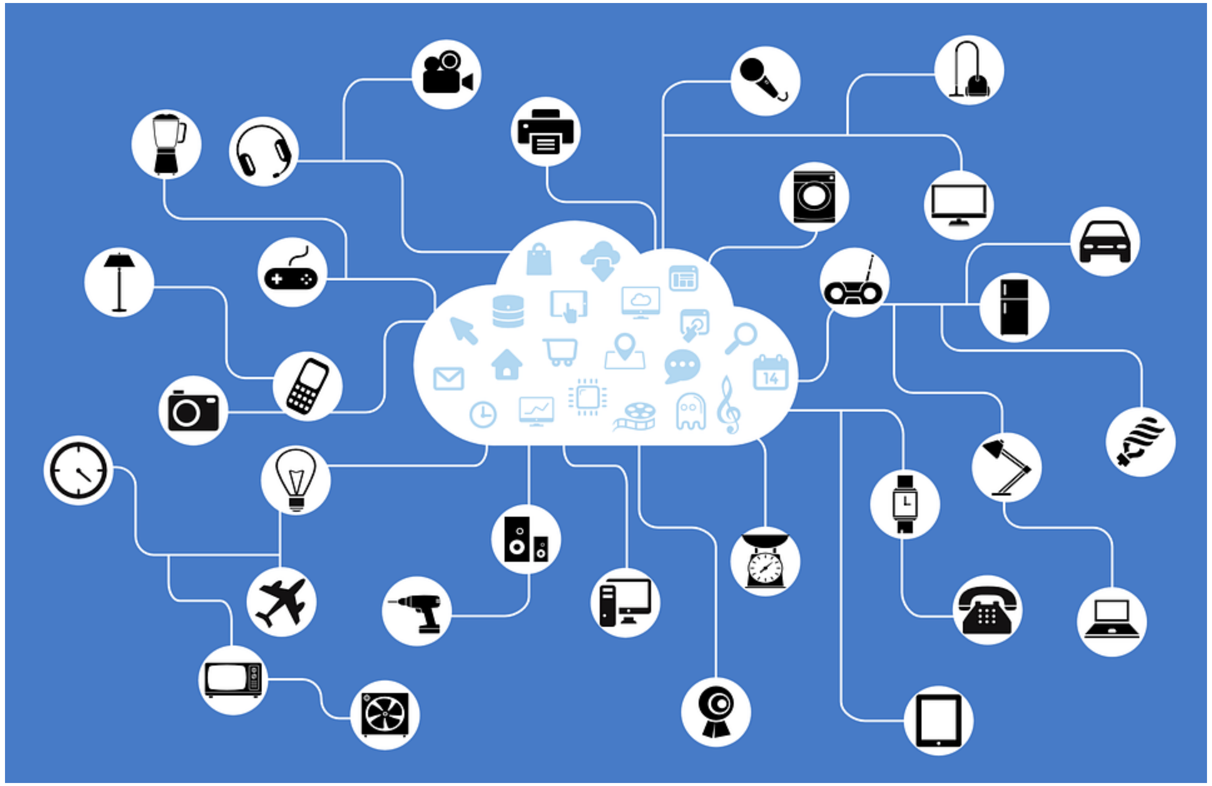
Internet of Things (IoT)

- IoT system applications
- IoT system architectures

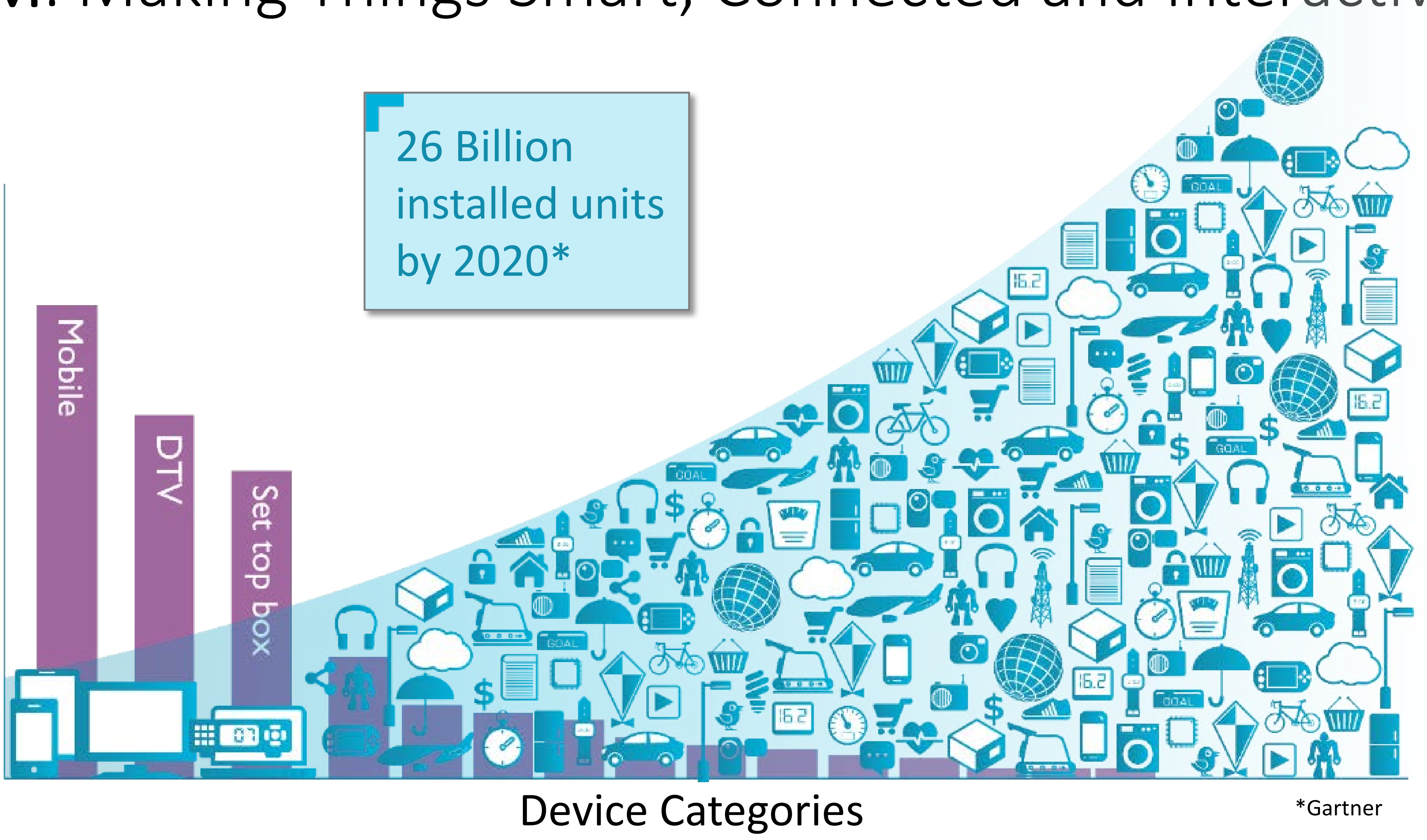
References: Wolf Text: Chapter 8

ARM SoC/IoT Presentations



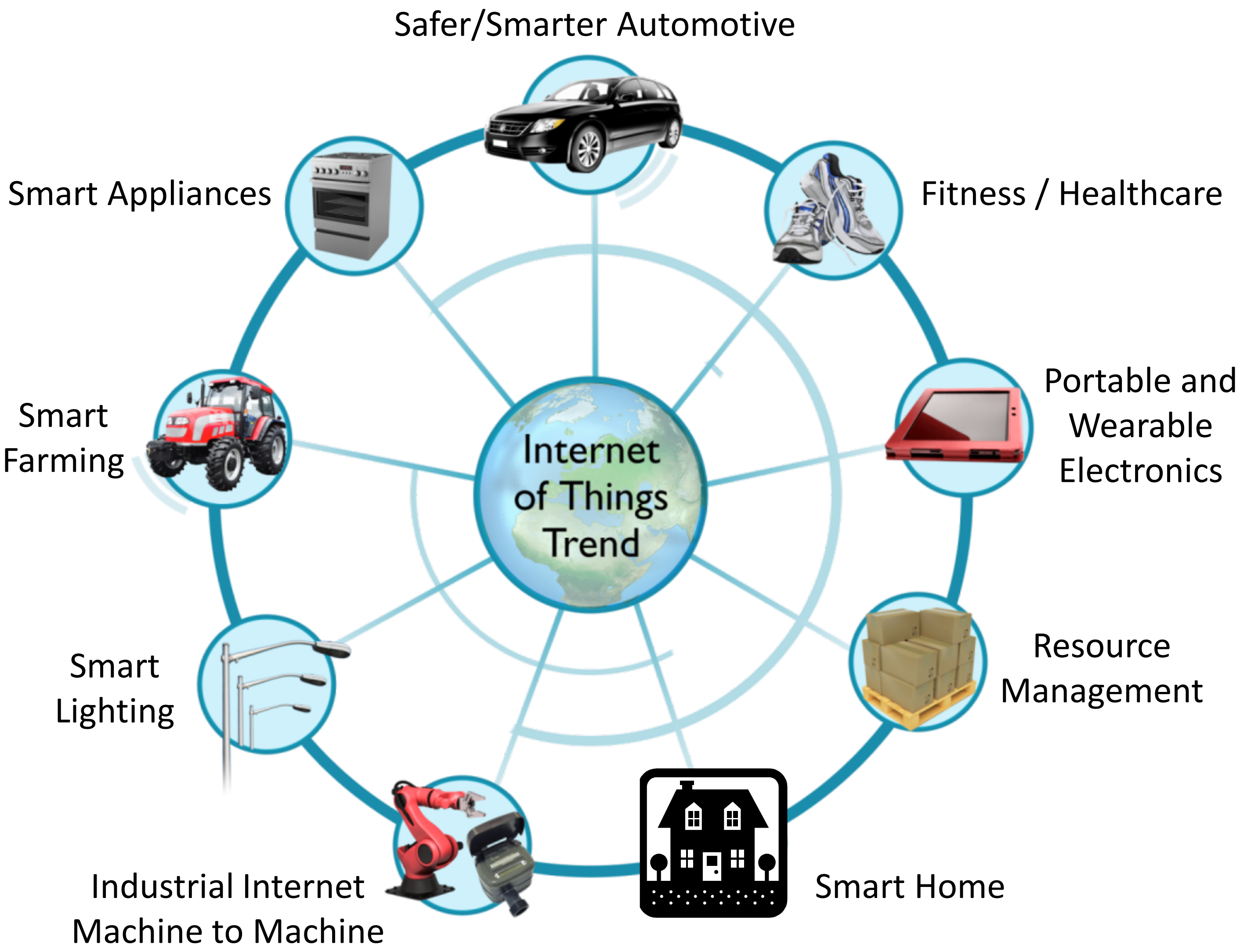
https://pixabay.com/en/network-iot-internet-of-things-782707/

ARM: Making Things Smart, Connected and Interactive



*Gartner

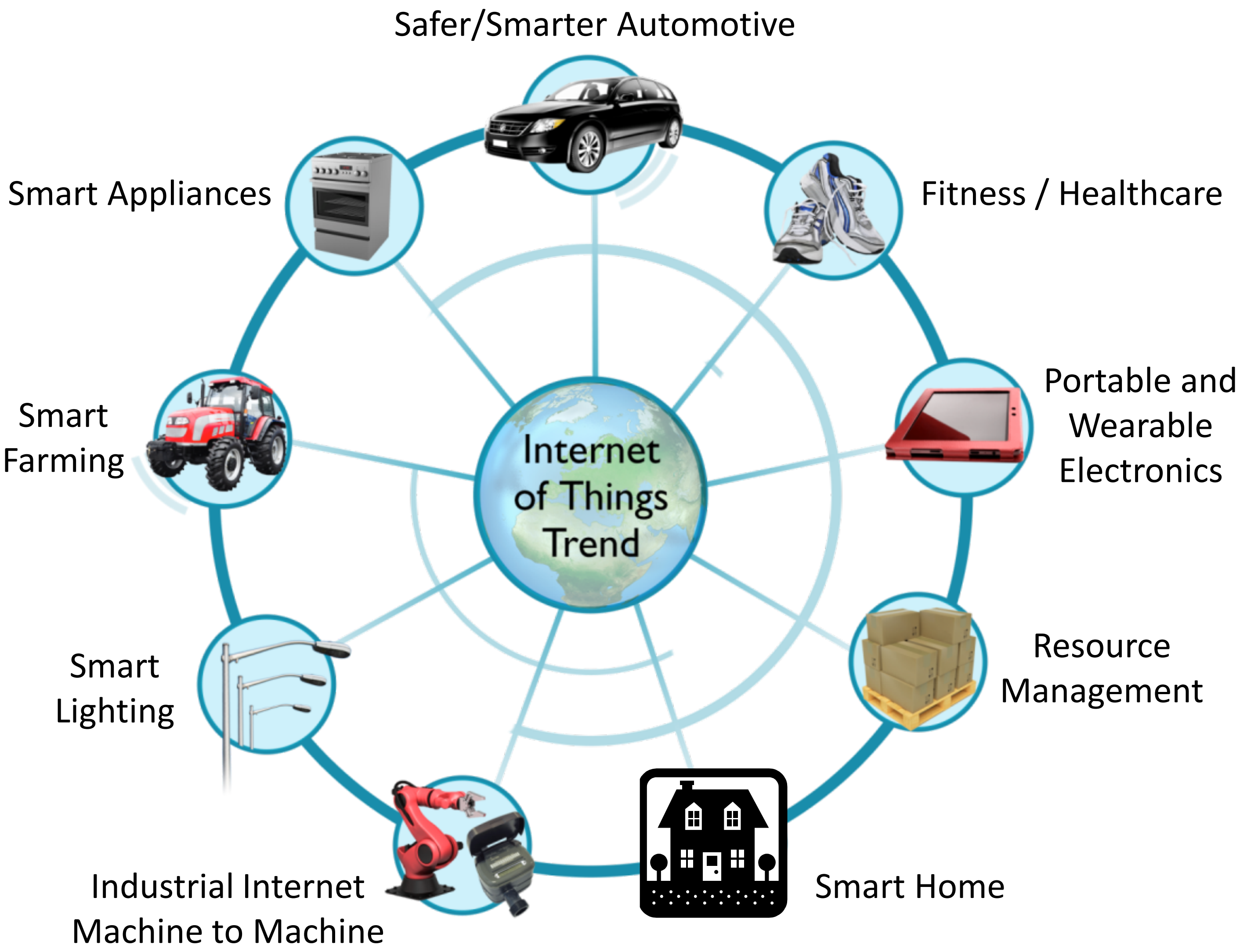
Internet of Things (IoT)



What is it?

