# INTERNET OF THINGS – INTERNET IN THE SMALL

H. Schulzrinne

(+ Jan Janak & other CUCS IRT contributors)

IIT RTC, October 1, 2014

# Overview

- The Internet of Things is many things
  - Most of them aren't new or exciting
- The network part isn't (all that) exciting
  - but usable security, software and system integration are
- It's a software thing → multi-devices services, APIs, IFTTT, SECE, …
- About being a nice IoT citizen
- ShellShock for light switches?

# Internet of Things (IoT)

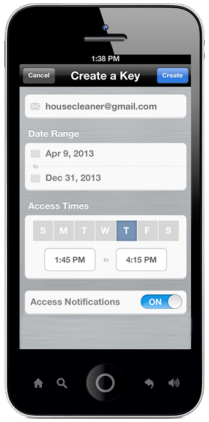
- Also sometimes called
  - "industrial Internet" (subset)
  - "machine-to-machine" (M2M)
  - "cyber-physical systems" (NSF)
  - "smart city" (IBM)
- Concept dates to late 90's
  - Initially, tag physical objects (RFID)
  - Now, **networked** sensors and control of previously mechanical or electrical objects

# M2M/IoT/CPS is not…

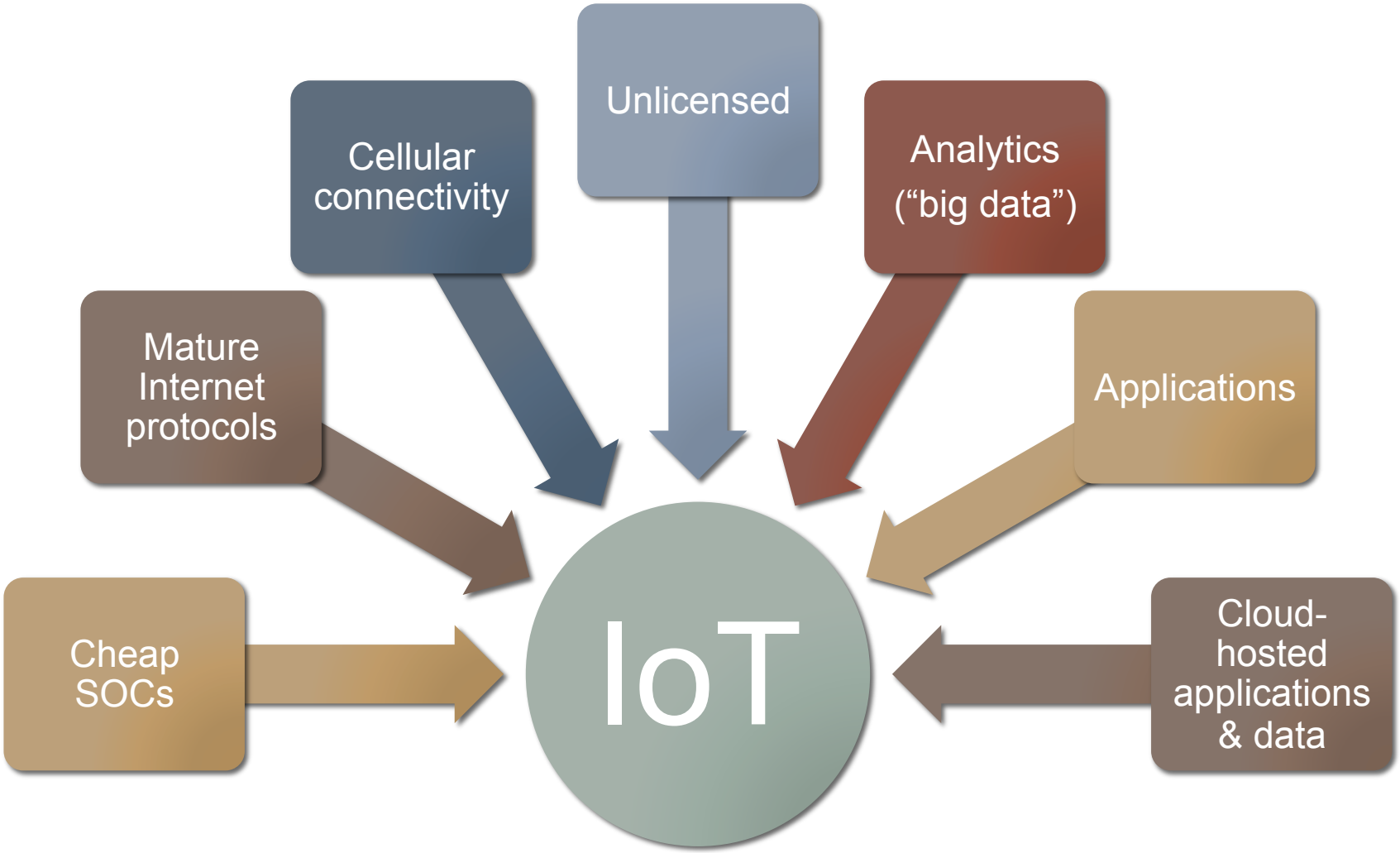
- isn't just about fancy thermostats and $199 door bells
- doesn't always uses cellular networks
- is not always energy-constrained
- is not always cost-constrained
- doesn't always use puny microcontrollers
- is not always run by large organizations
  - many small & mid-sized providers
  - usually embedded into other products

