An Introduction to IoT Operating Systems

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August 2, 2015

Outline

- Part I: IoT OS
- Part II: IoT Protocol Stack
- Part III: IoT Development
- Conclusion

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- Part I: IoT OS
    - Introduction
    - IoT Requirements & Challenges
    - IoT OS
    - Existing OSs
- Part II: IoT Protocol Stack
- Part III: IoT Development
- Conclusion

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  - Traditional Stack
  - IoT Requirements
  - IoT Stack
  - Comparison
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  - Comparison
- Part III: IoT Development
  - IoT Lab test
  - RIOT environment
  - Compilers
  - Development environment
- Conclusion

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IoT?!!

What is IoT...

[Wikipedia]: The network of physical objects or "things" embedded with electronics, software, sensors, and connectivity to enable objects to exchange data with the manufacturer, operator and/or other connected devices based on the infrastructure of ITU's Global Standards Initiative

What is IoT...

[ITU]: A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies

What is IoT...

[WhatIs]: 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 IoT can be any natural or man-made object can be assigned IP(v6) 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.

IoT's Applications

- Environmental monitoring
- Infrastructure management
- Manufacturing
- Energy management
- Medical and healthcare systems
- Building and home automation
- Transportation
- ...

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- Part I: IoT OS
  - Introduction
  - IoT Requirements & Challenges
    - R1: Heterogeneous Hardware Constraints
    - R2: Autonomy
    - R3: Programmability
    - Effect of the requirements on OS
  - IoT OS
  - Existing OSs
- Part II: IoT Protocol Stack
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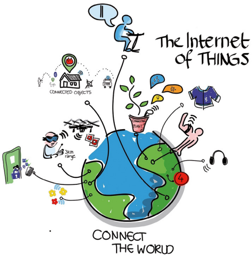
R1: Heterogeneous Hardware Constraints

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

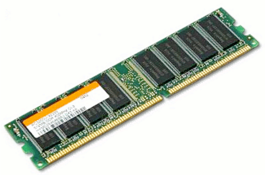


Memory Requirements

- Many of typical IoT devices have very little memory (typically between 5kB and some hundreds of megabytes)
- This concerns RAM as well as persistent program storage.

Effects on OS

- Kernel image should be very small
- The RAM footprint should be very low
- The OS should be modular!

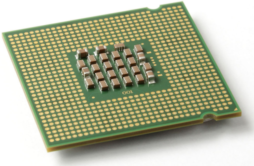


CPU Requirements

- Some of the IoT systems are MCU based (instead of CPU)
- Some of the MCUs/CPUs in a IoT system will work at a very low clock cycle.

Effects on OS

- The complexity of OS must be kept very low
- Should be scalable, to accommodate a wide range of different classes of devices



Limited Features

- IoT's hardware may have not advanced components like a Memory Management Unit (MMU) or a Floating-Point Unit (FPU).

Effects on OS

- Software for IoT must be able to run on constrained HW
- Should be scalable, to accommodate a wide range of different classes of devices

Platform Support

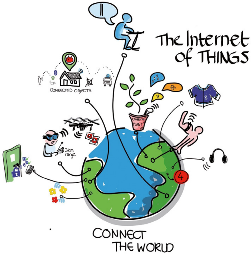
- IoT platforms may have very limitted resources; e.g., battery, IO, storage, ...
- IoT platforms may composed of widly different components

Effects on OS

- Must be able to leverage the capabilities of less constrained platforms
- Should be scalable, to accommodate a wide range of different classes of devices

R2: Autonomy

- Energy efficiency
- Adaptive Network Stack
- Reliability

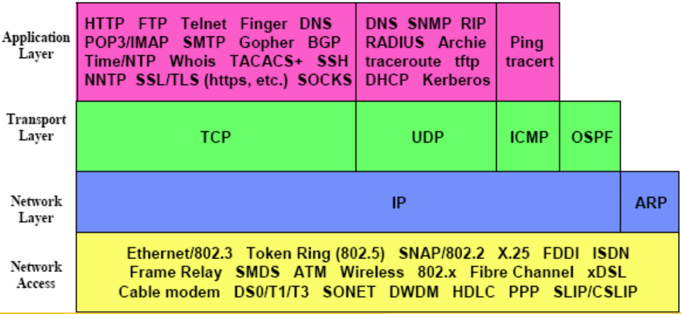


Energy efficiency

- 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.