- *"The Internet of Things (IoT) is the interconnection of uniquely identifiable embedded computing devices within the existing Internet infrastructure."* wikipedia.org
- Buzzword, trend, convenient categorisation, industrial and consumer

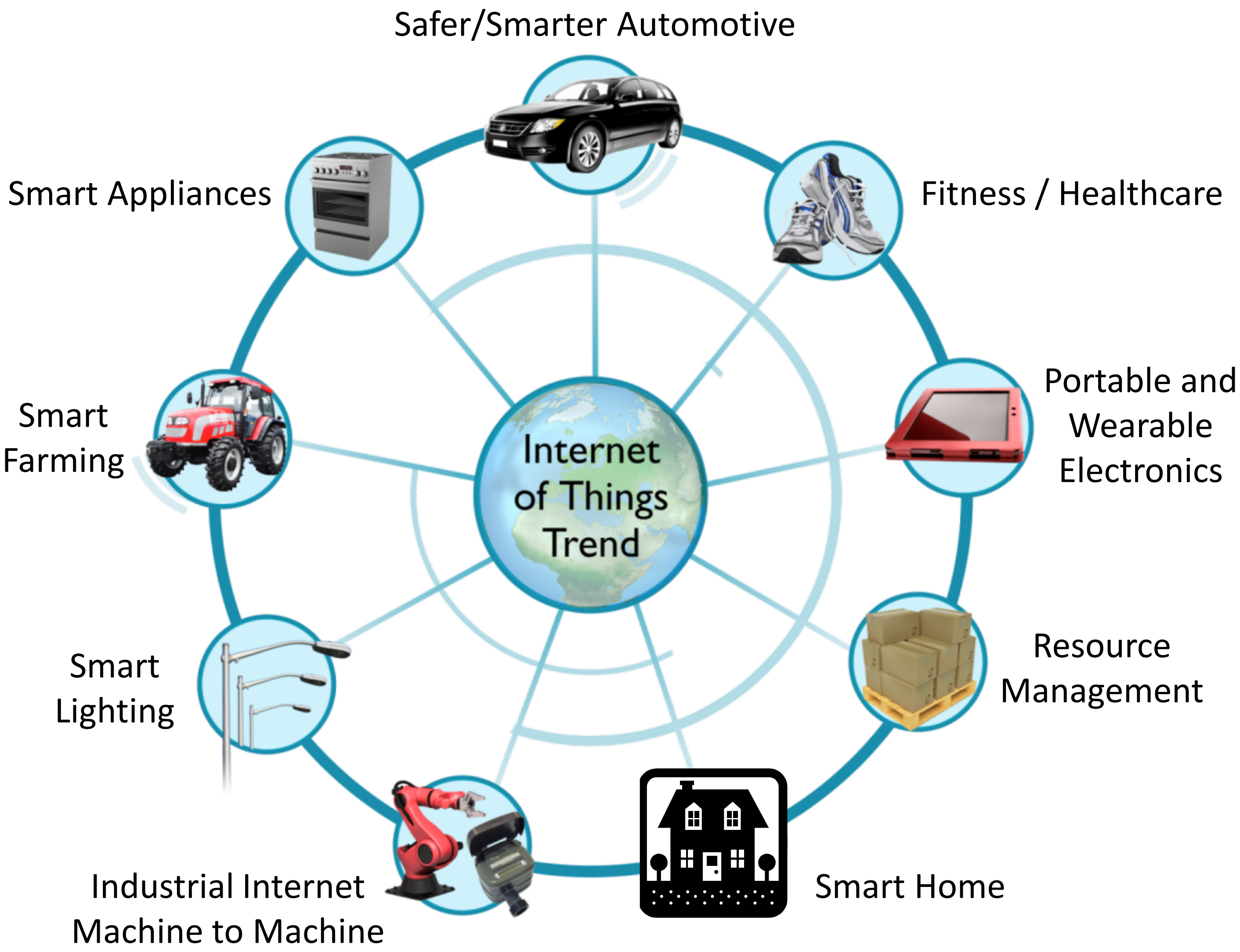
Internet of Things (IoT)



Why Now?

- Embedded chips are becoming:
  - Cheaper (<50c)
  - Smaller (<1mm^2)
  - Lower power (µW)
  - Commoditised HW and SW
- Communication is growing faster (broadband)
- New socio-economic demands (globalisation, competition, mobility)

Internet of Things (IoT)

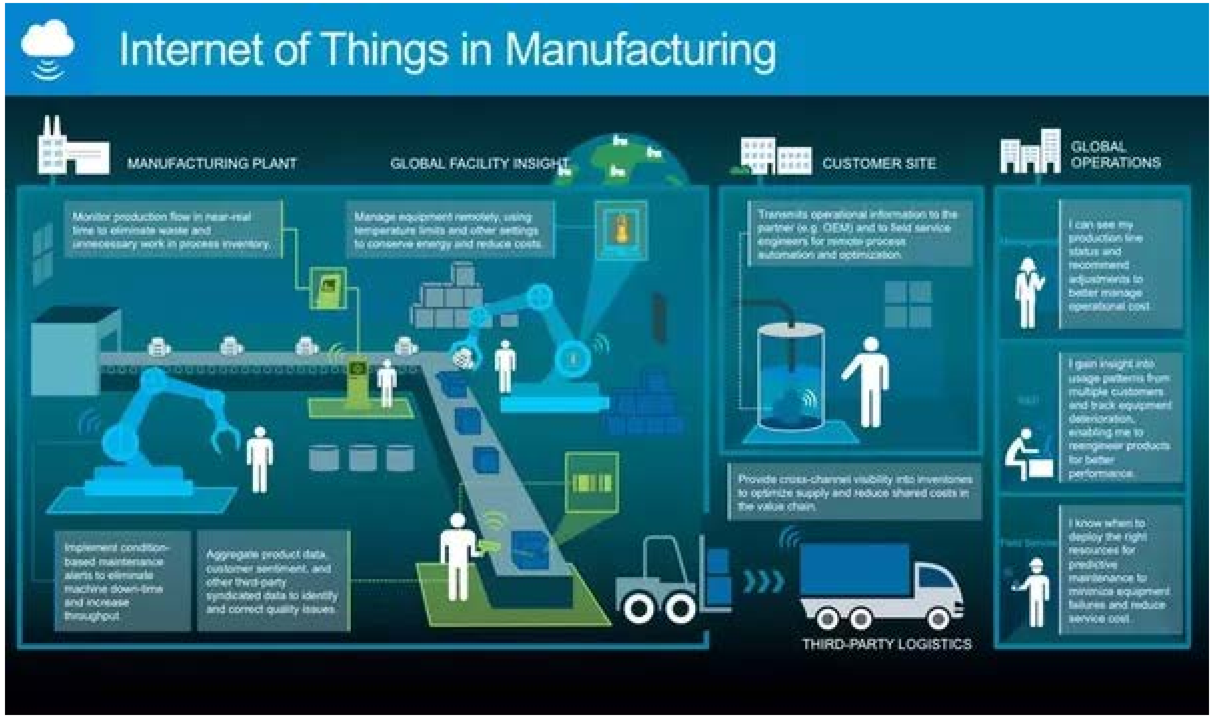


Socio-Economic Benefits

- Automation (higher productivity)
- Smart monitoring, control and maintenance (higher efficiency, lower cost, higher quality, better optimisation/outcomes)
- Better safety (early warning)
- Higher responsiveness (dynamic response to varying demands)
- Huge and varied applications in industry, agriculture, health, transport, infrastructure, smart living, consumer etc.

IoT system applications

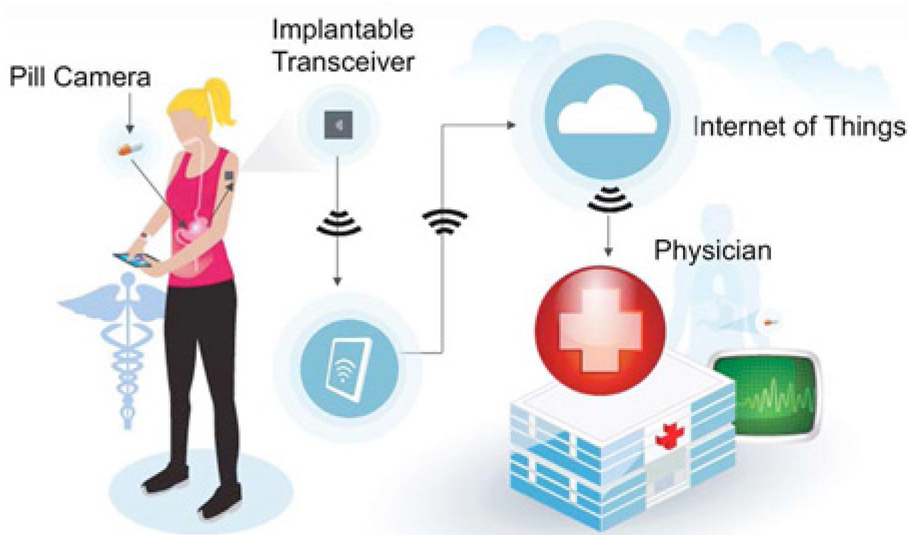
- Soft real-time networked embedded system.
  - Input devices: tags, sensors, etc.
  - Output devices: motor controllers, displays, etc.
- Examples:
  - Computer-readable identification code for objects.
  - Appliances controlled by cell phone interface.
  - Sensor network with analytics.



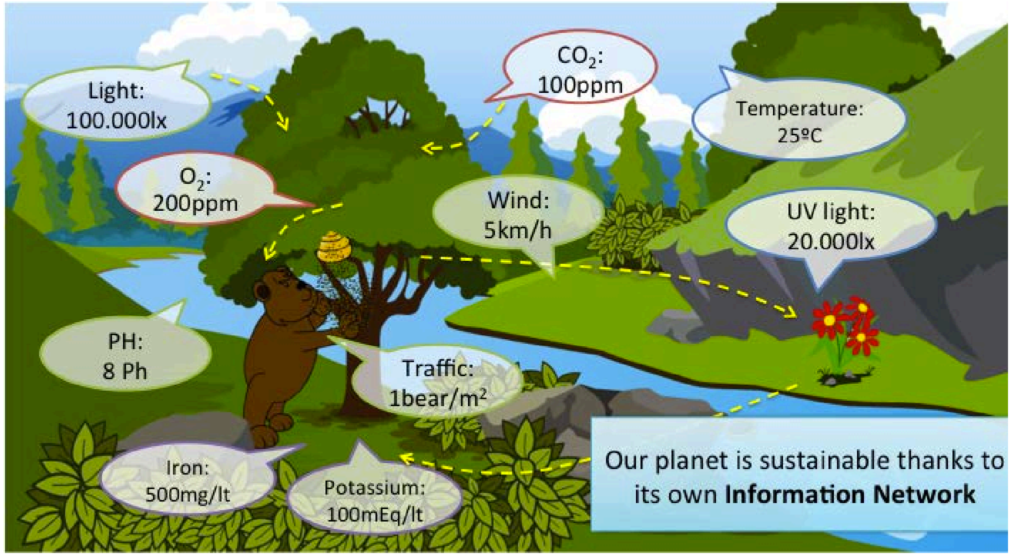
https://www.quora.com/How-is-IOT-useful-in-manufacturing

Devices

- People:
  - Implanted devices in the body.
  - Wearable devices on the body.
  - Environmental devices outside the body.
- Objects:
  - Interior: temperature sensor, etc.
  - Exterior: RFID, etc.
  - Environmental: camera, motion sensor, etc.



https://www.meddeviceonline.com/doc/how-revolutionizing-healthcare-0001



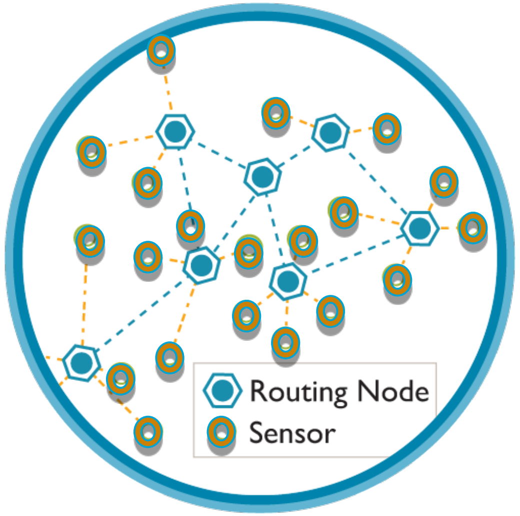
https://communicationandmediastudies.wordpress.com/2012/10/24/the-internet-of-things/

Connecting the Physical and Digital Worlds

Sensing and Controlling

- Integrated sensors, memory and processing
- Low power systems
- Little Data

Things ("Edge" Devices)



Wireless Network

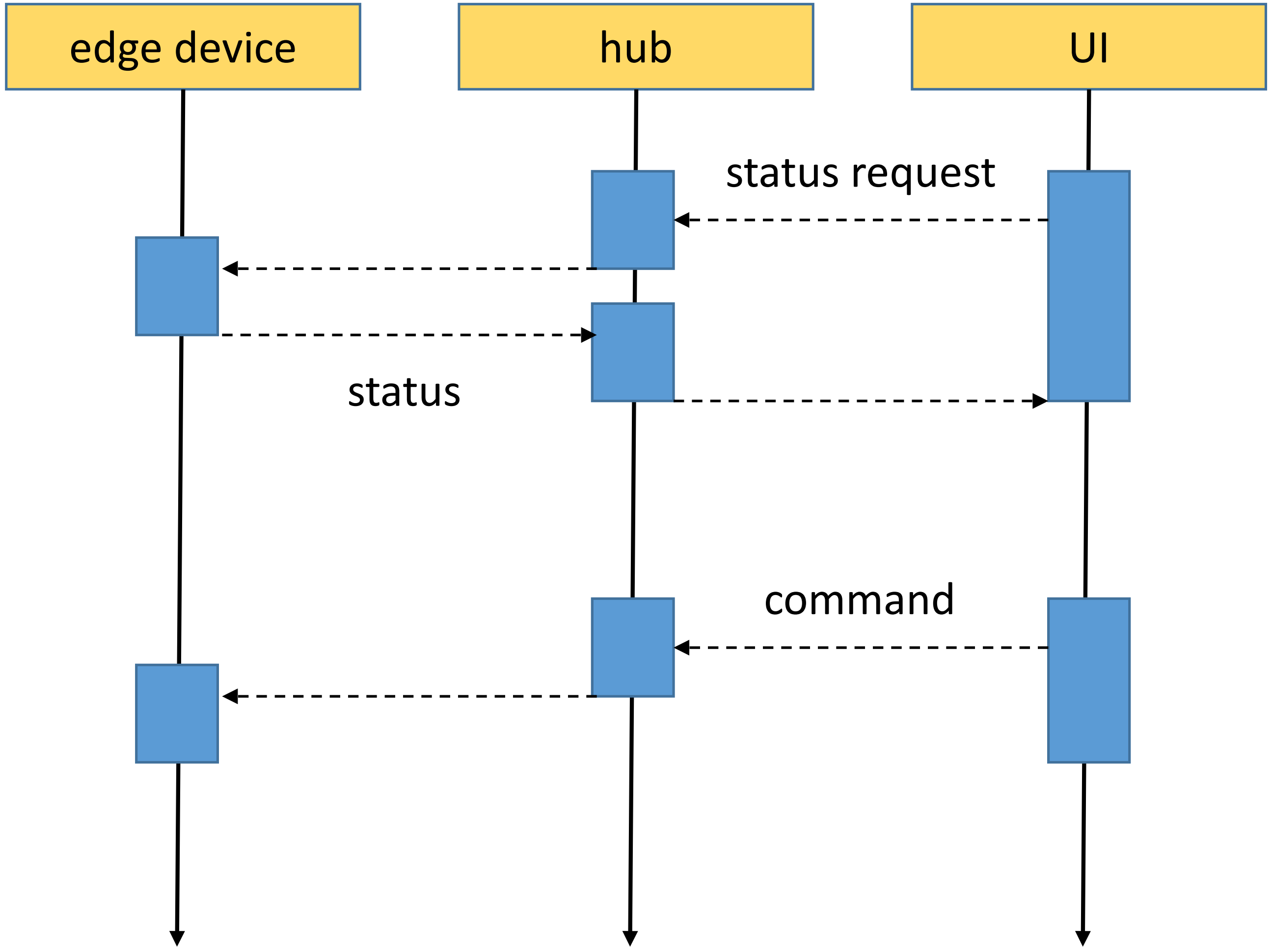
- High throughput networks
- Low power wireless networks

