

An Introduction to the Operating Systems of the IoT

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Outline

- ▶ Introduction
- ▶ IoT Requirements & Challenges
- ▶ IoT OS
- ▶ Existing OSs
- ▶ Protocol stack
- ▶ Test & Development Environments
- ▶ Conclusion

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Introduction Outline

- ▶ Introduction
 - What is IoT

What is IoT...

The Internet of Things (IoT) is a scenario in which objects, animals or people are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction.



What is the IoT

- ▶ A **thing**, in the Internet of Things, can be any natural or man-made object can be assigned **IP address**.
- ▶ So far, the Internet of Things has been most closely associated with machine-to-machine (M2M) communication.
- ▶ Although the concept wasn't named until 1999, the Internet of Things has been in development for decades.



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IoT Requirements & Challenges Outline

► IoT Requirements & Challenges

- Heterogeneous Hardware Constraints
- Autonomy
- Programmability
- Effect of the requirements on OS

Heterogeneous Hardware Constraints

- ▶ Memory Requirements
- ▶ CPU Requirements
- ▶ Limited Features
- ▶ Platform Support



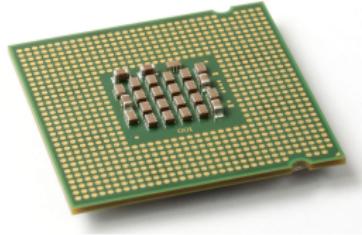
Memory Requirements

- ▶ As many of typical IoT devices have very little memory (typically between 5kB and some hundreds of megabytes), the minimum memory requirement of the software has to be very low.
- ▶ This concerns RAM as well as persistent program storage.



CPU Requirements

- ▶ The complexity of operations must be kept very low, because some of the MCUs in a IoT system will work at a very low clock cycle.



Limited Features

- ▶ Software for IoT must be able to run on constrained hardware without more advanced components like a Memory Management Unit (MMU) or a Floating-Point Unit (FPU).



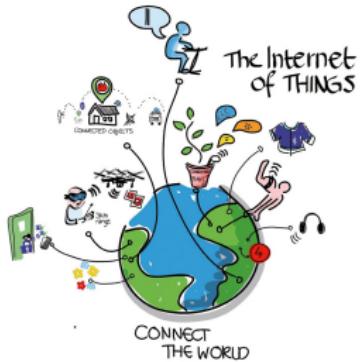
Platform Support

- ▶ Software for IoT must support a variety of hardware platforms, run on constrained platforms, but also be able to leverage the capabilities of less constrained platforms.



Autonomy

- ▶ Energy efficiency
- ▶ Adaptive Network Stack
- ▶ Reliability



Energy efficiency

- ▶ The software must exploit the power saving features of the hardware and allow for large sleep cycles as much as possible.



Adaptive Network Stack

- ▶ The network stack should provide full-fledged TCP/IP implementations as well as a 6LoWPAN stack aiming for more constrained devices.
- ▶ It should also be modular in a way that the protocols at each layer can be easily replaced.

| | | | |
|-------------------|---|--|-----------------|
| Application Layer | HTTP FTP Telnet Finger DNS POP3/IMAP SMTP Gopher BGP Time/NTP Whois TACACS+ SSH NNTP SSL/TLS (https, etc.) SOCKS | DNS SNMP RIP RADIUS Archie traceroute tftp DHCP Kerberos | Ping tracert |
| Transport Layer | TCP | UDP | ICMP OSPF |
| Network Layer | IP | | ARP |
| Network Access | Ethernet/802.3 Token Ring (802.5) Frame Relay SMDS ATM Wireless Cable modem 802.x Fibre Channel DWDM HDLC PPP SLIP/CSLIP | | |

Reliability

- ▶ IoT systems are often deployed in critical applications in which physical access is difficult and related to high costs in many cases. For that reason, it is important that the system is robust and thus that the operating system runs very reliably.



