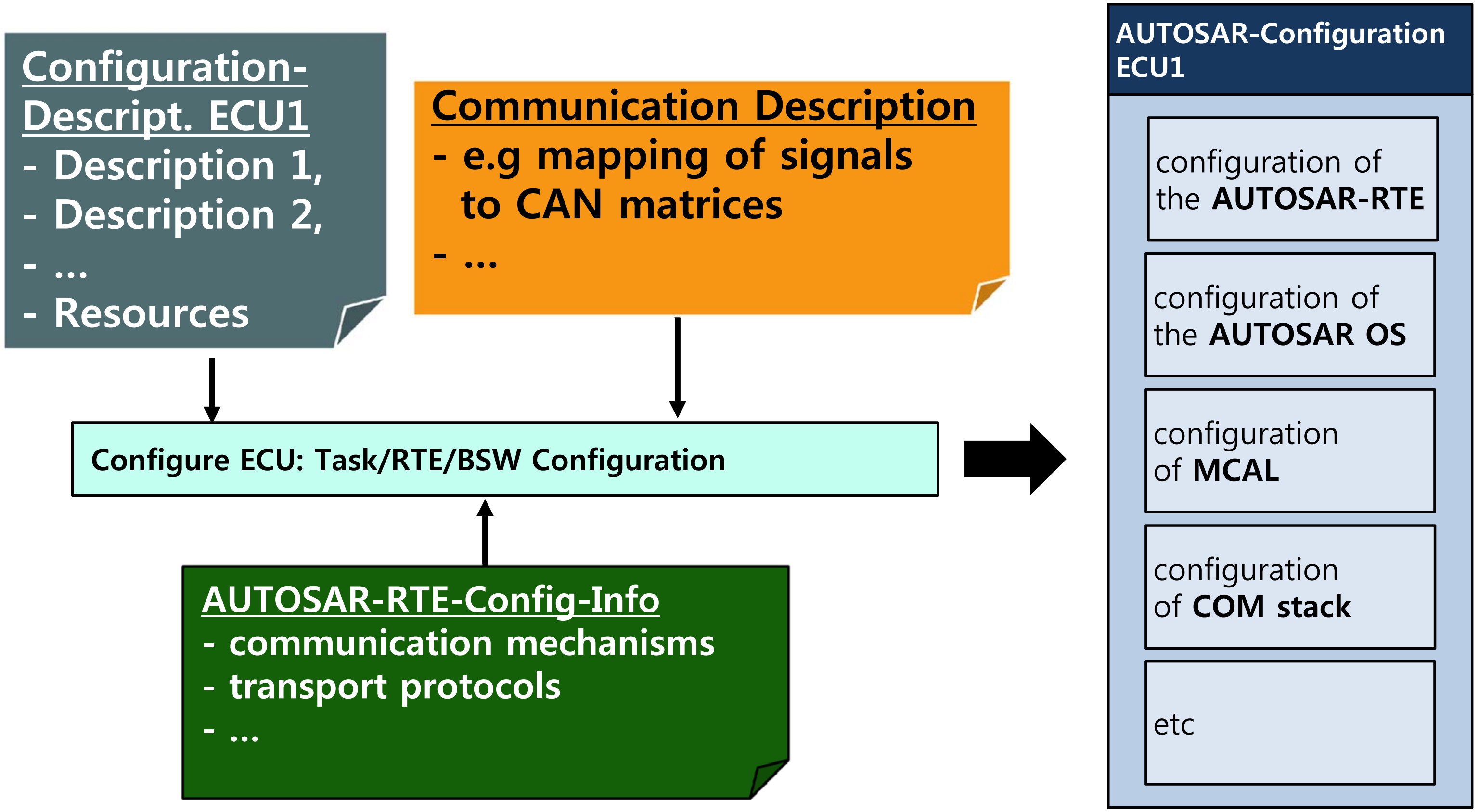
- Completely describes the frames running on the networks and the contents and timing of those frames