Cloud

- High performance efficient servers
- High capacity storage
- Software as a service
- Big Data

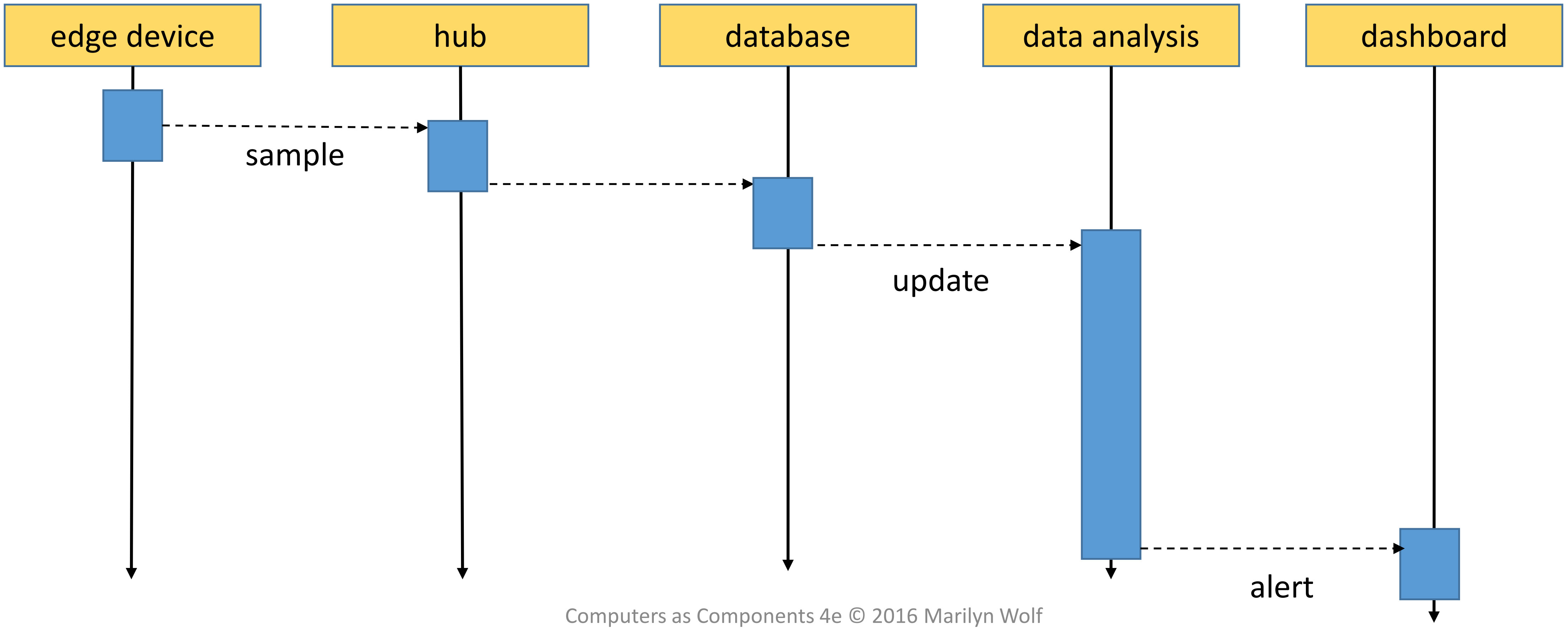
IoT system architectures

- **Edge**: I/O devices.
- **Cloud**: centralized processing.
- **Smart appliance** = connected appliance + network + UI.



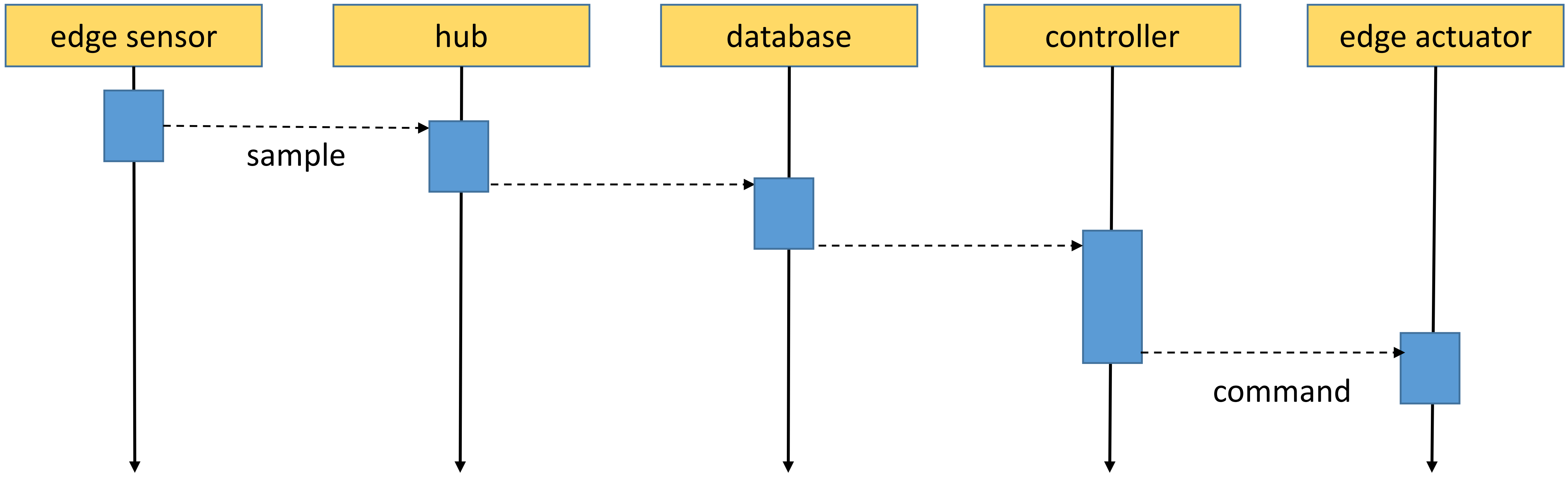
IoT system architectures, cont'd.

- **Monitoring system** = sensors + network + database + dashboard.

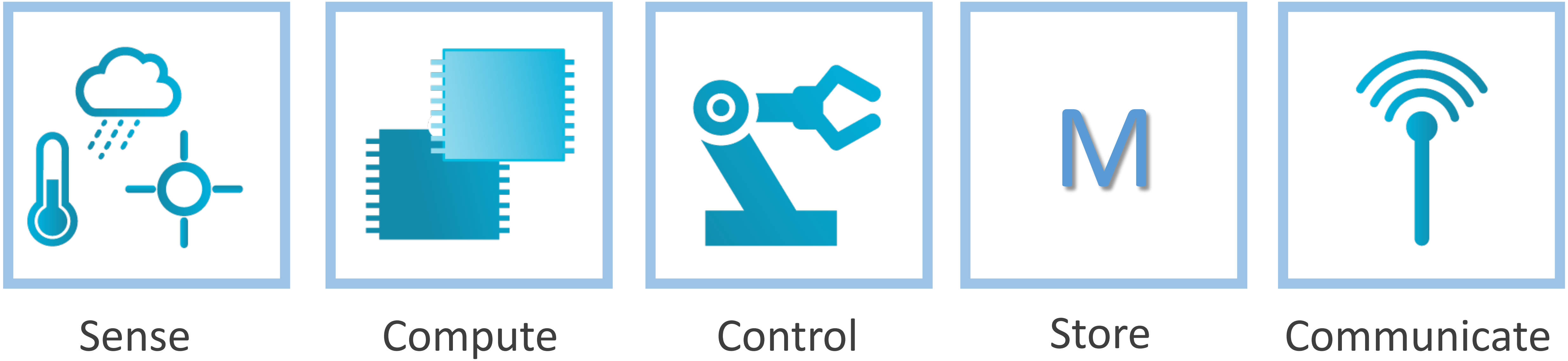


IoT system architectures, etc.

- **Control system** = sensors + database + controller + actuator.