# Natural evolution

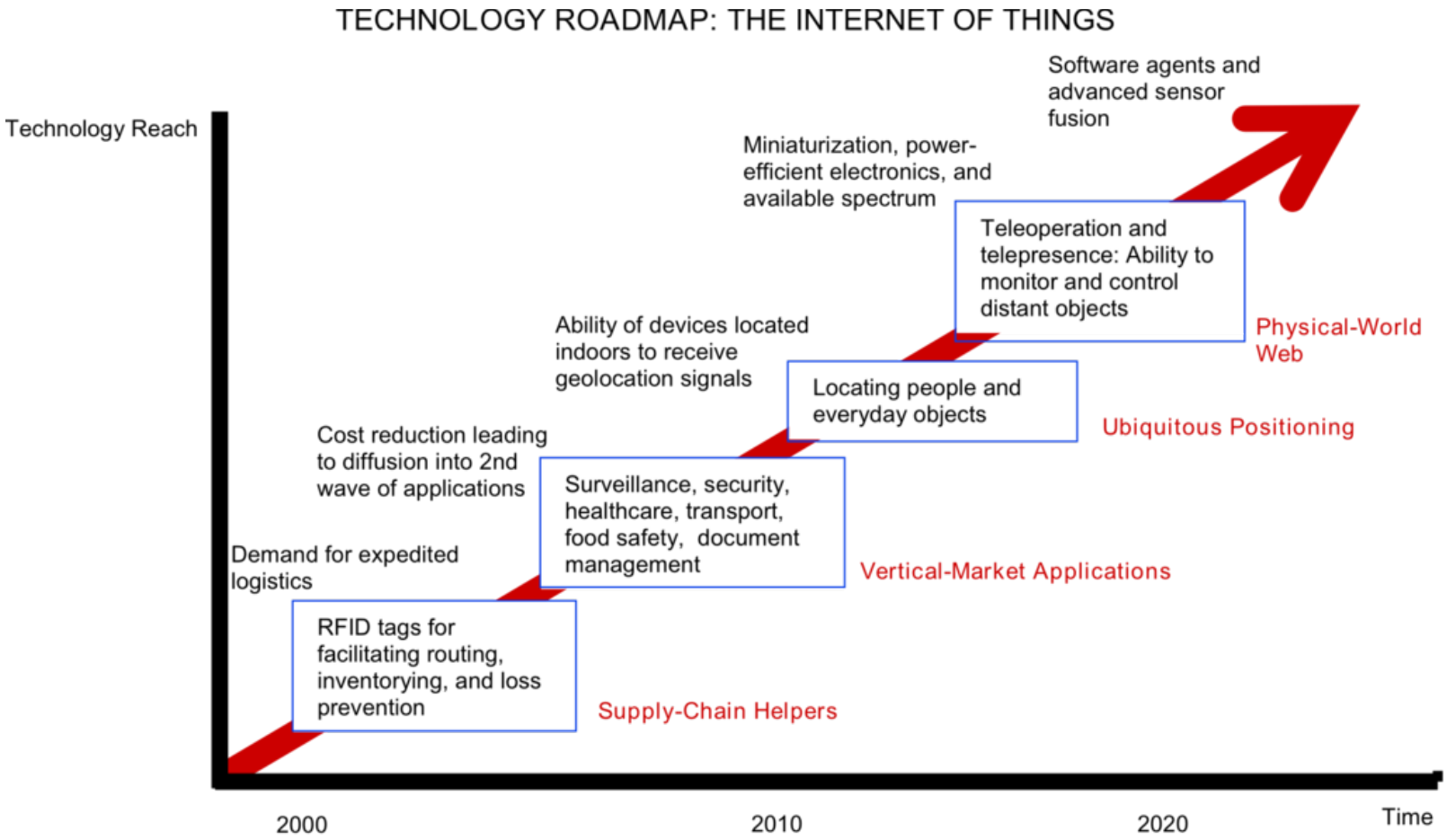




# Key enablers

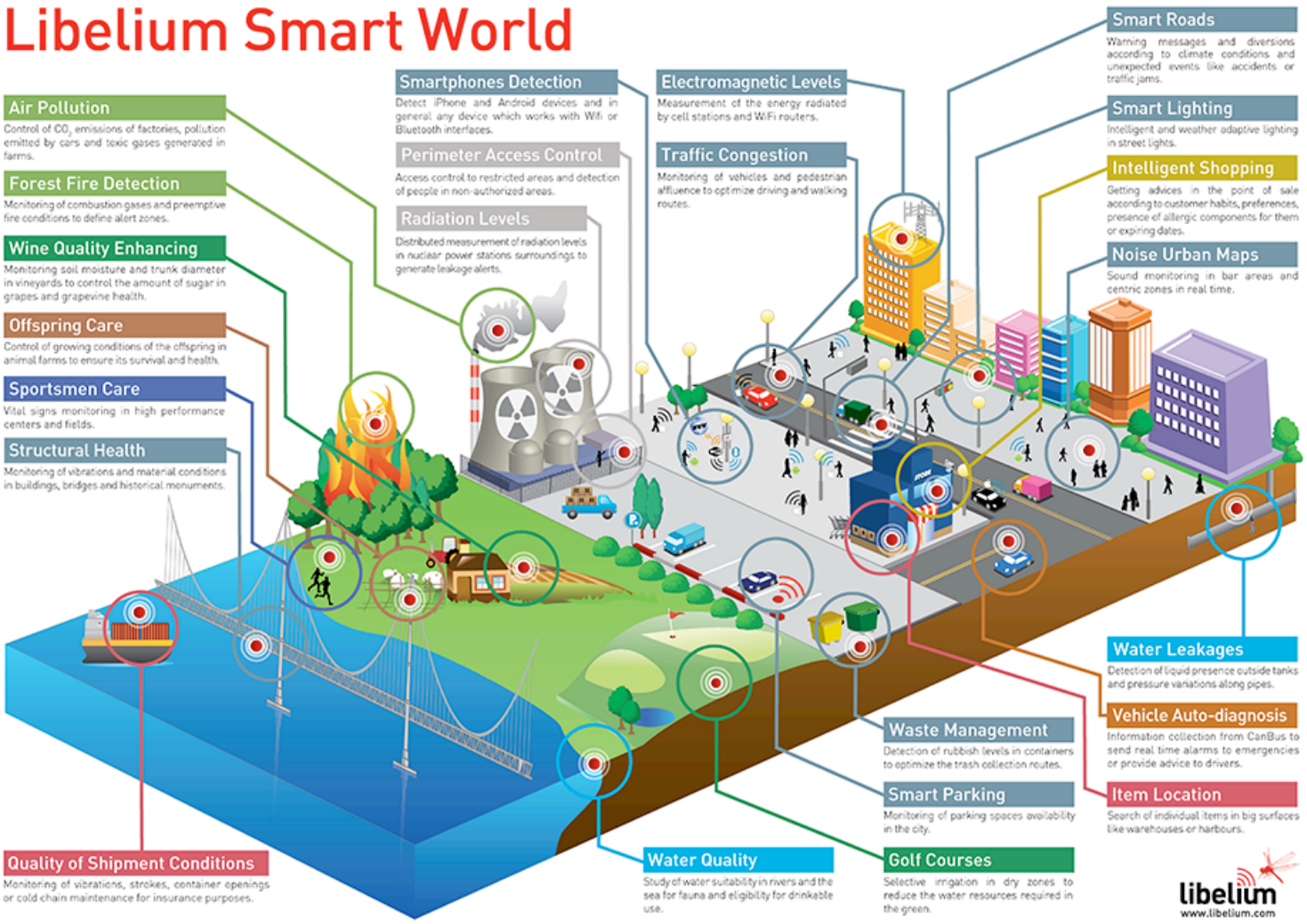


# Internet of Things roadmap

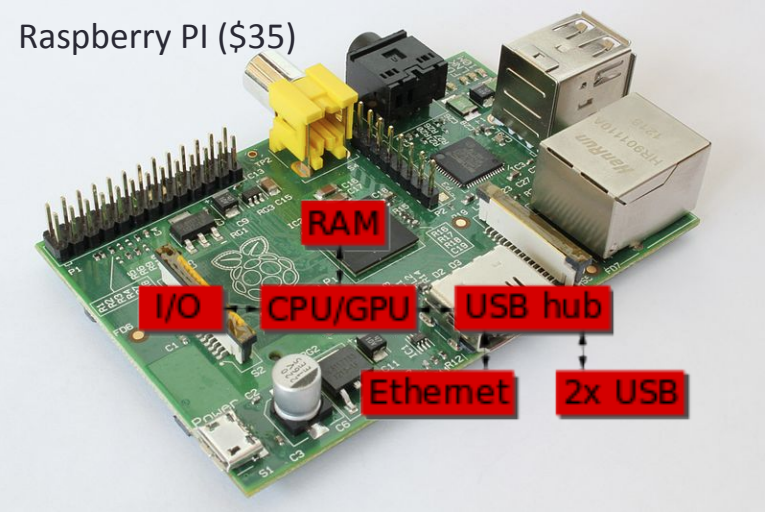


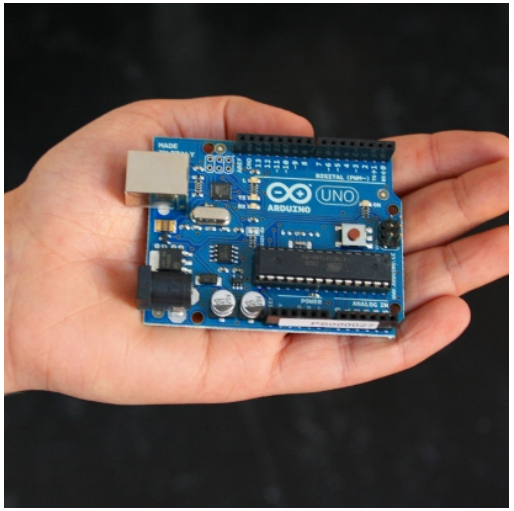

Source: SRI Consulting Business Intelligence

# Environmental sensing

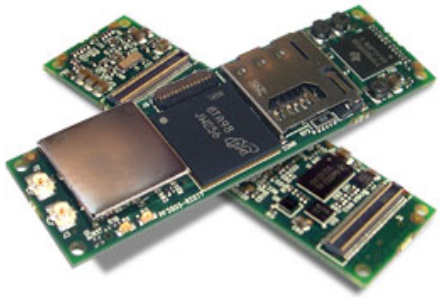


# IoT = cheap microcontrollers + network interfaces



Arduino Uno, €20