Programmability

- ▶ Standard API
- ▶ Standard Programming Languages



Standard API

- ▶ In order to ease software development and simplify the porting of existing software, a standard programming interface such as POSIX or STL should be provided.



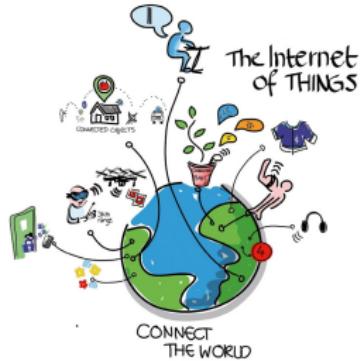
Standard Programming Languages

- ▶ Support for standard high level programming languages, such as C++, is vital.



IoT Challenges

- ▶ Heterogeneous hardware
- ▶ Slow CPU, often no FPU
- ▶ Little memory, often no MMU
- ▶ Limited energy resources
- ▶ Robustness and self-organization
- ▶ Real-Time requirements



Effect of the requirements on OS

- ▶ **Scalable**, to accommodate a wide range of different classes of devices
- ▶ **Modular**, so you can choose only the components you need to meet tight RAM requirements
- ▶ **Connected**, so you can move data in and out of the device via Wi-Fi, Ethernet, USB, or Bluetooth.
- ▶ **Reliable**, so your device can be certified for safety-critical applications

Outline

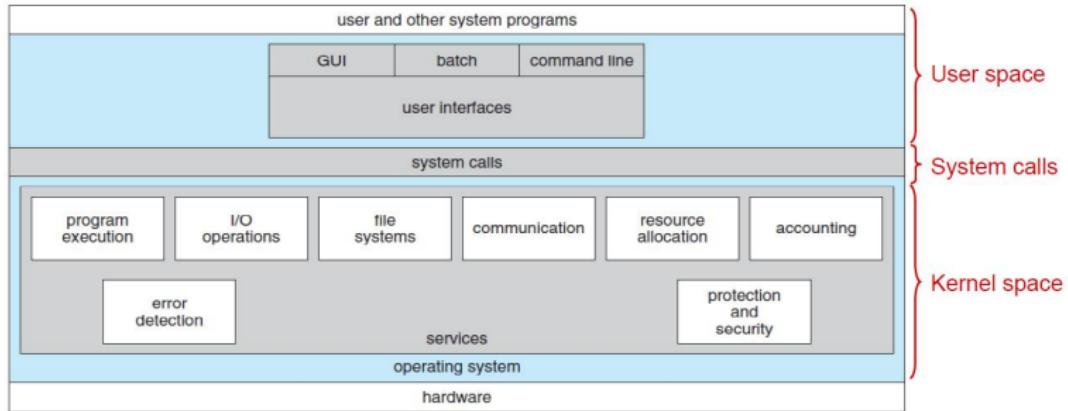
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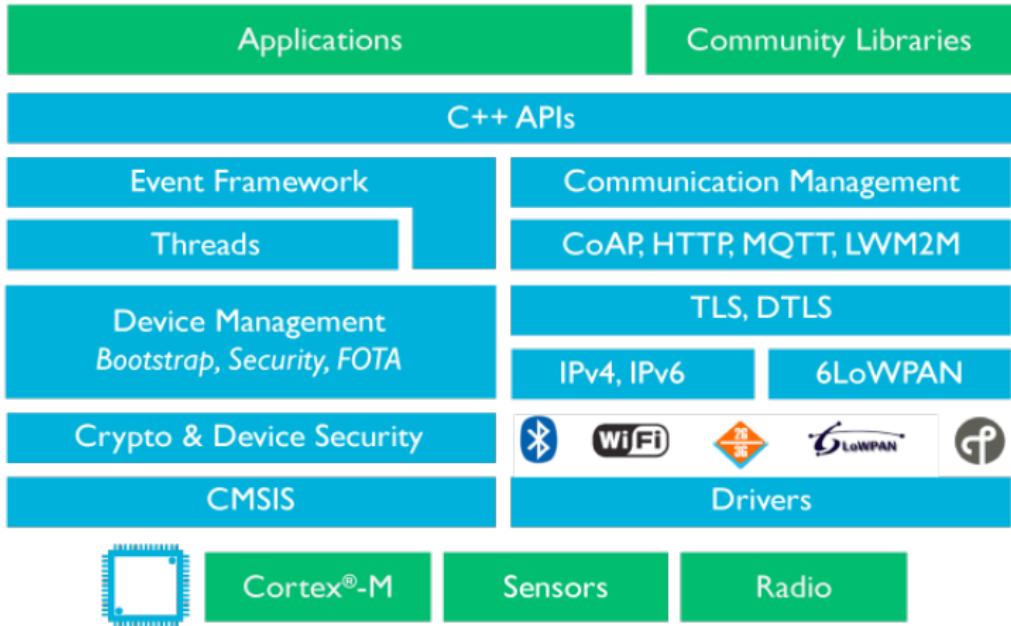
IoT OS Outline