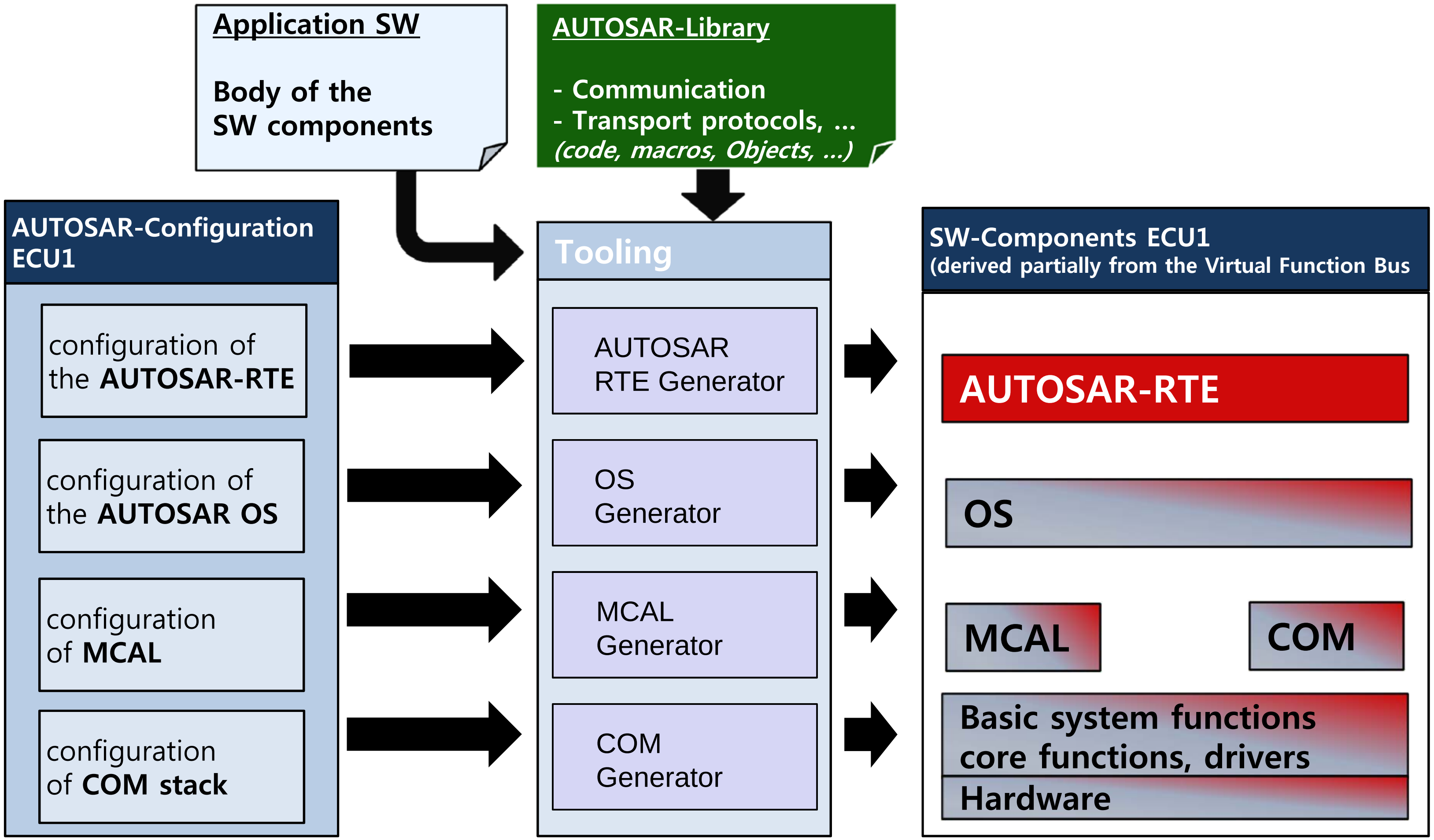
ECU Configuration

component안에 독립적으로 실행될수 있는 코드 - Runnable <- os(scheduler)가 독립적인 thread로 실행될수 있게 해준다.

- ❐ Runnable-to-task mapping and task scheduling
- ❐ RTE and BSW configuration



Software Generation



Workflow and Tools

Work	Tools
1. Control Function Design	• MATLAB, Simulink, Stateflow (Mathworks) → MIL (Model-in-the-Loop) simulation support
2. Code Generation	• Real-Time Workshop Embedded Coder (Mathworks) • TargetLink (dSPACE)
3. System Architecture Design	• SystemDesk (dSPACE) → SIL (SW-in-the-Loop) simulation support • DaVinci Developer (Vector Informatik) • RTA-RTE (ETAS) • Volcano Vehicle System Architect (Mentor Graphics)
4. BSW Configuration and Generation	• EB tresos Studio and AutoCore (Electrobit) • MICROSAR (Vector Informatik)
5. Experimenting, Testing and Debugging	• ControlDesk (dSPACE) • NUnit (Vector Informatik) • DaVinci Component Tester (Vector Informatik) • EB tresos Inspector (Electrobit)

matlab 선언형 구조로 code translation이 상대적으로 쉽다.