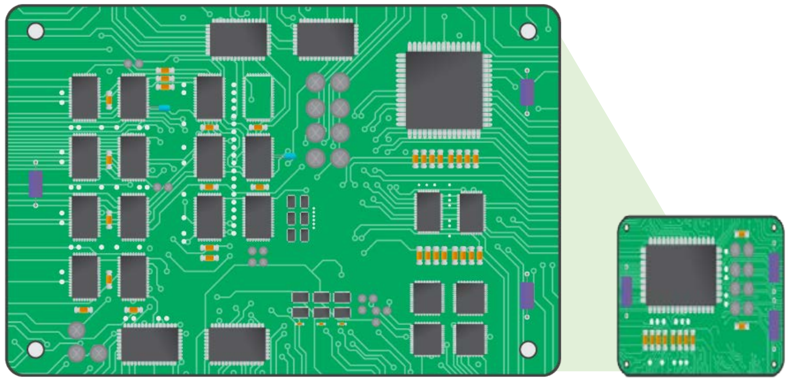


Things: Basic Building Functional Blocks



Unlock a greater potential with custom SoCs

From PCB to custom SoC



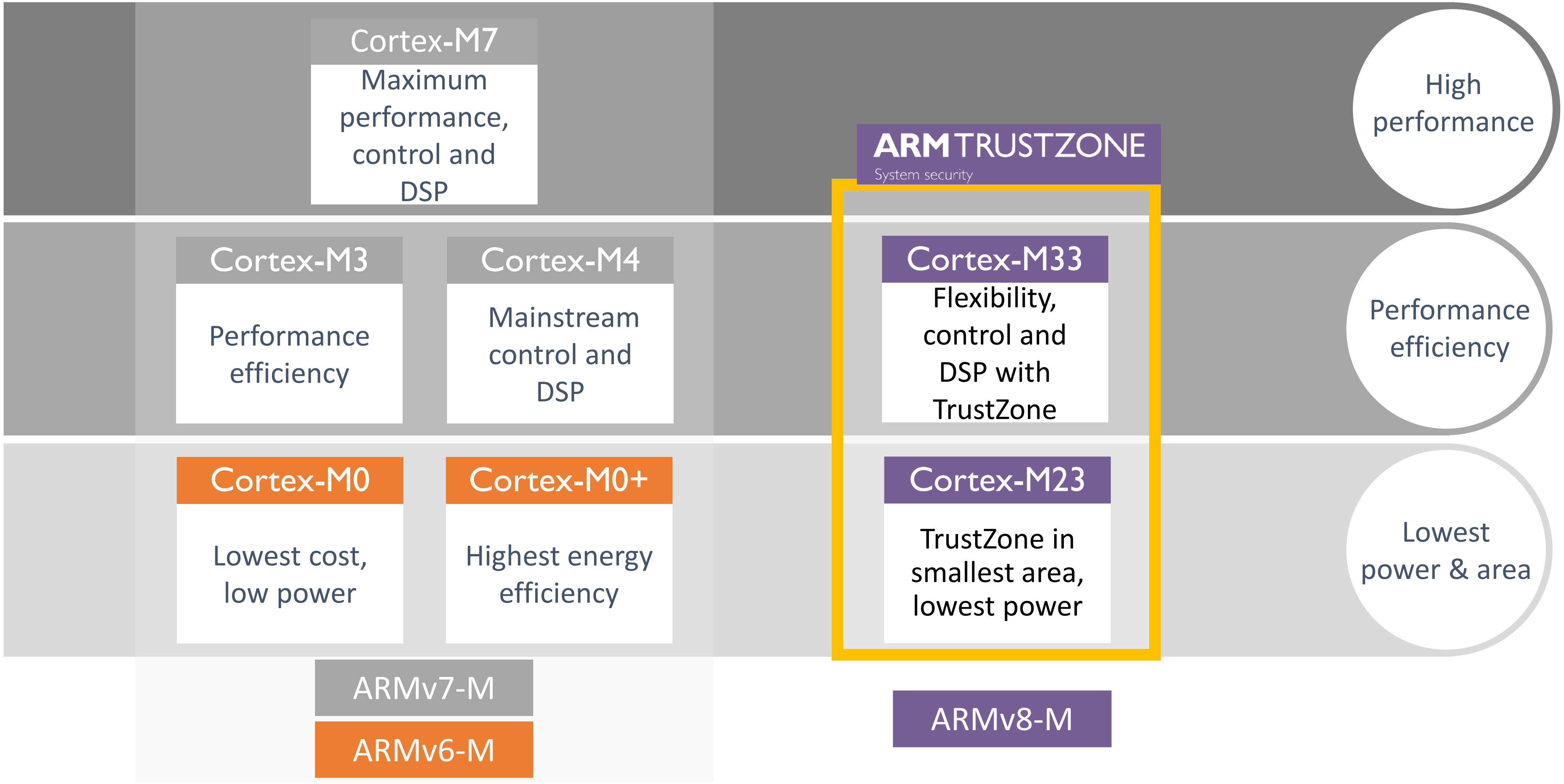
Increase margins by reducing

- Cost
- Complexity
- Size

Enhance designs with greater

- Efficiency
- Reliability
- Differentiation
- IP protection

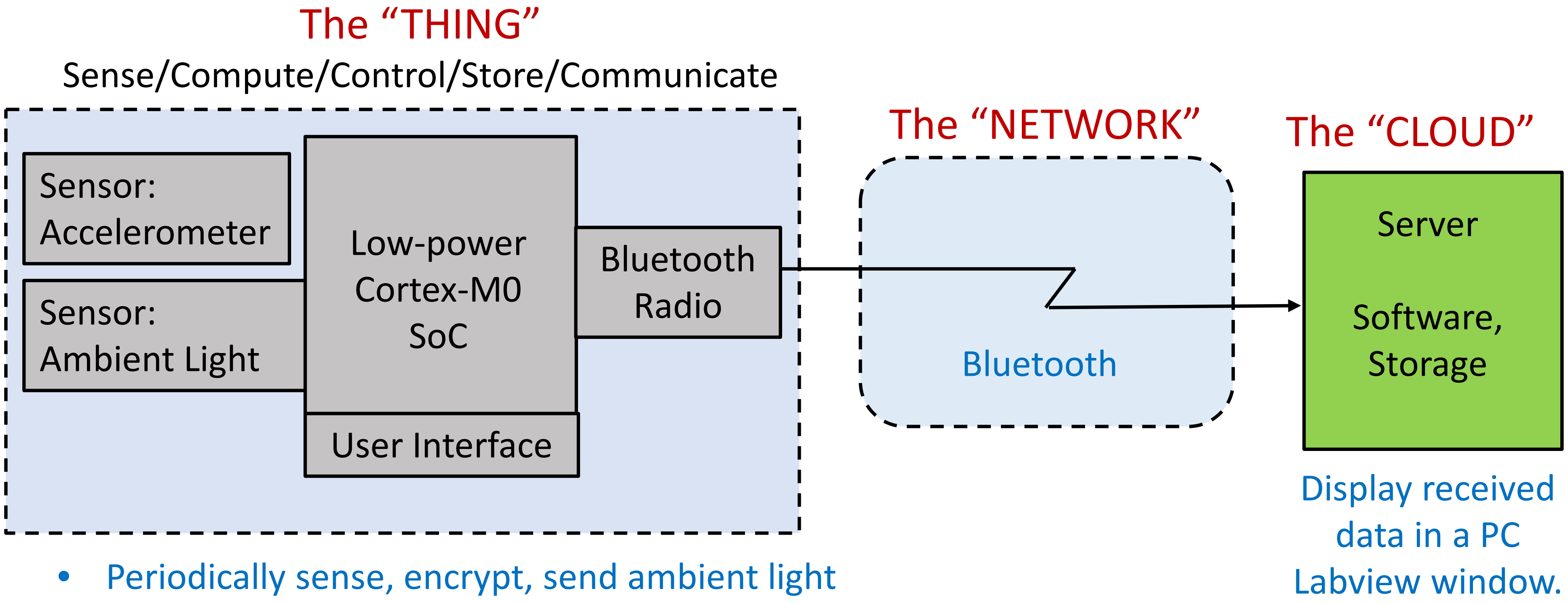
Cortex-M: Scalable, compatible and trusted



ARM Cortex-M0 DesignStart Processor

- **Subset of the full ARM Cortex-M0**
  - Low gate count, 32-bit processor, 3-stage pipeline
  - Implements ARMv6-M architecture
  - Can achieve around 0.9 DIPS/MHz
- **Provided as synthesizable Verilog model**
  - CPU contained in top-level macro-cell “**CORTEXM0DS**” (instantiated in the SoC system model) and submodule “**cortexm0ds_logic**” (pre-configured, obfuscated)
  - Top-level macro-cell implements memory and system bus interface compatible with *AMBA 3 AHB-Lite* specification, including interrupt and event inputs, 3 status outputs, and an event output.
- **DesignStart Kit** includes:
  - Simulation testbench, a set of AHB-Lite peripherals, example SoC systems

IoT Demo Architecture



- Periodically sense, encrypt, send ambient light and acceleration data to "The Cloud".
- Based on ARM SoC LiB and Cortex-M0 CPU.
- Platform: FPGA board

  (Digilent Nexys4 DDR, Numato Labs Mimas V2)

IoT SoC Application

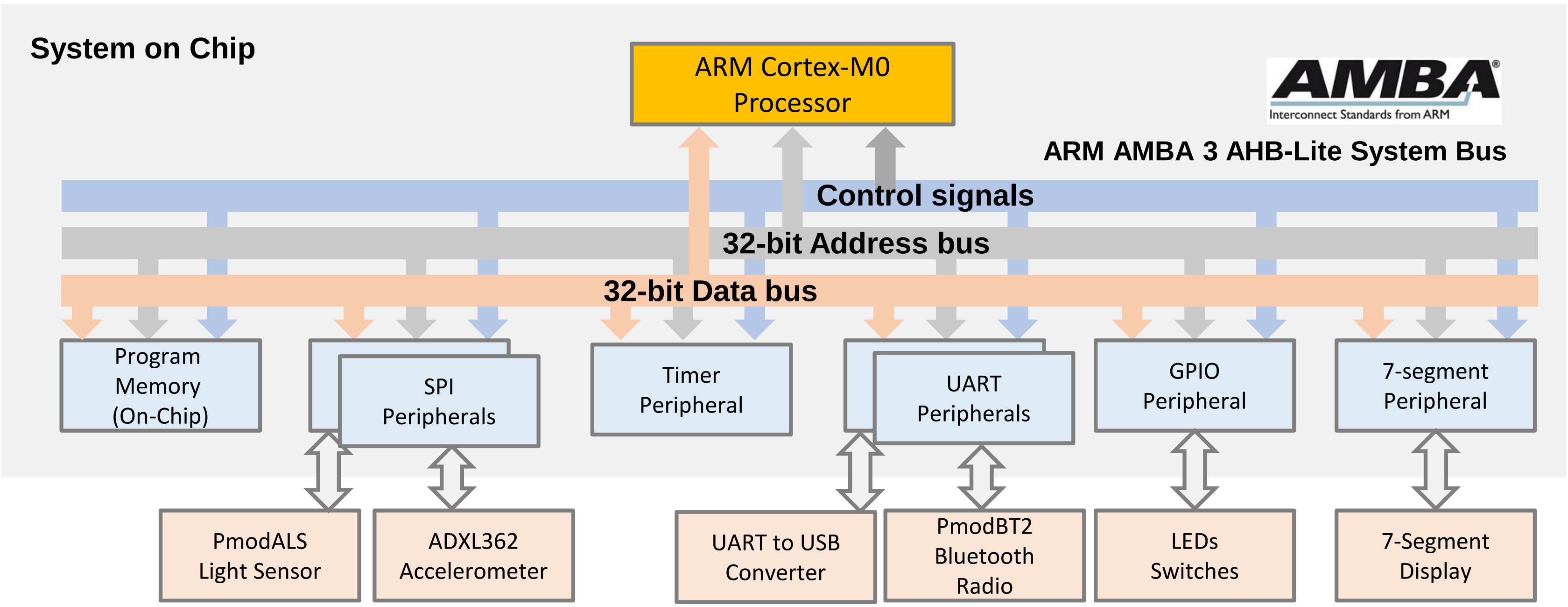
- **Periodically capture sensor data**
  - Read ambient light sensor data
  - Read X-axis/Y-axis/Z-axis acceleration data
  - Sample at 1Hz frequency (timer interrupt-driven)
- **Encrypt sensor data**
  - Tiny Encryption Algorithm (TEA)
  - Encrypt before sending (for debug - decrypt back to original data if Switch 1 on)
- **Transmit data via Bluetooth to server**
  - Simulated wireless network and “Cloud” server
  - For debug (Switch 0 on) transmit via hard-wired USB to server
- **Display sensor data in server terminal window**

IoT Demo Sensors & Communication

- **ADXL362 3-axis Accelerometer**
  - 12-bit X/Y/Z axis values + 12-bit temperature
  - On Nexys4 DDR board
  - SPI interface
- **PmodALS Ambient Light Sensor**
  - Vishay Semiconductor TEMT6000X01 ambient light sensor
  - Texas Instruments ADC081S021 analog to digital converter
  - SPI interface
- **PmodBT2 Bluetooth Interface**
  - Roving Networks RN-42 Bluetooth (2.1, 2.0, 1.2, 1.0)
  - UART interface

IoT SoC Hardware

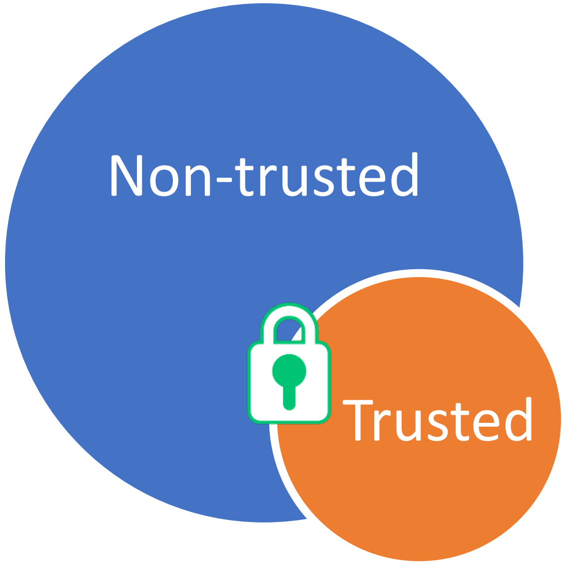
- ARM Cortex-M0 “Design Start” CPU
- Program and data in distributed/block RAM in FPGA
- Peripherals: basic I/O, timer, UART, SPI (all except SPI in the SoC LiB)
  - Sensors accessed via SPI
  - Wireless and wired communication via UARTs
- CPU and peripherals interconnected via *AHB-Lite* bus



Things: The Security Challenge

Flexible embedded device security

- Security important as more embedded devices become connected
- Even the smallest of devices need to
  - Safely store and process secrets
  - Have secure communications (i.e., encryption)
  - Offer trust in the integrity of the device and its software
  - Be able to isolate trusted resources from non-trusted
  - Reduce attack surface of key components



… without compromising on latency, determinism or footprint.

ARM TrustZone Technology

ARM TRUSTZONE
System Security

Bringing ARM security extensions to the embedded world

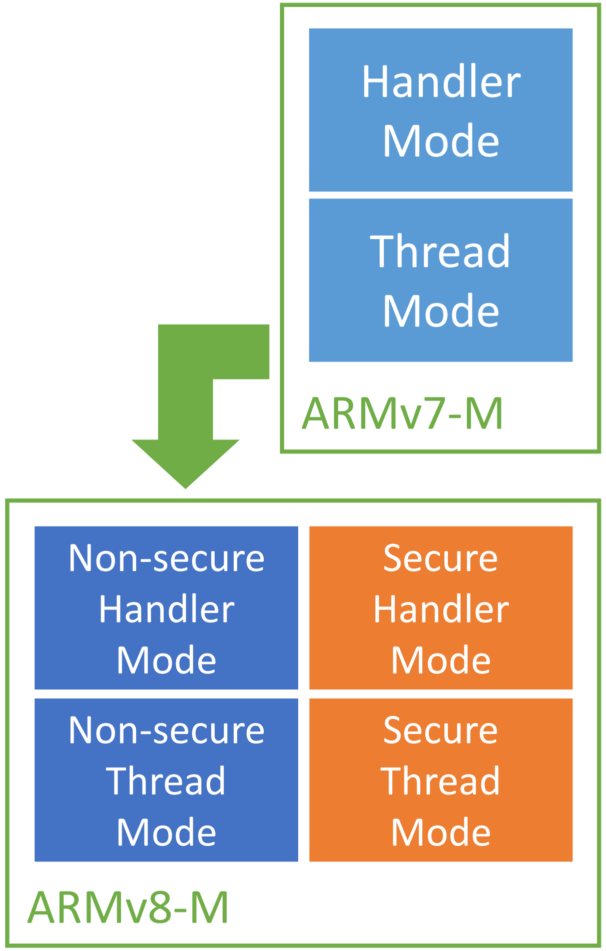
- Optional security extension for the ARMv8-M architecture
  - Security architecture for deeply embedded processors
  - Enables containerisation of software
  - Simplifies security assessment of embedded devices.

- Conceptually similar and compatible with existing TrustZone technology
  - New architecture tailored for embedded devices
    - Preserves low interrupt latencies of Cortex-M
    - Provides high performance cross-domain calling.

ARMv8-M Additional States

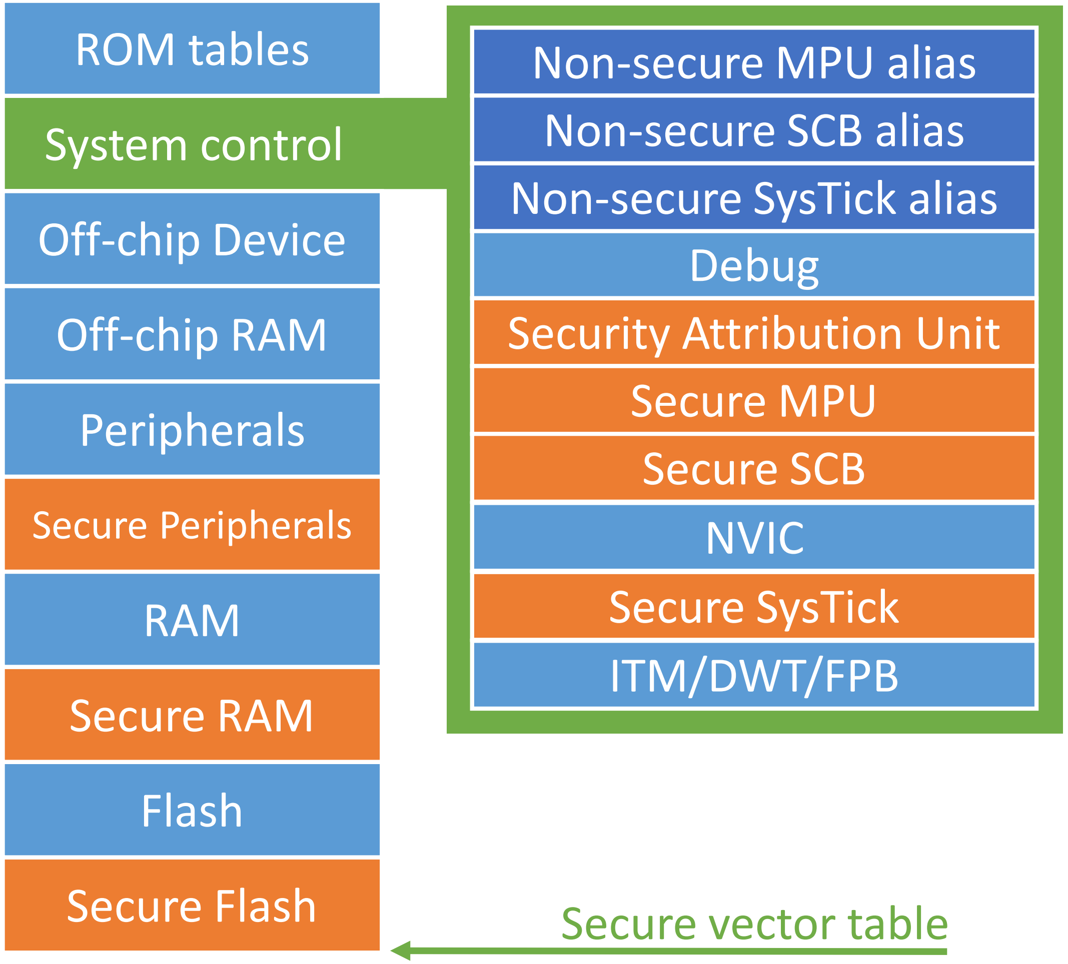
Existing handler and thread modes mirrored with secure and non-secure states

- Secure and Non-Secure code run on a single CPU
  - For efficient embedded implementation.
- Secure state for trusted code
  - New Secure stack pointers for robust operation
  - Addition of stack-limit checking.
- Dedicated resources for isolation between domains
  - Separate memory protection units for Secure and Non-secure
  - Private SysTick timer for each state.
- Secure side can configure target domain of interrupts.