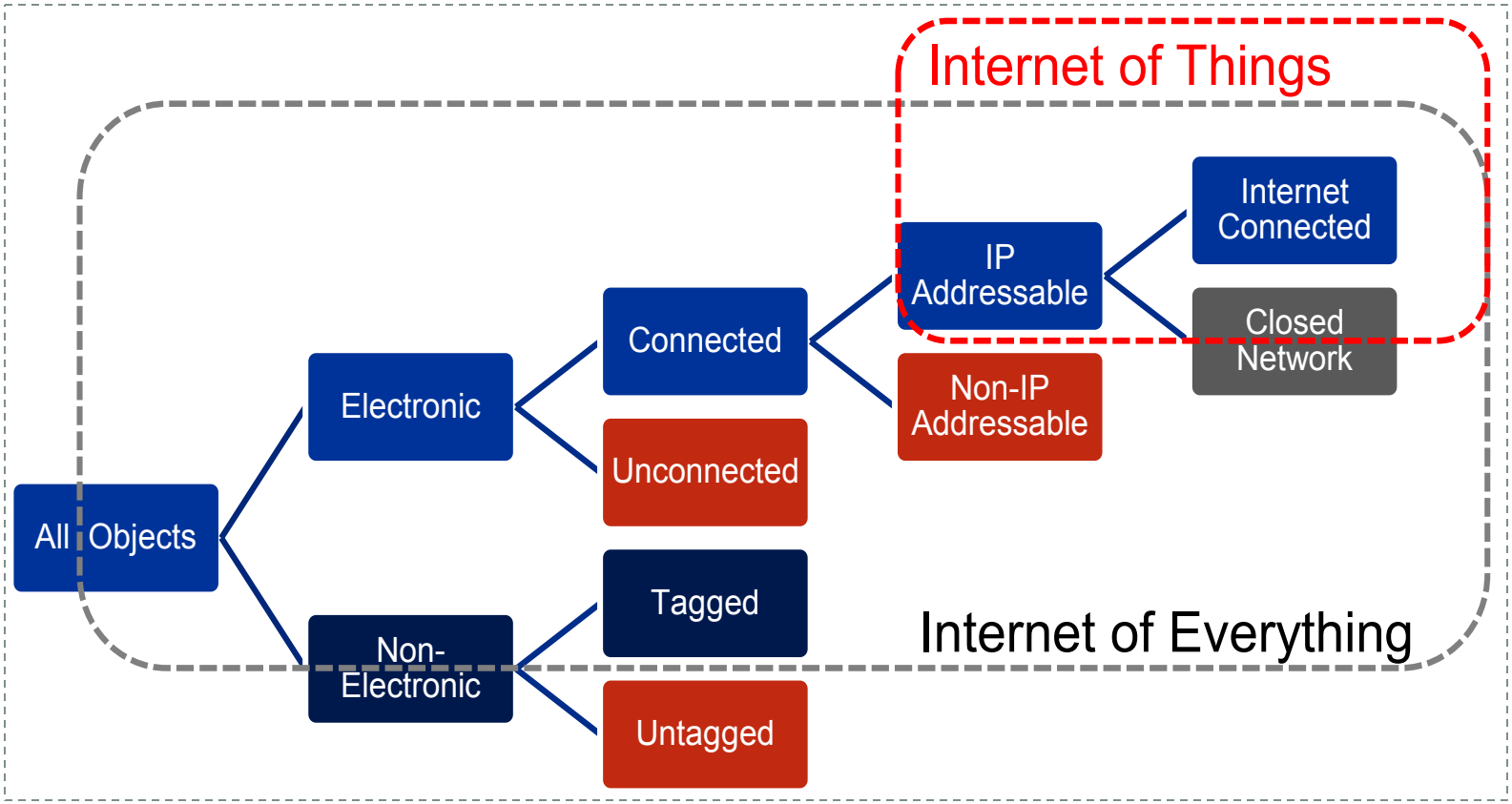


Gumstix (WiFi, BT): 58 mm, $199

# Where does IoT make sense?

- Automate manual data extraction
  - health, car, electric/gas meter, …
- Remote maintenance
  - vending machines, appliances, cars & trucks, trains, pumps, …
- Incorporate additional information
  - thermostats, light switches, traffic lights, parking meters, …