► IoT OS

- General OS vs IoT OS
- What are the main requirements in IoT OS
- What are the main components in IoT OS

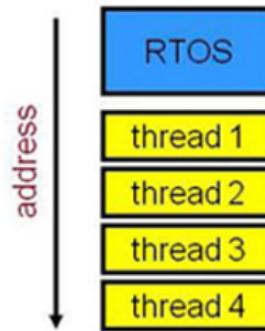
General OS





Multi-Tasking, Thread Model (IoT OS)

- ▶ Most RTOS products on the market are thread model.
- ▶ Tasks are now called threads.
- ▶ All the tasks code and data occupy the same address space, along with that of the RTOS itself.
- ▶ Or every tasks can run in its own thread and has its own memory stack.



What are the main requirements in IoT OS

- ▶ IoT Protocol Stack Support
- ▶ Efficient Memory Managing
- ▶ Real-Time Task Scheduling

What are the main components in IoT OS

- ▶ Networking
- ▶ Memory Manager
- ▶ Task Scheduler

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Existing OSs Outline

- ▶ Existing OSs
 - OS Classification
 - Overview of Open Source OSs
 - Overview of Closed Source OSs
 - Why Not Linux?

► Design Aspects for an IoT OS

- Monolithic fashion
- Layered approach
- Microkernel architecture

► Programming Model for an IoT OS

- All tasks are executed within the same context and have no segmentation of the memory address space.
- Every process can run in its own thread and has its own memory stack.

Overview of Open Source OSs

- ▶ FreeRTOS
- ▶ RIOT
- ▶ Contiki
- ▶ TinyOS
- ▶ Embedded Linux
- ▶ OpenWSN



- ▶ FreeRTOS is designed to be **small** and **simple**.
- ▶ The kernel itself consists of only three or four C files.
- ▶ It provides methods for multiple threads or tasks, mutexes, semaphores and software timers.
- ▶ Key features are **very small memory footprint**, **low overhead**, and **very fast execution**.



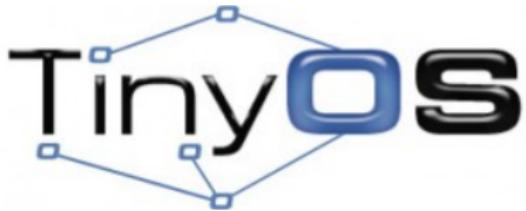
- ▶ RIOT is a **real-time multi-threading** operating system.
- ▶ RIOT implements a **microkernel** architecture
- ▶ RIOT is based on design objectives including:
 - Energy-Efficiency
 - Reliability
 - Real-Time Capabilities
 - Small Memory Footprint
 - Modularity
 - Uniform API Access
independent of the underlying hardware
(this API offers partial POSIX compliance)



- ▶ Contiki is an open source operating system for **networked, memory-constrained** systems
- ▶ Contiki provides three network mechanisms:
 - The uIP stack, which provides IPv4 networking,
 - The uIPv6 stack, which provides IPv6 networking,
 - The Rime stack, which is a set of custom lightweight networking protocols designed specifically for low-power wireless networks.