ARMv8-M Programmers' Model Memory Map

Secure state view

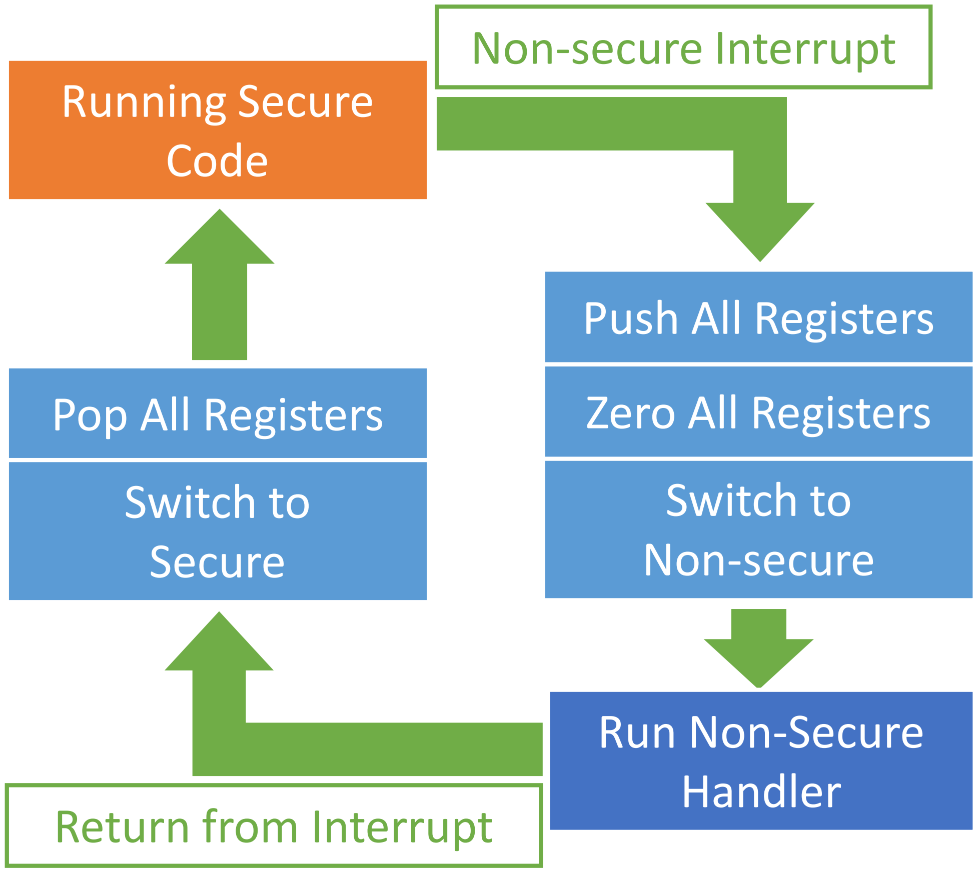


- Secure memory view permits access to Secure Flash, RAM, and peripherals.
- Load/store access to all regions is possible from Secure state.
- Security of regions can be configured using the Security Attribution Unit (SAU).

ARMv8-M Interrupt Security

High-performance interrupt handling with register protection

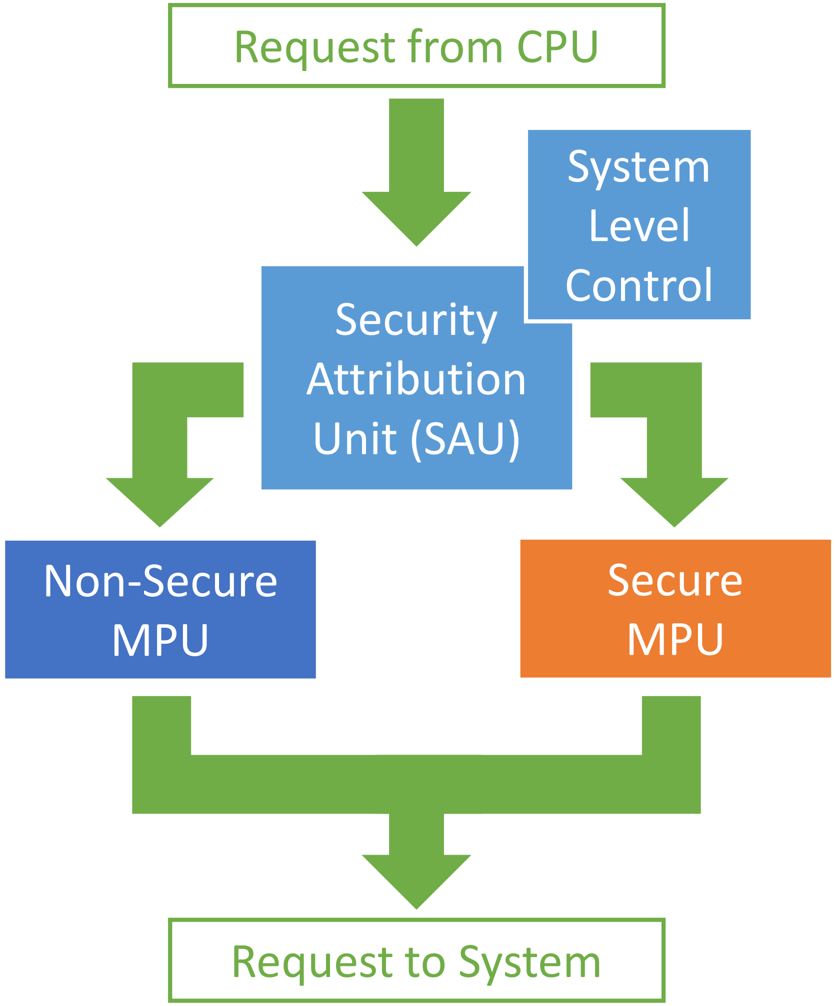
- Subject to priority, Secure can interrupt Non-secure and vice versa
  - Secure can boost priority of own interrupts
  - Uses current stack pointer to preserve context.
- Uses ARMv7-M exception stacking mechanism
  - Hardware pushes selected registers.
- Non-secure interruption of Secure code
  - CPU pushes all registers and zeroes them
    - Removes ability for Non-secure to snoop Secure register values.



Security Defined by Address

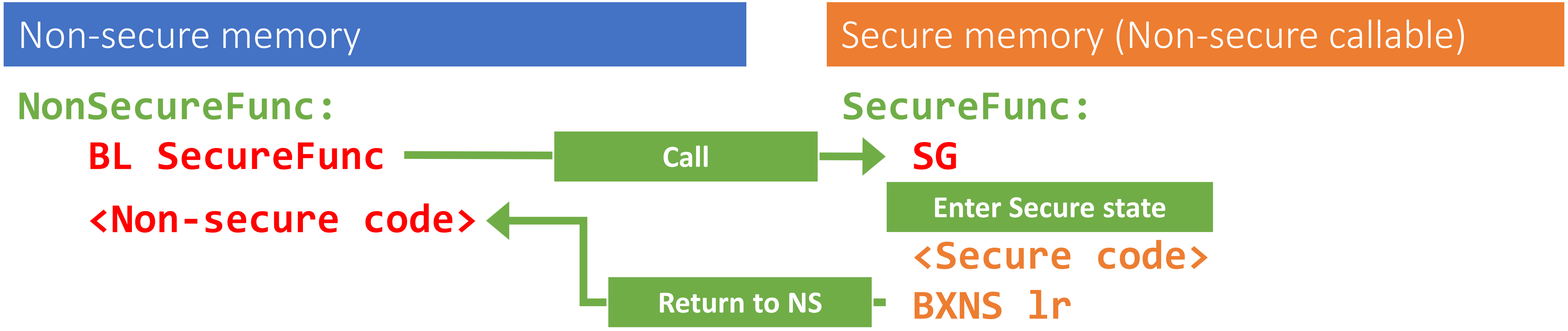
All transactions from core and debugger checked

- All addresses are either Secure or Non-secure.
- Policing managed by Secure Attribution Unit (SAU)
  - Internal SAU similar to MPU
  - Supports use of external system-level definition
    - E.g. based on flash blocks or per peripheral.
- Banked MPU configuration
  - Independent memory protection per security state.
- Load/stores acquire NS attribute based on address
  - Non-secure access attempts to Secure address = memory fault.



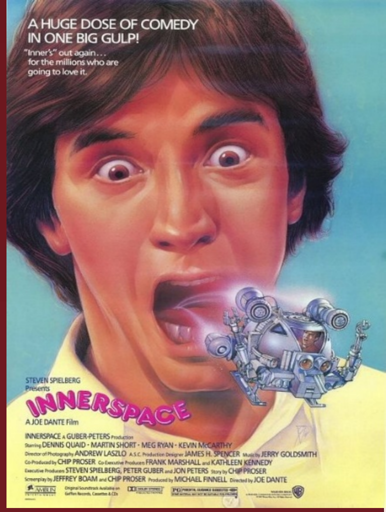
Cross-Domain Function Calls

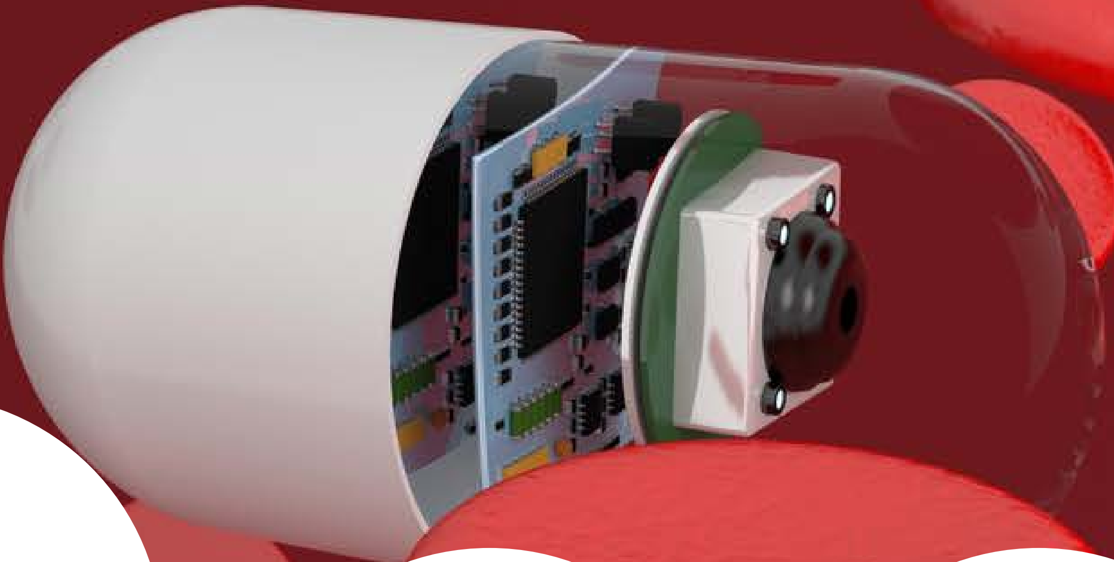
An assembly code level example



- Guard instruction (SG) polices entry point
  - Placed at the start of function callable from non-secure code.
- Non-secure → secure branch faults if SG isn't at target address
  - Can't branch into the middle of functions
  - Can't call internal functions.
- Code on Non-secure side identical to existing code.

Cortex-M23: Imagine the possibilities





- 32-bit performance
- TrustZone for ARMv8-M
- Long battery life
- Small area, low cost

ARM

Cortex-M23 enhancements over Cortex-M0+

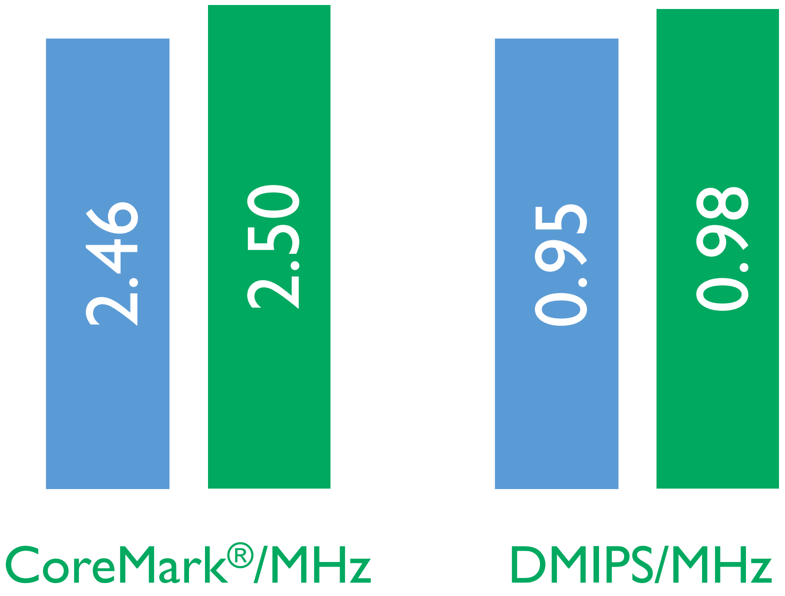
Cortex-M0+

- NVIC (max 32 IRQs)
- MPU (PMSAv6)
- AHB Lite
- WIC
- Fast I/O bus
- MTB
- Serial wire / JTAG
- ARMv6-M

Cortex-M23

- TrustZone
- Stack limit checking
- Hardware divide
- Exclusive memory accesses
- Enhanced debug
- ETM
- NVIC (max 240 IRQs)
- MPU (PMSAv8)
- AHB5
- WIC
- Fast I/O bus
- MTB
- Serial wire / JTAG
- ARMv8-M baseline