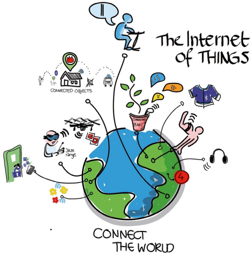


Reliability

- 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.

R3: 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.

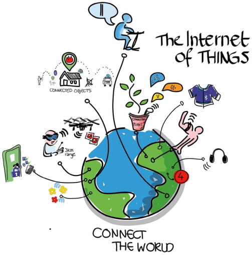
Standard Programming Languages

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

IoT Challenges

References are useful & needed

- 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

- Part I: IoT OS
  - Introduction
  - IoT Requirements & Challenges
  - IoT OS
    - General OS vs IoT OS
    - What are the main requirements in IoT OS
    - What are the main components in IoT OS
  - Existing OSs
- Part II: IoT Protocol Stack
- Part III: IoT Development
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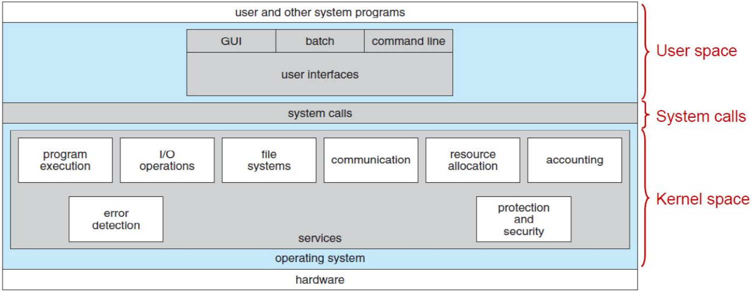
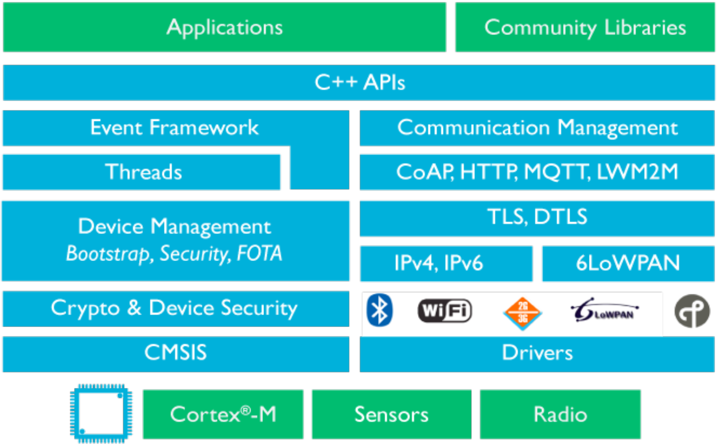
General OS


user and other system programs
GUI
batch
command line
user interfaces
system calls
program execution
I/O operations
file systems
communication
resource allocation
accounting
error detection
protection and security
services
operating system
hardware
User space
System calls
Kernel space

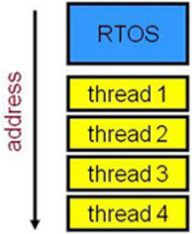
IoT OS



Applications
Community Libraries
C++ APIs
Event Framework
Threads
Communication Management
CoAP, HTTP, MQTT, LWM2M
Device Management
Bootstrap, Security, FOTA
TLS, DTLS
IPv4, IPv6
6LoWPAN
Crypto & Device Security
WiFi
2G 3G
LoWPAN
CMSIS
Drivers
Cortex®-M
Sensors
Radio

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
    - OS Classification
    - Overview of Open Source OSs
    - Overview of Closed Source OSs
    - Why Not Linux?
- Part II: IoT Protocol Stack
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OS Classification