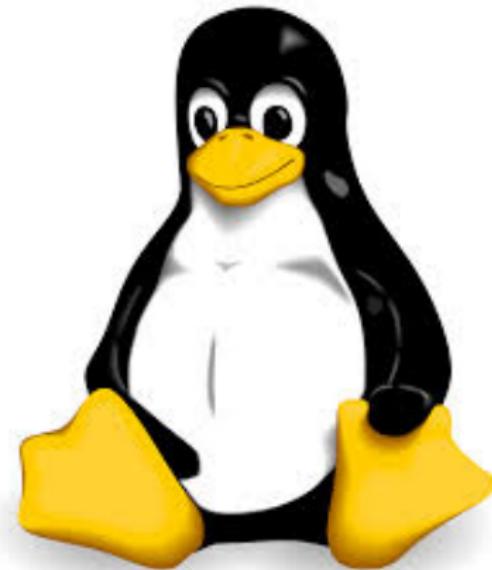


- ▶ TinyOS is a **component-based** operating system and platform targeting wireless sensor networks.
- ▶ TinyOS is an embedded operating system written in the **nesC programming language** as a set of cooperating tasks and processes.



Embedded Linux

- ▶ Embedded Linux is created using OpenEmbedded, the build framework for embedded Linux.
- ▶ OpenEmbedded offers a best-in-class cross-compile environment.



- ▶ The goal of the OpenWSN project is to provide open-source implementations of a complete protocol stack based on Internet of Things standards, on a variety of software and hardware platforms.

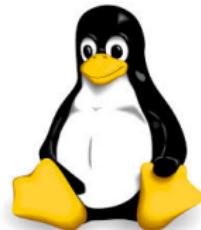


Comparison

| OS | Min RAM | Min ROM | C Support | C++ Support |
|---------|---------|---------|-----------------|--------------|
| Contiki | < 2kB | < 30kB | Partial support | No support |
| Tiny OS | < 1kB | < 4kB | No support | No support |
| Linux | ~ 1MB | ~ 1MB | Full support | Full support |
| RIOT | ~ 1.5kB | ~ 5kB | Full support | Full support |

Contiki

TinyOS



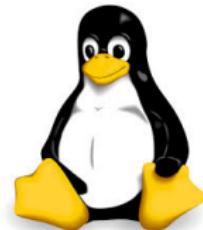
RIOT

Comparison

| OS | Multi-Threading | Modularity | Real-Time |
|---------|-----------------|-----------------|-----------------|
| Contiki | Partial support | Partial support | Partial support |
| Tiny OS | Partial support | No support | No support |
| Linux | Full support | Partial support | Partial support |
| RIOT | Full support | Full support | Full support |

Contiki

TinyOS



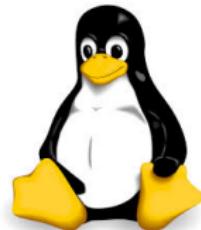
RIOT

Operating Systems Availability

| OS | Wsn430 Node | M3 Node | A8 Node |
|---------|--------------|--------------|--------------|
| Contiki | Full support | Full support | No support |
| Tiny OS | Full support | No support | No support |
| Linux | No support | No support | Full support |
| RIOT | Full support | Full support | No support |

Contiki

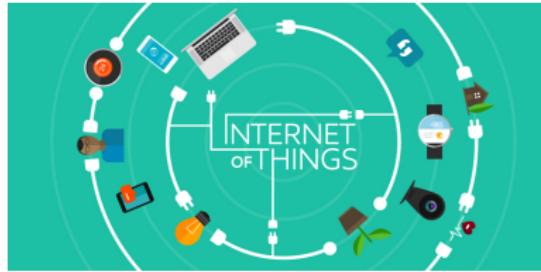
TinyOS



RIOT

Overview of Closed Source OSs

- ▶ ARM mbed
- ▶ Huawei LiteOS
- ▶ Google Brillo



- ▶ Automation of power management
- ▶ Software asset protection and secure firmware updates for device security & management
- ▶ Connectivity protocol stack support for Bluetooth low energy, Cellular, Ethernet, Wi-fi, Zigbee IP, Zigbee NAN, 6LoWPAN

ARM® mbed™

- ▶ The company says that its **LiteOS** is the **lightest** software of its kind and can be used to power a range of smart devices



Google Brillo

- ▶ Brillo is derived from Android but polished to just the lower levels.
- ▶ It supports Wi-Fi, Bluetooth Low Energy, and other Android things.