New or updated



Addressing diverse embedded and IoT opportunities

Automotive

Logistics

Industrial

Retail

Smart lighting

Agriculture

Wearables

Smart building

Environmental

Healthcare

Home automation

Cortex-M33

32-bit performance

TrustZone for ARMv8-M

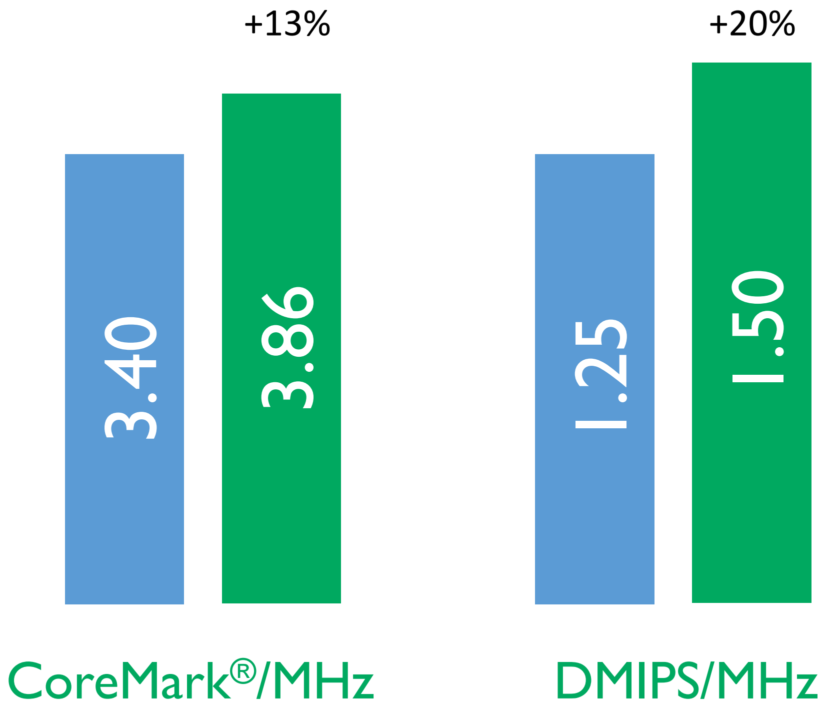
Configurability, extensibility

Digital signal processing

Cortex-M33 enhancements over Cortex-M4

Cortex-M4	Cortex-M33
	TrustZone
	Stack limit checking
	Co-processor interface
	Enhanced debug
	MTB
ETM	ETM
NVIC (max 240 IRQs)	NVIC (max 480 IRQs)
MPU (PMSAv7)	MPU (PMSAv8)
AHB Lite	AHB5
FPU	FPU
SIMD/ DSP	SIMD/ DSP
WIC	WIC
Serial wire / JTAG	Serial wire / JTAG
ARMv7-M	ARMv8-M mainline

New or updated



IoT systems and networks

- OSI model for networks.
- Internet protocol.
- IoT networking concepts.
- Example networks:
  - Classic Bluetooth, Bluetooth Low Energy.
  - 802.15.4 and Zigbee.
  - Wi-Fi.

Network Abstractions: OSI model

- International Standards Organization (ISO) Open Systems Interconnection (OSI) to describe networks:
  - 7-layer model.
- Standard way to classify network components and operations.

application	end-use interface
presentation	data format
session	application dialog control
transport	connections
network	end-to-end service
data link	reliable data transport
physical	mechanical, electrical

OSI layers

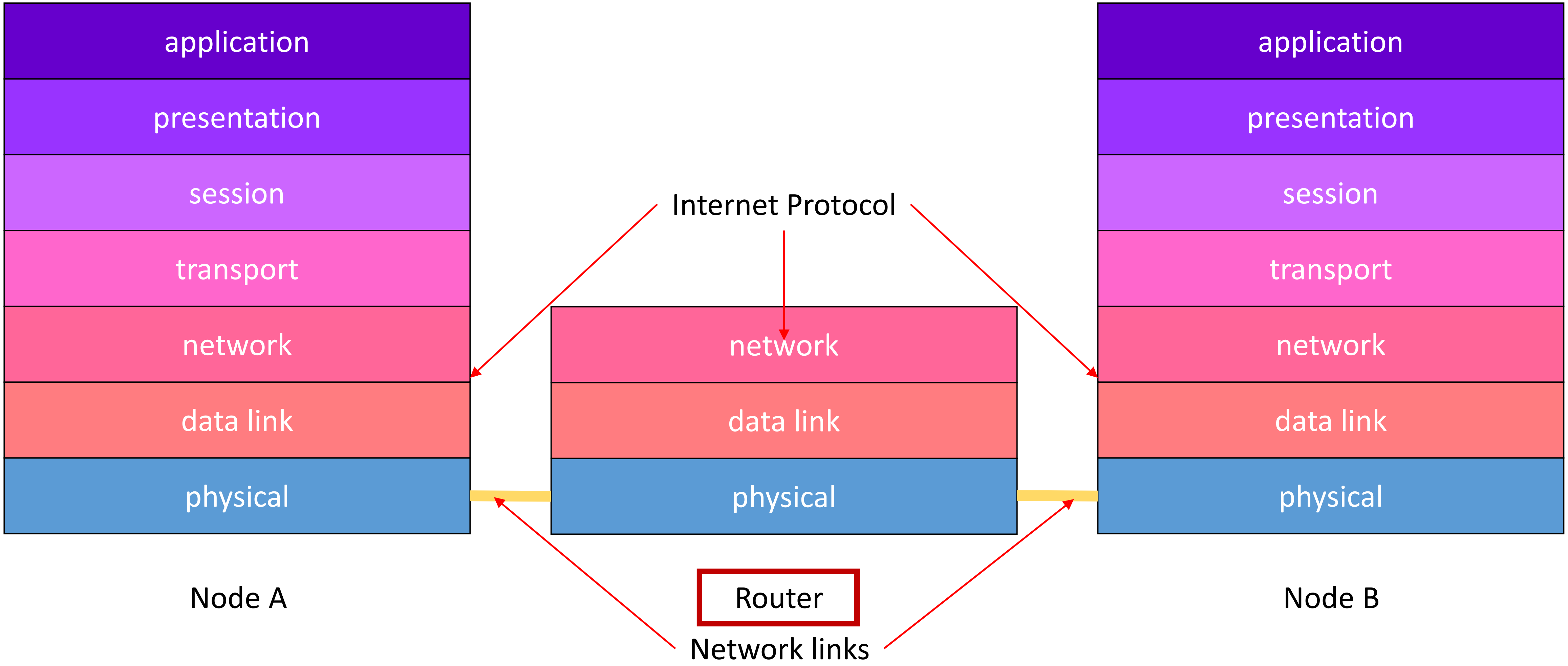
- Physical: connectors, bit formats, etc.
- Data link: error detection and control across a single link (single hop).
- Network: end-to-end multi-hop data communication.
- Transport: provides connections; may optimize network resources.
- Session: services for end-user applications: data grouping, checkpointing, etc.
- Presentation: data formats, transformation services.
- Application: interface between network and end-user programs

PHY and MAC

- PHY = physical layer.
  - Circuitry to transmit and receive bits.
- MAC = media access control.
  - Provides link-level services.

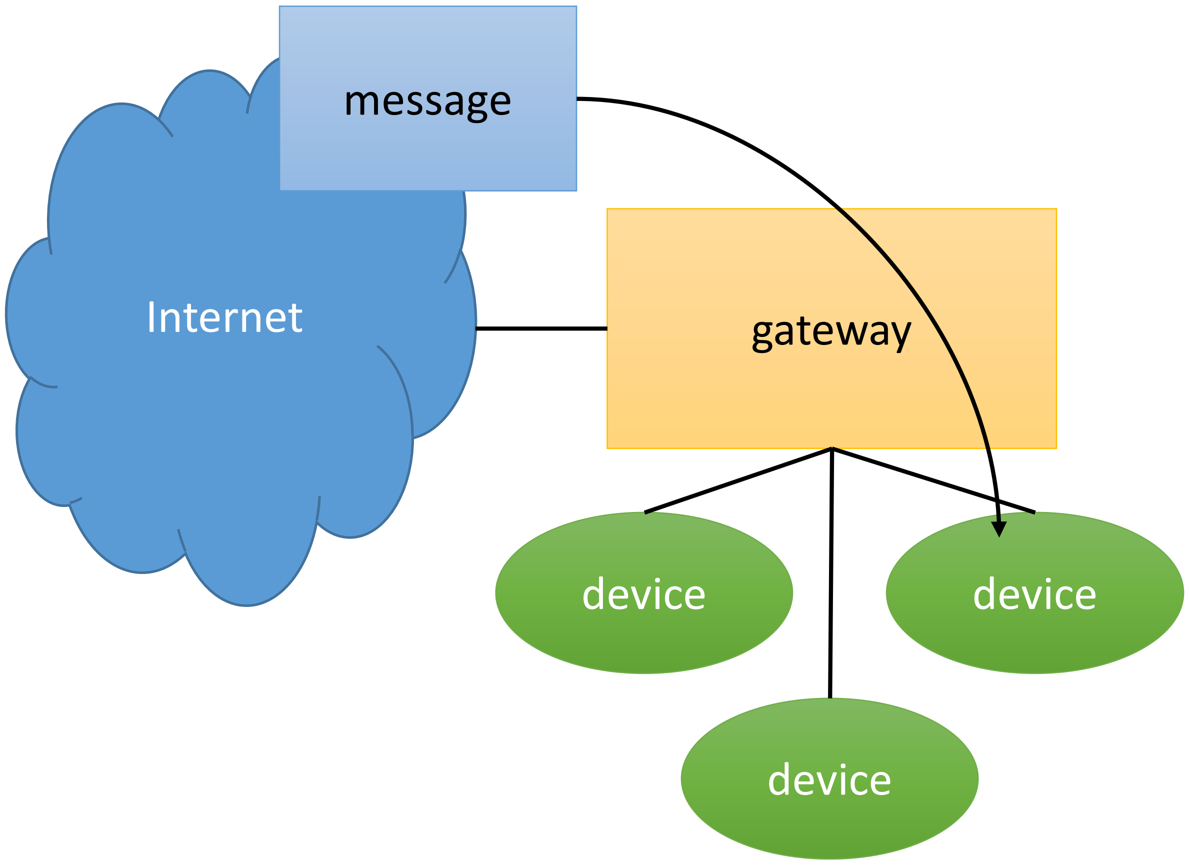
Internet Protocol (IP)

Internet = network of networks: transports data from one network to another.

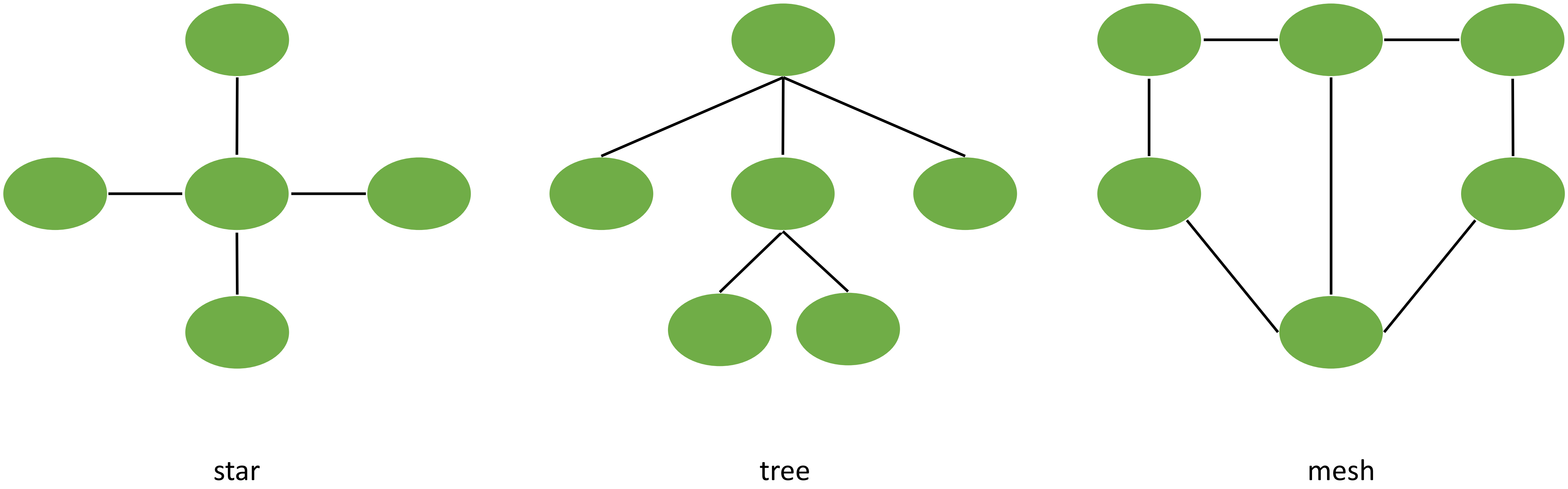


IoT networking concepts

- Edge device may not run IP protocol.
  - IP connection may be provided by hub or gateway.
  - Non-IP networks are known as edge networks.
- Ad hoc network is self-organized---not set up by system administrator.
- Ad hoc network services:
  - Authentication of eligibility to join network.
  - Authorization for access to given pieces of information on the network.
  - Encryption and decryption.

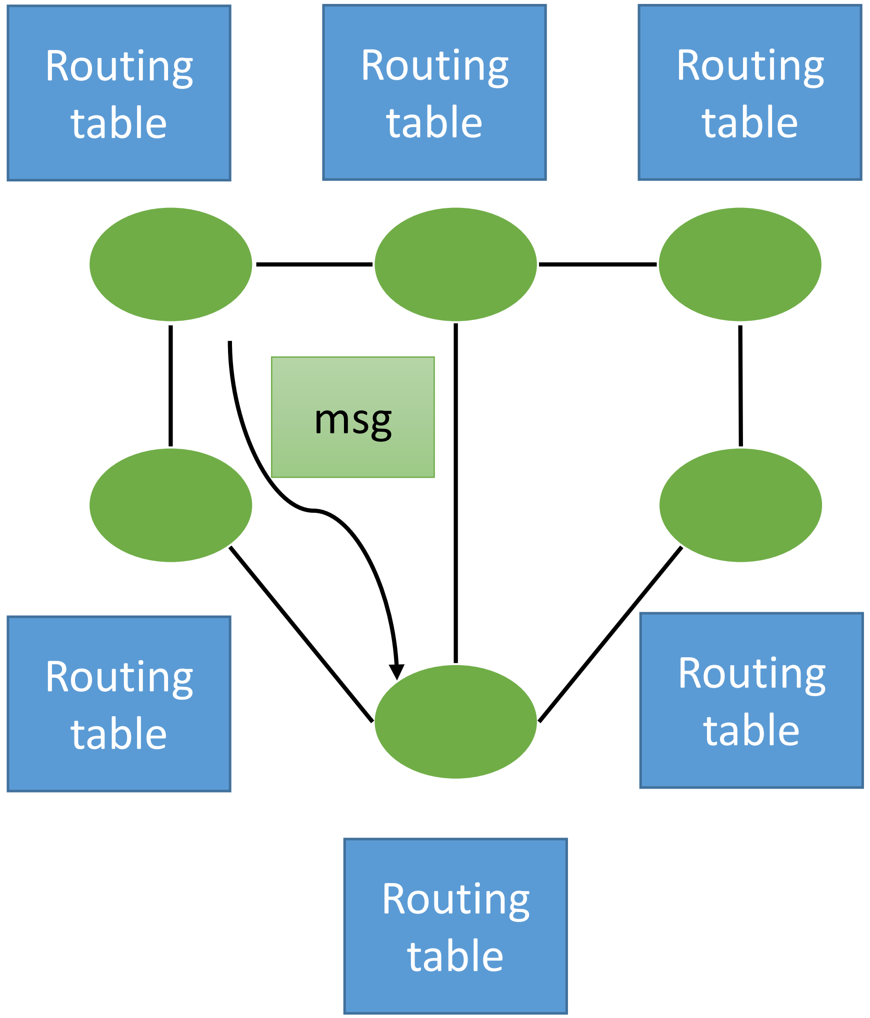


Network topologies



Routing

- Routing discovery determines routes between source/destination pairs.
- Routing is driven by routing tables at the nodes.