- Software-Defined Mechanics
  - locks, light switches
- But where does it solve more than 1st world problems?
  - commercial maintenance savings?
  - in-home customizable assistive technology

# A taxonomy




Bill Morelli, IHS

# Connectivity Framework

## Three dominant classes of wireless IoT links (there are others)

1. **Thing to Thing** (vehicles, sensors/actuators, etc.)

   LAN/PAN range; use spectrum suited to short distances; extensive spatial reuse

2. **Thing to Proxy** (e.g., gateways, hubs, hubs within vehicles, etc.)

   LAN/PAN* range; use spectrum suited to short distances; extensive spatial reuse

   - IoT adds significant load to existing services, such as WiFi and BT
   - Traffic upstream from proxies shares allocations and adds significant load to existing services used to link WiFi, etc. to core Internet.

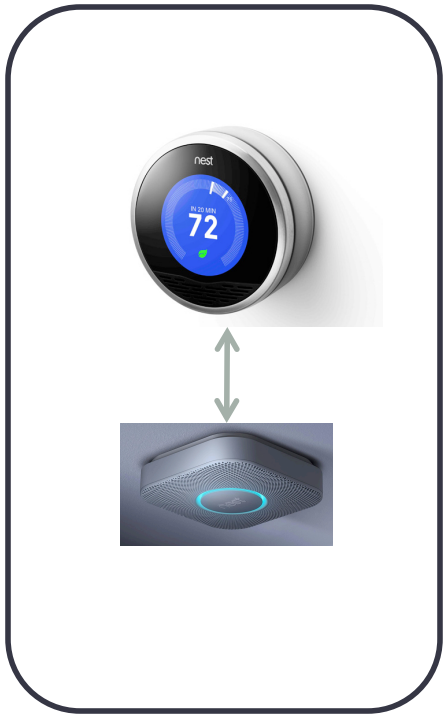
3. **Thing to Internet** (e.g., direct connection to 4G networks, WISPs, TVWS, etc.)

   *last mile* range; share spectrum with and/or use other wide area services

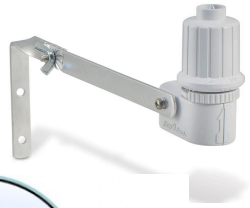
   - IoT adds load to 4G/TVWS services and poses challenges wrt long-lived things