Why Not Linux?

Real-Time Linux

Controlling a laser with Linux is crazy, but everyone in this room is crazy in his own way. So if you want to use Linux to control an industrial welding laser, I have no problem with your using PREEMPT_RT.

- Linus Torvalds



Why Not Linux?

- ▶ Linux certainly is a robust, developer-friendly OS
- ▶ Linux has a disadvantage when compared to a real-time operating system:
 - Memory footprint
 - It simply will not run on 8 or 16-bit MCUs
- ▶ Linux will certainly have many uses in embedded devices, particularly ones that provide graphically rich user interfaces.
- ▶ There are thousands of applications for which Linux is ill suited.



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Protocol stack Outline

► Protocol stack

- Traditional Stack
- IoT Requirements
- IoT Stack
- Comparison

Protocol stack

- ▶ Can you build an IoT system with familiar Web technologies?

Protocol stack

- ▶ Can you build an IoT system with familiar Web technologies?
- ▶ Yes you can, although the result would not be as **efficient** as with the **newer protocols**.

Traditional Stack

- ▶ Existing Internet protocols such as HTTP and TCP are not optimized for very **low-power communication**.
- ▶ Energy is wasted by transmission of **unneeded data, protocol overhead**, and **non-optimized communication patterns**.

IoT Requirements

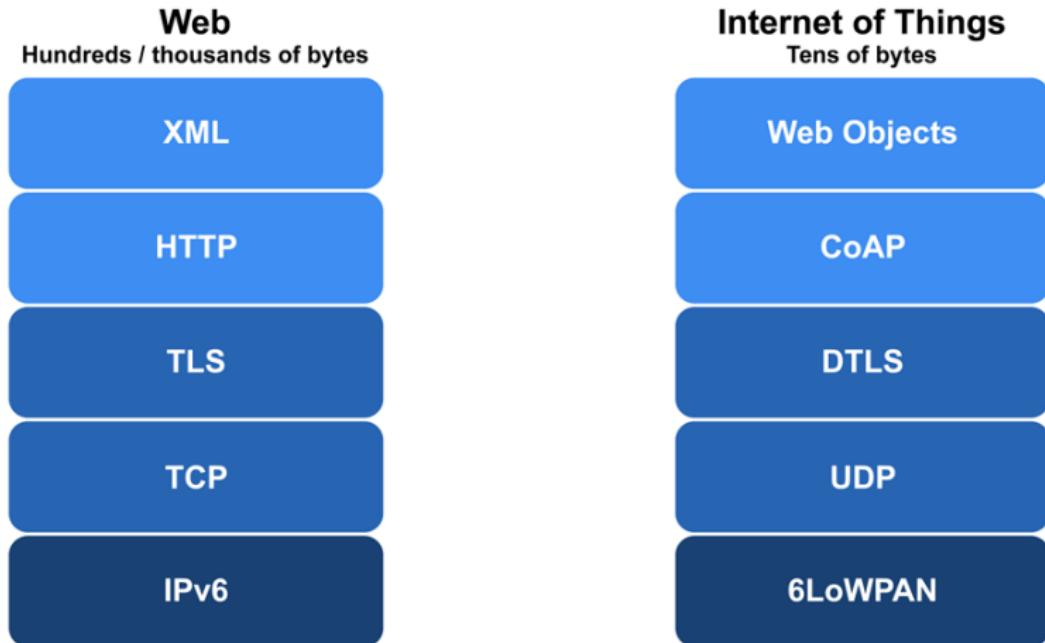
- ▶ A Low Power Communication Stack.
- ▶ A Highly Reliable Communication Stack.
- ▶ An Internet-Enabled Communication Stack.