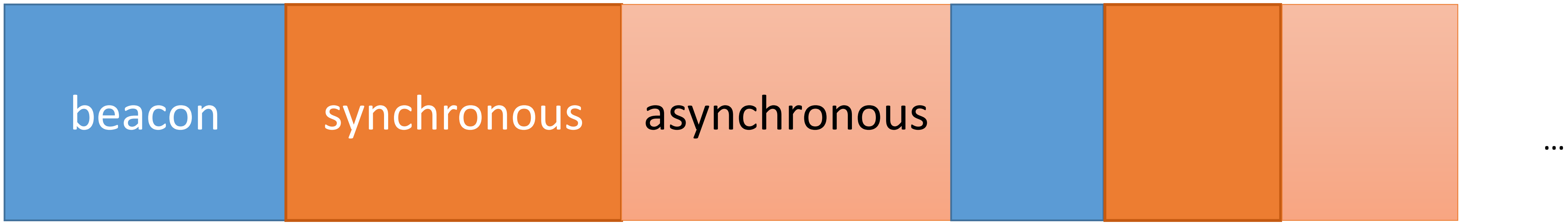


QoS

- Many networks support synchronous and asynchronous communication.
  - Asynchronous: data records, etc.
  - Synchronous: voice, etc.
- Quality-of-service (QoS): bandwidth and periodicity characteristics.
- Admission control ensures that network can handle the QoS demands of a request.

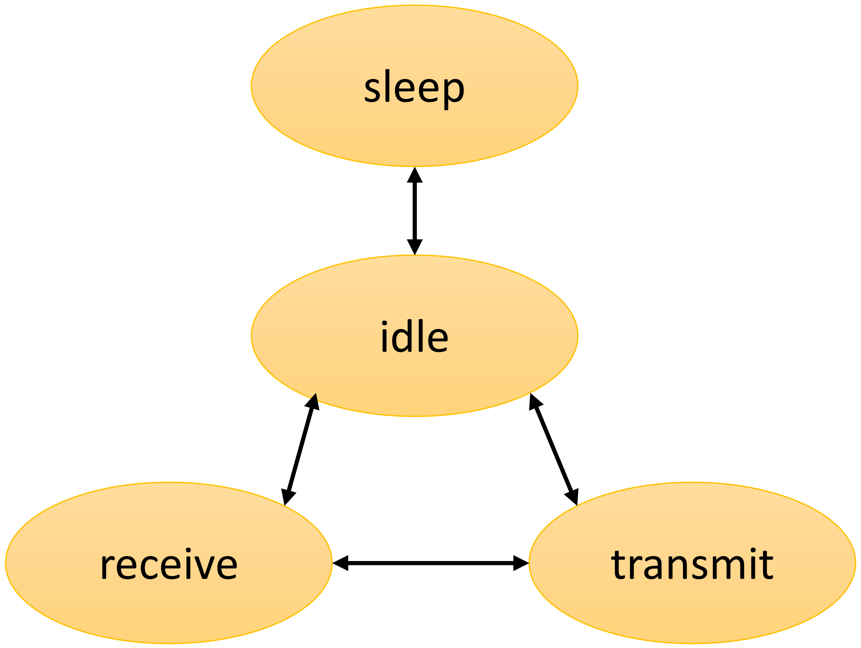
Synchronization and beacons

- Many network operations require nodes to be synchronized.
- Synchronization can be performed using beacon.
  - Beacon transmission marks the beginning of a communications interval.

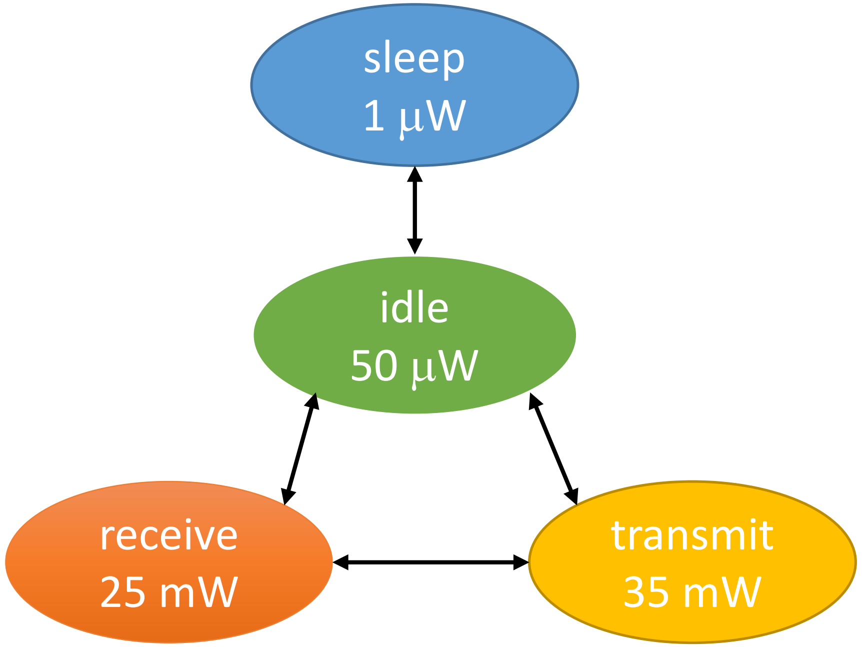


Communcations energy

- Communications energy is a large part of node energy consumption.
- Comm energy consumption depends on many factors and parameters.
  - Generally evaluated for a set of use cases.
- We can use power state machine to model communications energy cost.



Communications power state machine example



step	state	time	energy
1	sleep	1 ms	1 nJ
2	idle	10 μs	0.5 nJ
3	receive	50 μs	1.25 nJ
4	transmit	50 μs	1.75 nJ
5	receive	50 μs	1.25 nJ
6	transmit	50 μs	1.75 nJ
			total = 7.5 nJ

Bluetooth

- Introduced in 1999, originally for telephony applications.
- Classic Bluetooth operates in instrumentation, scientific, and medical (ISM) band in the 2.4 GHz range.
- Bluetooth networks organized as piconet.
  - One master, several slaves.
  - Slave can be active or parked.
  - A device can be a slave on several networks simultaneously.

Bluetooth stack

- Transport protocol:
  - Radio, baseband layer, link manager, logical link control and adaptation protocol (L2CAP).
- Middleware:
  - RFCOMM for serial port, service discovery protocol, Internet Protocol, IrDA, etc.
- Applications.

Bluetooth protocol

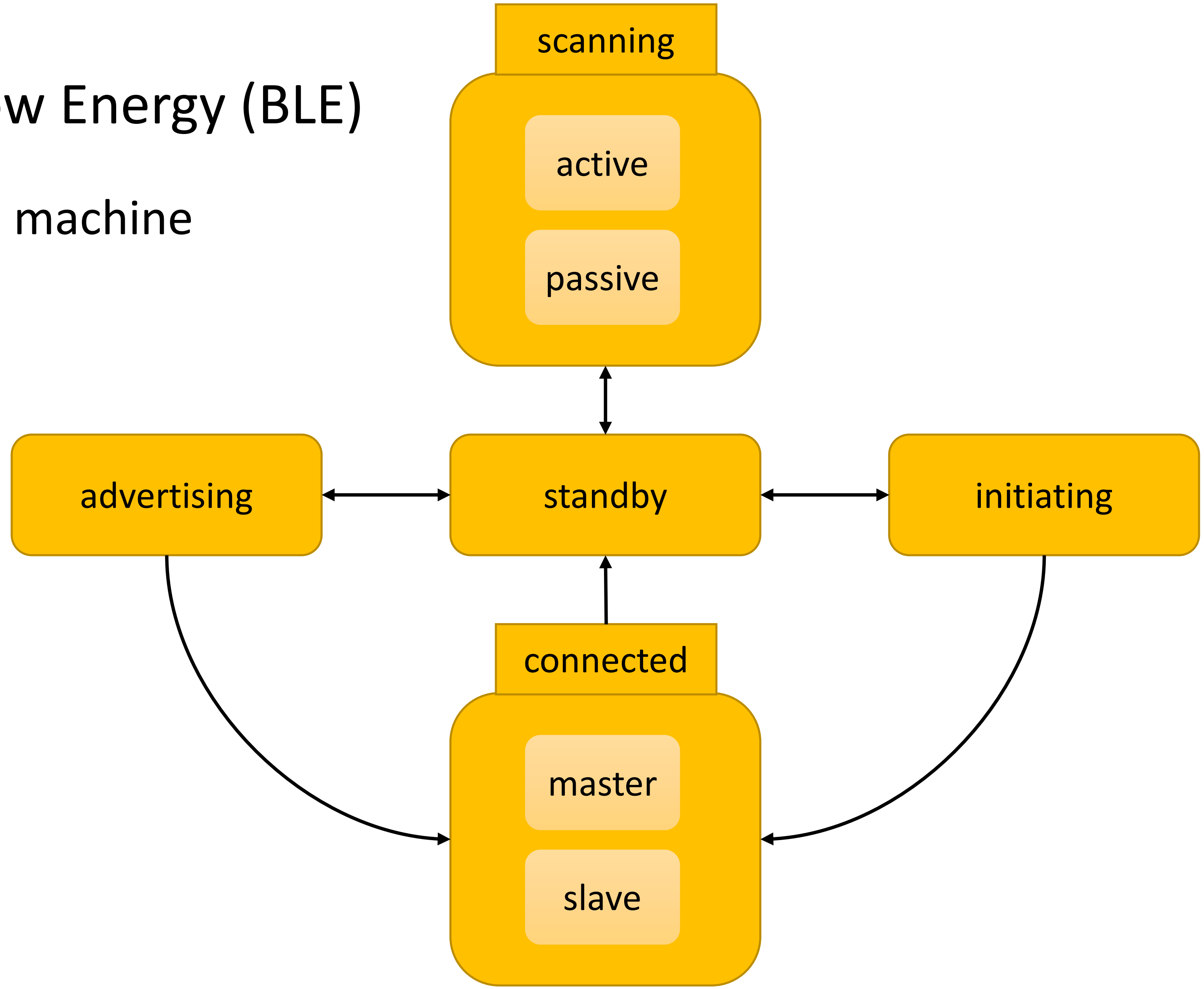
- Every Bluetooth device has a 48-bit Bluetooth Device Address.
- Every device has a Bluetooth clock.
- Transmissions alternate between master and slave directions.
- Two types of packets:
  - Synchronous connection-oriented (SCO) packets for QoS-oriented traffic.
  - Asynchronous connectionless (ACL) packets for non-QoS traffic.
  - SCO traffic has higher priority than ACL packets.

Bluetooth Low Energy

- Designed for very low energy operation such as button-sized battery.
  - Goal: minimize radio on-time.
- Part of Bluetooth standard but deviates from Classic Bluetooth in several ways.
- Advertising transmissions can be used to broadcast, discover devices, etc.
- Connections can be established.
- Attribute Protocol Layer allows devices to create application-specific protocols.
- Generic Attribute Profile Layer (GATT) defines basic attributes for all BLUE devices.
- Pairing devices uses a short-term key to send a long-term key.
  - Bonding: storing long-term key in device database.
  - Optional data encryption using AES.

Bluetooth Low Energy (BLE)

Link-level state machine



802.15.4 and ZigBee

- 802.15.4 defines MAC and PHY layers.
  - Supports full-function and reduced-function devices.
  - Either star or peer-to-peer topology.
  - Communication performed using frames.
  - Optional superframe provides a beacon mechanism and QoS.
- ZigBee is a set of application-oriented standards.
  - NWK layer provides network services.
  - APL layer provides application-level services.
  - Supports many different topologies.

Wi-Fi

- Originally designed for portable and mobile applications.
  - Has been adapted for lower-energy operation.
- Supports ad hoc networking.
- Network provides a set of services:
  - Distribution of messages from one node to another.
  - Integration delivers messages from another network.
  - Association relates a station to an access point.

IoT Systems Databases

- Database holds data about devices, helps to analyze data.
- Relational database management system:
  - Domain1 X domain2 X … -> Range.
- Database organized into records or tuples:
  - Attribute: table column.
  - Record: table row.
- One column is the primary key---uniquely identifies a record.