* Personal Area Network -- typically operates within a range < 10M

# IoT islands vs. IoT eco system

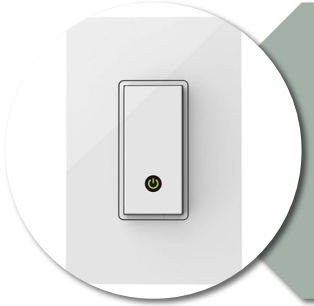






# IoT: more than programmable light bulbs

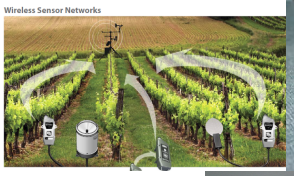
public sensors & actuators

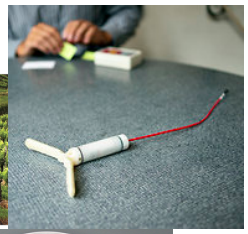


semi-private


private

# IoT varies in communication needs



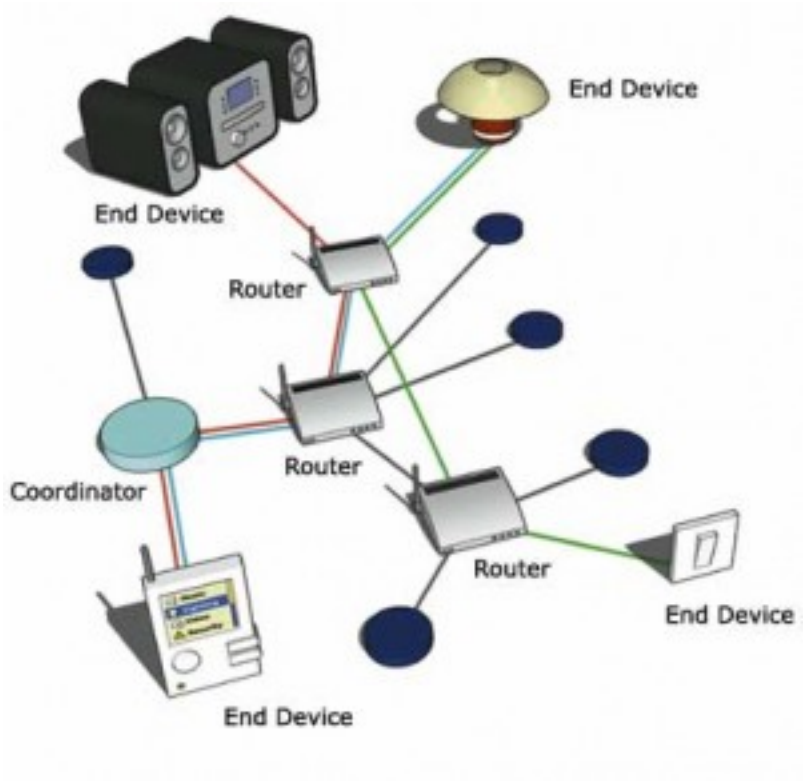


sensors

1/hour 1/minute 1/second 10/second

actuators


# Not just cellular *or* unlicensed

# M2M communication models

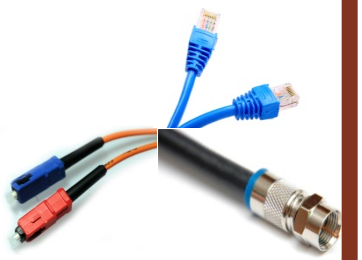
| | | |
|---|---|---|
| dispersed | Smart grid, meter, city<br>Remote monitoring | Car automation<br>eHealth<br>Logistics<br>Portable consumer electronics |
| concentrated | smart home<br>factory automation<br>eHealth | on-site logistics |
| | fixed | mobile |

Source: OECD (2012), "Machine-to-Machine Communications: Connecting Billions of Devices", *OECD Digital Economy Papers, No. 192, OECD Publishing.* http://dx.doi.org/10.1787/5k9gsh2gp043-en

# IoT Connectivity Technologies

## Wired

- Ethernet, Coax, Fiber, etc. considered as a single category



## WPAN

- ANT+
- Bluetooth – Classic & Smart Ready
- Bluetooth Smart

## WLAN

- ZigBee PRO
- ZigBee RF4CE
- ZigBee Multi-Protocol
- EnOcean
- ISA100.11a
- WirelessHART
- Z-Wave
- Other 802.15.4

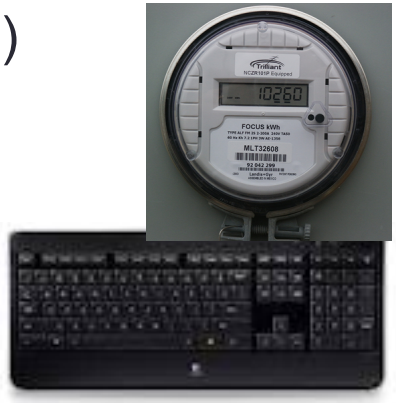
- 802.11a/b/g
- 802.11n
- 802.11ac
- 802.11ad
- Other 802.11
- DECT ULE
- Other 2.4GHz
- Other Sub-GHz