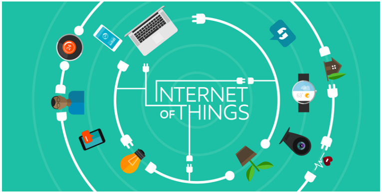
- Design Aspects for an IoT OS
  - Monolithic fashion
  - Layered approach
  - Microkernel architecture

OS Classification

- 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

- 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

- 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

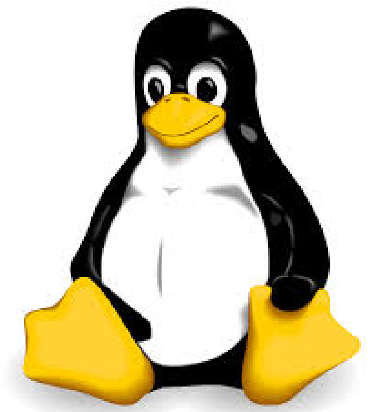
- Contiki is an open source operating system for networked, memory-constrained systems
- Contiki provides three network mechanisms:
  - The uIP stack, which provides IPv4 networking,
  - The uIPv6 stack, which provides IPv6 networking,
  - The Rime stack, which is a set of custom lightweight networking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

TinyOS

- 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.



OpenWSN

- 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	$\sim 1MB$	$\sim 1MB$	Full support	Full support
RIOT	$\sim 1.5kB$	$\sim 5kB$	Full support	Full support

Comparison

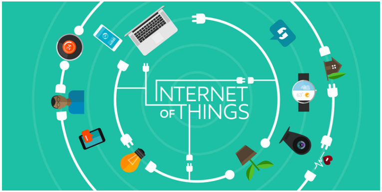
OS	Multi-Threading	Modularity	Real-Time
Contiki	Partial support	Partial support	Partial support
Tiny OS	Partial support	No support	No support
Linux	Full support	Partial support	Partial support
RIOT	Full support	Full support	Full support

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

Overview of Closed Source OSs

- ARM mbed
- Huawei LiteOS
- Google Brillo



ARM mbed

- 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™

Huawei LiteOS

- 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

- 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.

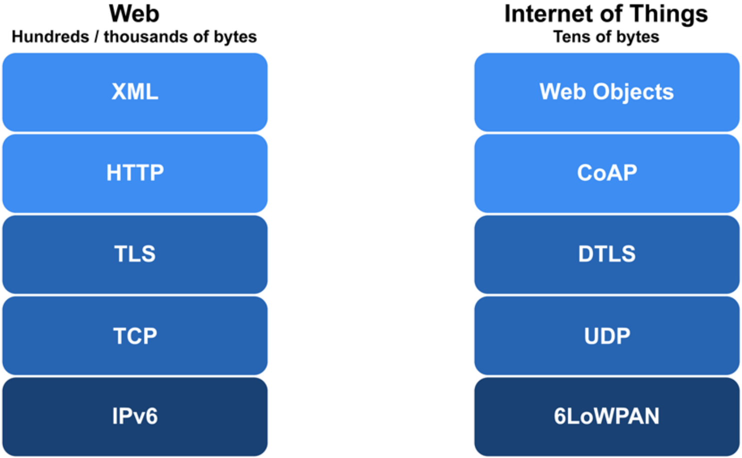
IoT Stack

- 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

Protocol	Transport	Messaging	2G,3G,4G (1000's)	LowPower and Lossy (1000's)	Compute Resources	Security	Success Stories	Arch
CoAP	UDP	Rqst/Rspnse	Excellent	Excellent	10Ks/RAM Flash	Medium - Optional	Utility field area ntwks	Tree
Continua HDP	UDP	Pub/Subsrb Rqst/Rspnse	Fair	Fair	10Ks/RAM Flash	None	Medical	Star
DDS	UDP	Pub/Subsrb 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/Subsrb 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/Subscrb Rqst/Rspnse	Excellent	Good	10Ks/RAM Flash	None	Consumer	P2P Client Server
XMPP	TCP	Pub/Subsrb Rqst/Rspnse	Excellent	Fair	10Ks/RAM Flash	High- Manditory	Rmt Mgmt White Gds	Client Server
ZeroMQ	UDP	Pub/Subscrb Rqst/Rspnse	Fair	Fair	10Ks/RAM Flash	High- Optional	CERN	P2P