- ▶ LOW-POWER PHYSICAL LAYER **IEEE 802.15.4**
- ▶ POWER-SAVING LINK LAYER **IEEE 802.15.4E**
- ▶ CONNECTING TO THE INTERNET - **IETF 6LoWPAN**
- ▶ ROUTING - **IETF ROLL**
- ▶ TRANSPORT LAYER AND ABOVE - **IETF CoAP**

IoT Stack

| <i>Protocol</i> | <i>Transport</i> | <i>Messaging</i> | <i>2G,3G,4G (1000's)</i> | <i>Low Power and Lossy (1000's)</i> | <i>Compute Resources</i> | <i>Security</i> | <i>Success Stories</i> | <i>Arch</i> |
|-----------------------|------------------|-----------------------------|------------------------------|---|------------------------------|-------------------|----------------------------|-------------------|
| CoAP | UDP | Rqst/Rspnse | Excellent | Excellent | 10Ks/RAM Flash | Medium - Optional | Utility field area ntwks | Tree |
| Continua HDP | UDP | Pub/Subsrbs Rqst/Rspnse | Fair | Fair | 10Ks/RAM Flash | None | Medical | Star |
| DDS | UDP | Pub/Subsrbs Rqst/Rspnse | Fair | Poor | 100Ks/RAM Flash +++ | High-Optional | Military | Bus |
| DPWS | TCP | | Good | Fair | 100Ks/RAM Flash ++ | High-Optional | Web Servers | Client Server |
| HTTP/ REST | TCP | Rqst/Rspnse | Excellent | Fair | 10Ks/RAM Flash | Low-Optional | Smart Energy Phase 2 | Client Server |
| MQTT | TCP | Pub/Subsrbs Rqst/Rspnse | Excellent | Good | 10Ks/RAM Flash | Medium - Optional | IoT Msging | Tree |
| SNMP | UDP | Rqst/Response | Excellent | Fair | 10Ks/RAM Flash | High-Optional | Network Monitoring | Client-Server |
| UPnP | | Pub/Subscrbs Rqst/Rspnse | Excellent | Good | 10Ks/RAM Flash | None | Consumer | P2P Client Server |
| XMPP | TCP | Pub/Subsrbs Rqst/Rspnse | Excellent | Fair | 10Ks/RAM Flash | High-Mandatory | Rmt Mgmt White Gds | Client Server |
| ZeroMQ | UDP | Pub/Subscrbs Rqst/Rspnse | Fair | Fair | 10Ks/RAM Flash | High-Optional | CERN | P2P |