Database example

devices

name	id (primary key)	address	type
door	234	10.113	binary
refrigerator	4326	10.117	signal
table	213	11.039	MV
chair	4325	09.423	binary
faucet	2	11.324	signal

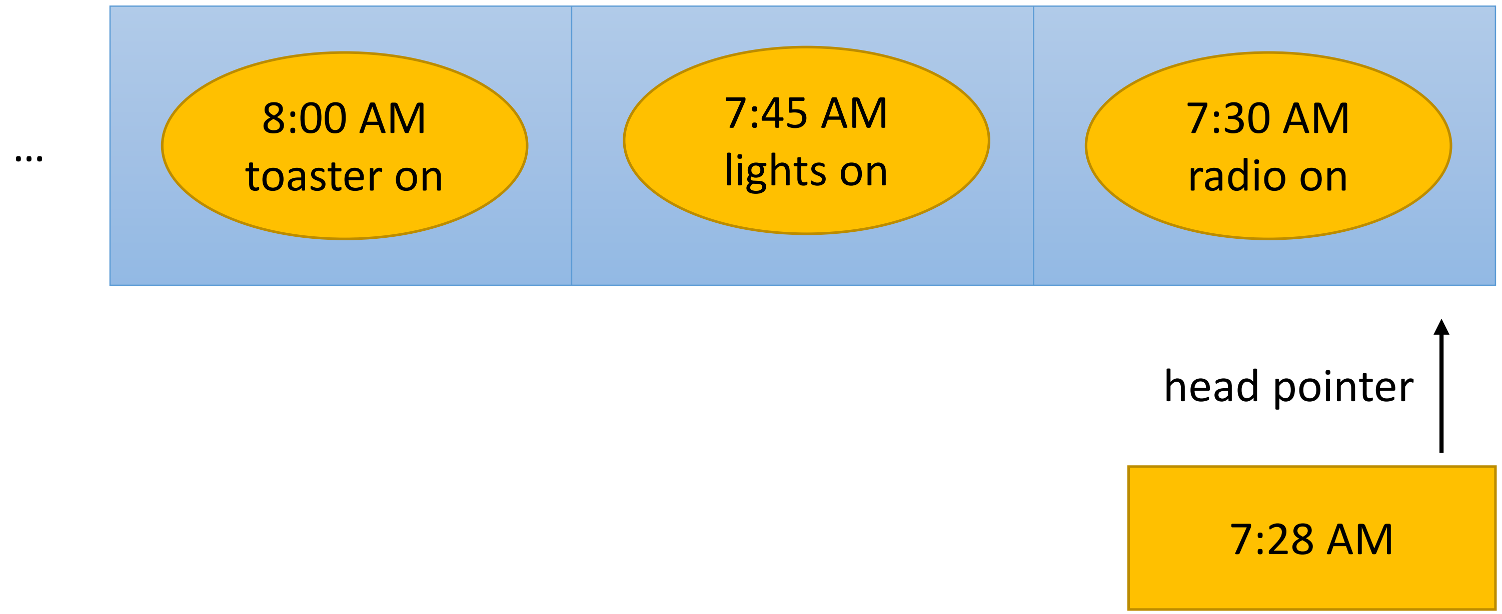
record

device_data

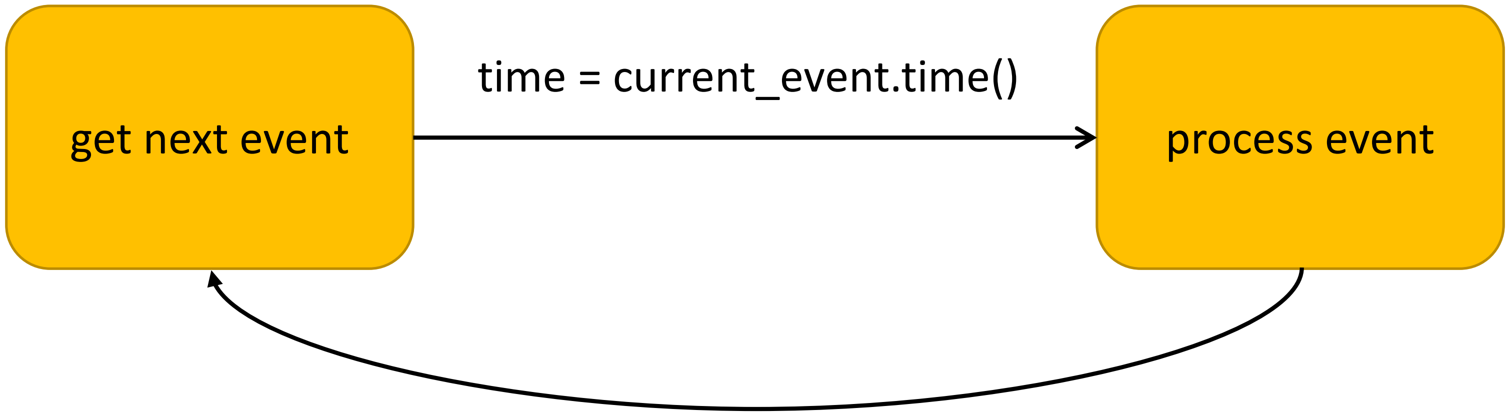
signature (primary key)	device	time	value
256423	234	11:23:14	1
252456	4326	11:23:47	40
663443	234	11:27:55	0

IoT Management - Timewheels

- Used to manage timing of events in the system.
- Timewheel is a time-sorted set of events.
  - Event placed in proper spot in timewheel queue upon arrival.
  - When current time is equal to time of event at head, event is processed.



Timewheel state diagram

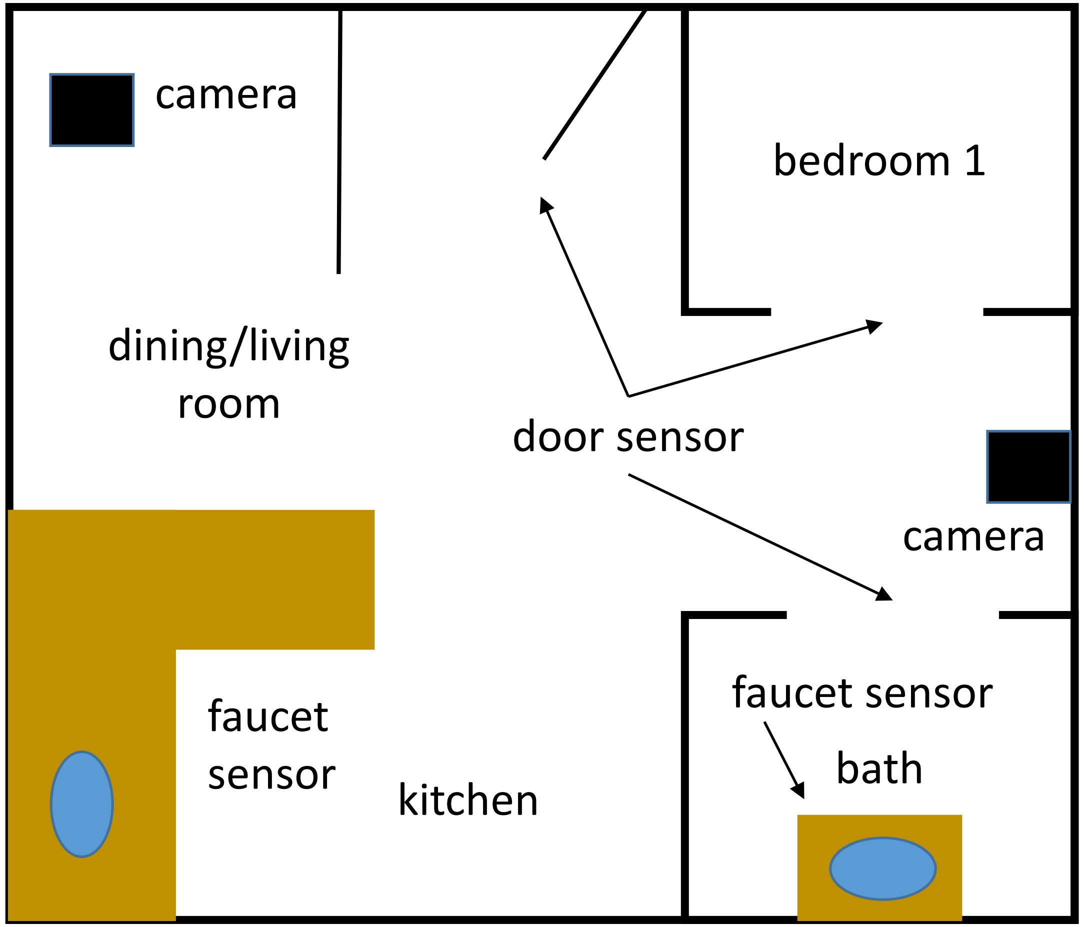


Example: smart home

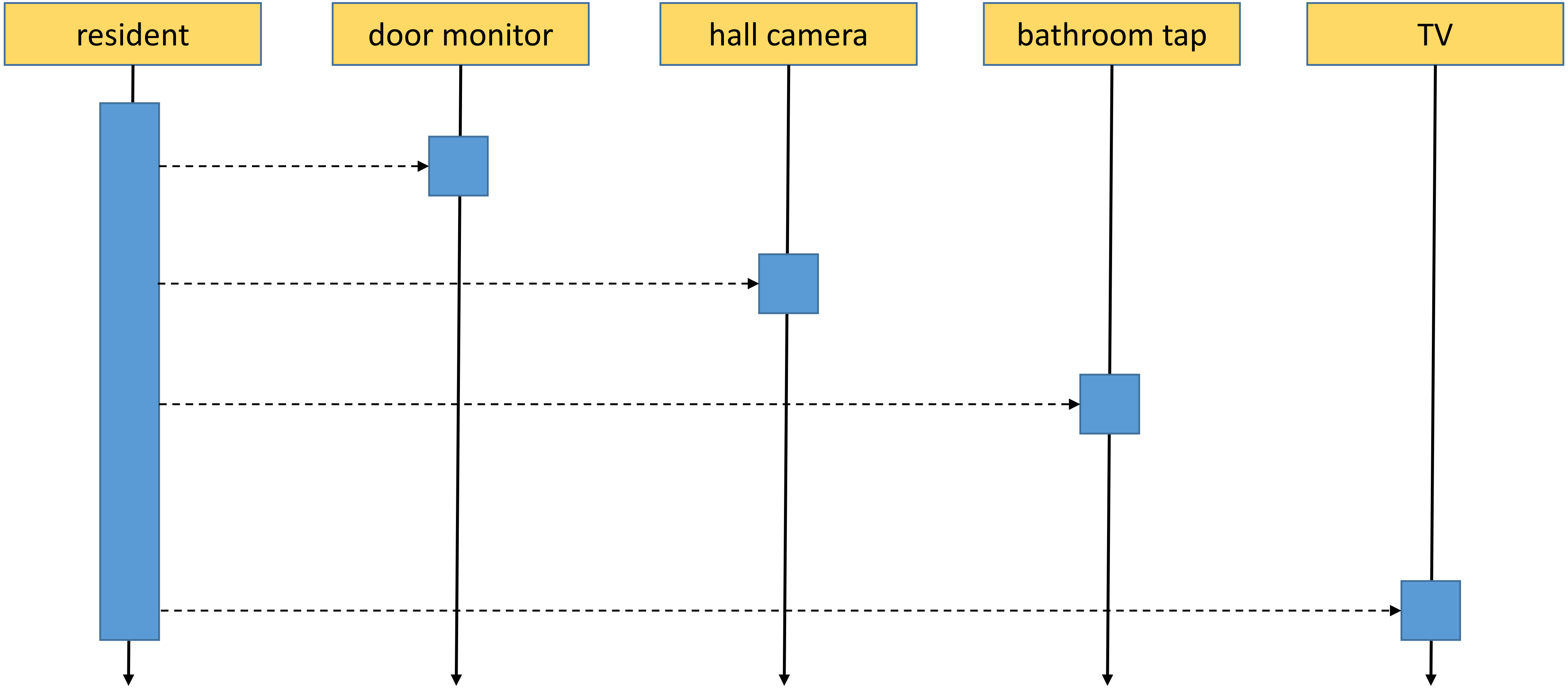
- Performs a variety of services:
    - Remote or automatic operation of lights and appliances.
    - Energy and water management.
    - Activity monitoring.
- Activity monitoring can help elderly, people with special needs:
    - Reports on daily activities.
    - Alerts for out-of-the-ordinary activity.
    - Recommendations.

Example smart home

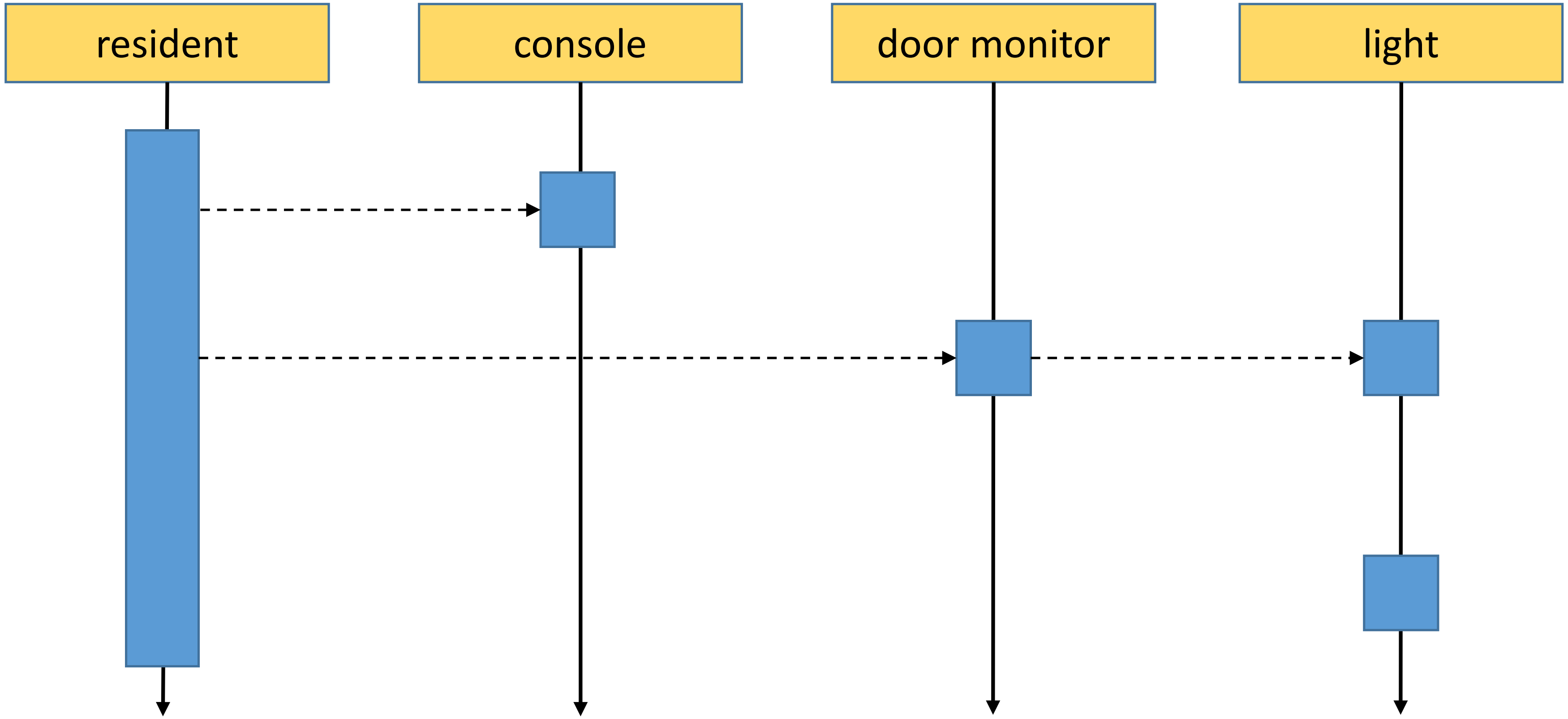
- Cameras can identify resident and their activity.
- Faucet, door sensors can identify activity but not who performs the activity.



Use case: activity monitoring



Use case: light control



Smart home object diagram