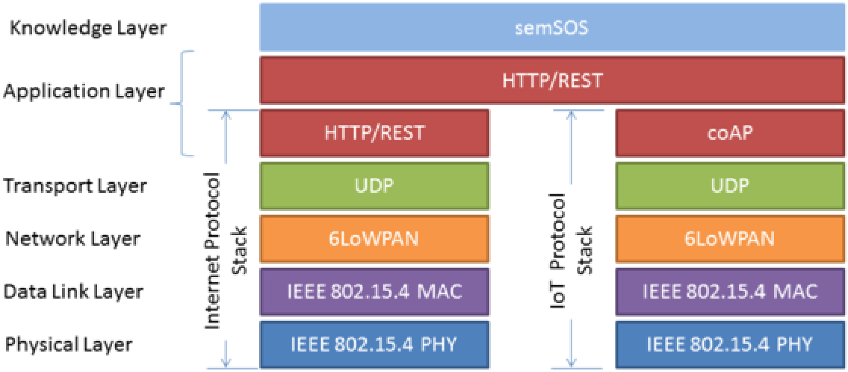
Comparison



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

- Efficient objects
- Efficient Web
- Optimized IP access

Comparison


Knowledge Layer
Application Layer
Transport Layer
Network Layer
Data Link Layer
Physical Layer
semSOS
HTTP/REST
HTTP/REST
coAP
UDP
UDP
6LoWPAN
6LoWPAN
IEEE 802.15.4 MAC
IEEE 802.15.4 MAC
IEEE 802.15.4 PHY
IEEE 802.15.4 PHY
Internet Protocol Stack
IoT Protocol Stack

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  - RIOT environment
  - Compilers
  - Development environment
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IoT Lab test

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

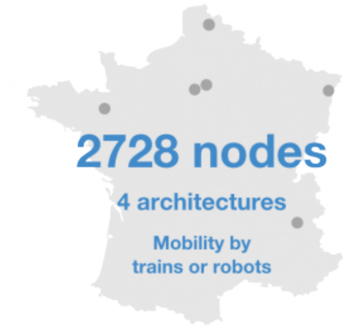
FIT IoT-lab

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.

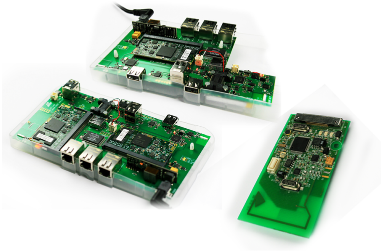
Different topologies and environments

- 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 guaranties the out of band signal network needed for command purposes and monitoring feedback.



A part of FIT

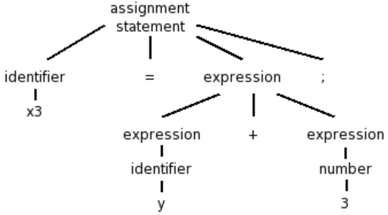
- IoT-LAB is a part of the FIT (Future Internet of the Things) platform.
- FIT is a set of complementary components that enable experimentation on innovative services for academic and industrial users.

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.

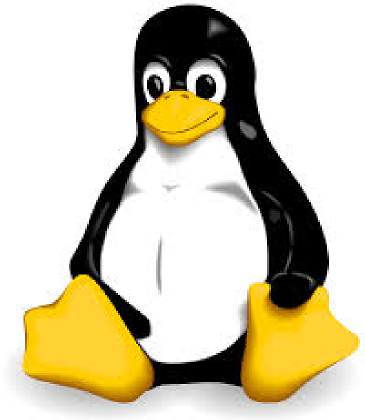
Compilers

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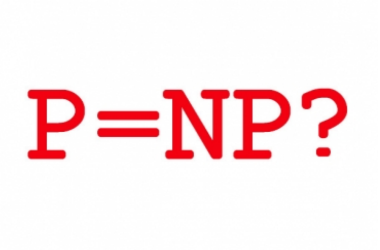
  - Open problems
  - Event-Driven, Non-Blocking I/O Model

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



Event-Driven, Non-Blocking I/O Model

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

Questions?