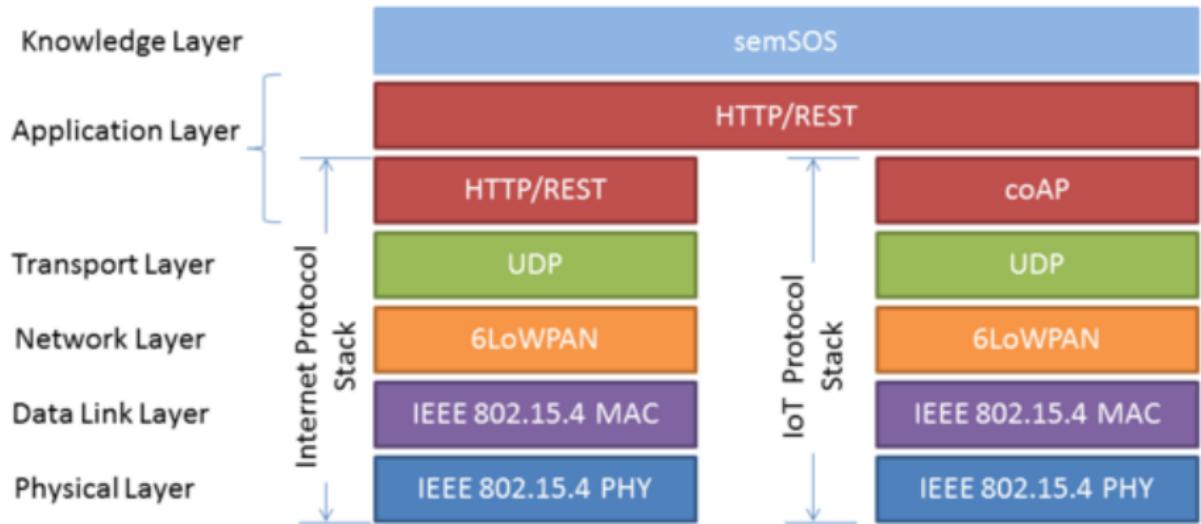
Comparison



- Inefficient content encoding
- Huge overhead, difficult parsing
- Requires full Internet devices

- Efficient objects
- Efficient Web
- Optimized IP access

Comparison



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Test & Development Environments Outline

► Test & Development Environments

- IoT Lab test
- RIOT environment
- Compilers
- Development environment

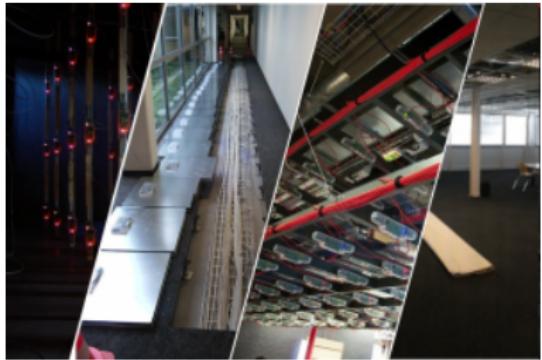
IoT Lab test

- ▶ A scientific testbed
- ▶ Different topologies and environments
- ▶ Different nodes
- ▶ A part of FIT

FIT IoT-lab

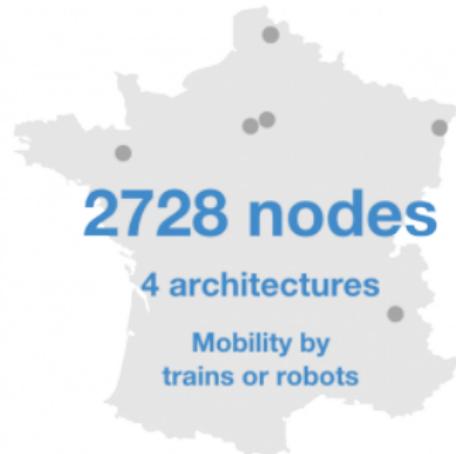
A scientific testbed

- ▶ IoT-LAB provides full control of network nodes and direct access to the gateways to which nodes are connected, allowing researchers to monitor nodes energy consumption and network-related metrics.



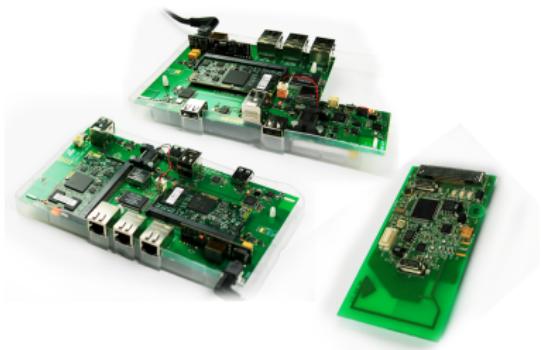
Different topologies and environments

- ▶ IoT-LAB testbeds are located at six different sites across France which gives forward access to **2728 wireless sensors nodes**.



Different nodes

- ▶ The IoT-LAB hardware infrastructure consists of a set of IoT-LAB nodes.
- ▶ A global networking backbone provides power and connectivity to all IoT-LAB nodes and guarantees the out of band signal network needed for command purposes and monitoring feedback.



A part of FIT

- ▶ IoT-LAB is a part of the FIT (Future Internet of the Things) platform.
- ▶ FIT is a set of complementary components that enable experimentation on innovative services for academic and industrial users.



RIOT environment

- ▶ RIOT features the native port with networking support.
- ▶ This allows you to run any RIOT application on your Linux or Mac computer and setup a virtual connection between these processes.



Compilers

► Family: ARM

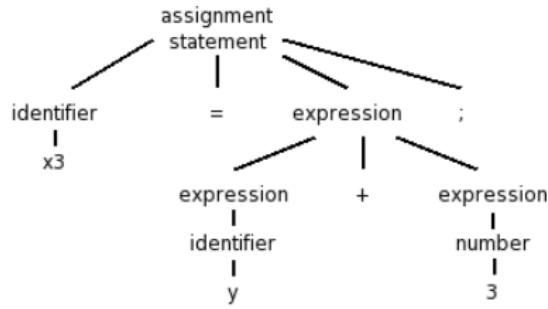
- gcc-arm-embedded toolchain
- CodeBench toolchain
- Linaro toolchain

► Family: ATmega

- Atmel AVR Toolchain

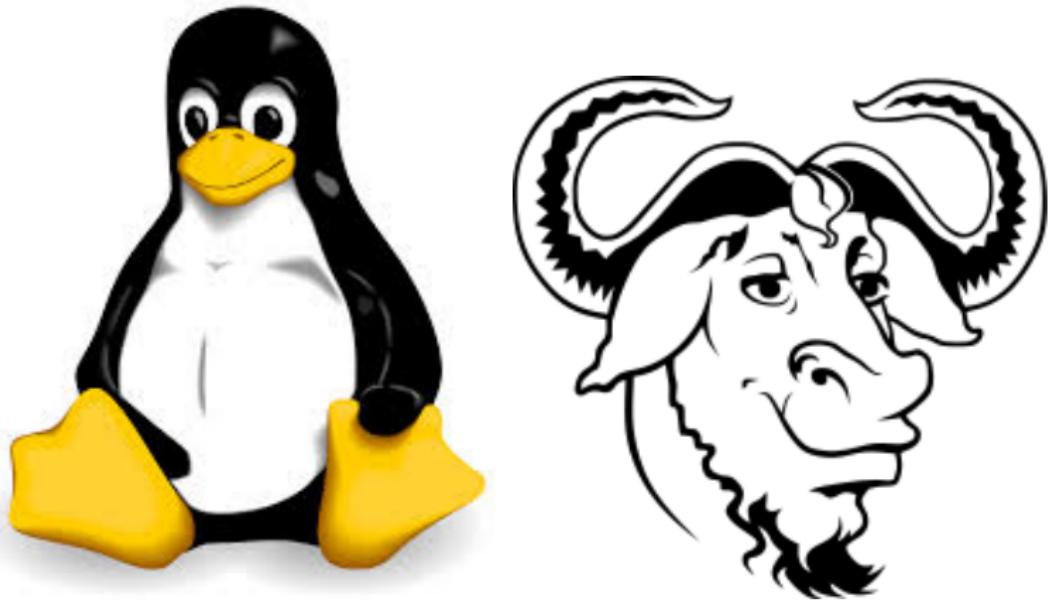
► Family: MSP430

- MSPGCC toolchain



Development environment

- ▶ Most of the IoT OS developed on **Linux** and use **traditional make** as build system.



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Conclusion Outline

► Conclusion

- Open problems
- Event-Driven, Non-Blocking I/O Model

Open problems

- ▶ Ideally, the capabilities of a full-fledged OS should be available on all IoT devices.
- ▶ Native Multi-Threading
- ▶ Hardware Abstraction
- ▶ Dynamic Memory Management
- ▶ Fulfill Strict Energy Efficiency

P=NP?

Event-Driven, Non-Blocking I/O Model

- ▶ Networking Event-Driven
- ▶ Non-Blocking I/O



Questions?