## WWAN

- 2G Cellular
- 3G Cellular
- 4G Cellular

# Network challenges

- Unlicensed
  - How do I attach and authenticate a device to a (home) network?
  - Credentials?
- Licensed
  - Reliability → multiple *simultaneous* providers
  - Mobility → different providers in different regions
  - Charging → often low, intermittent usage, sometimes deferrable ("Whispernet")
    - From $50/device/month → < $1/month?
- Authentication
  - Which devices can be used by whom and how?
    - "Any employee can monitor the room temperature in any public space, but only Facilities staff can change it"



# Phone numbers for machines?

< 2010

212 555 1212

254 mio.

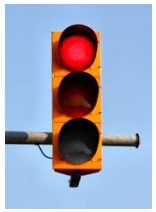
500 123 4567
(and geographic numbers)

OnStar by GM

12% of adults

500 123 4567
533, 544

5 mio.

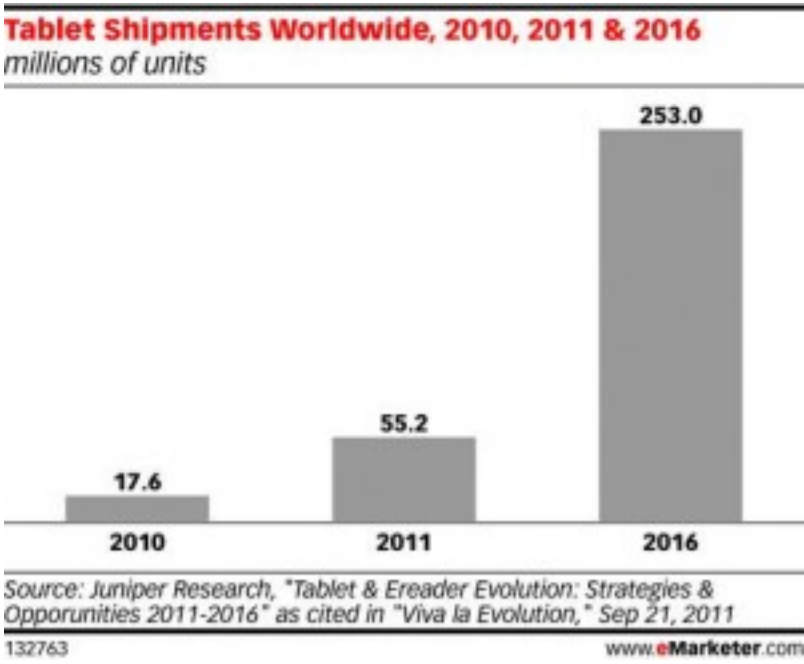


311,000



64 mio.

44.9 mio.




now: one 5XX code a year…
(8M numbers)

10 billion +1 #'s available

see Tom McGarry, Neustar

# Communication identifiers

| Property | URL owned | URL provider | E.164 | Service-specific |
|---|---|---|---|---|
| Example | alice@smith.name<br>sip:alice@smith.name | alice@gmail.com<br>sip:alice@ilec.com | +1 202 555 1010 | www.facebook.com/alice.example |
| Protocol-independent | no | no | yes | yes |
| Multimedia | yes | yes | maybe (VRS) | maybe |
| Portable | yes | no | somewhat | no |
| Groups | yes | yes | bridge number | not generally |
| Trademark issues | yes | unlikely | unlikely | possible |
| Privacy | Depends on name chosen (pseudonym) | Depends on naming scheme | mostly | Depends on provider "real name" policy |

→ IoT will likely be assigned local IP address space and owner-based names (meter17.pseg.com) [if any]

# The age of application-specific {sensors, spectrum, OS, protocol …} is over

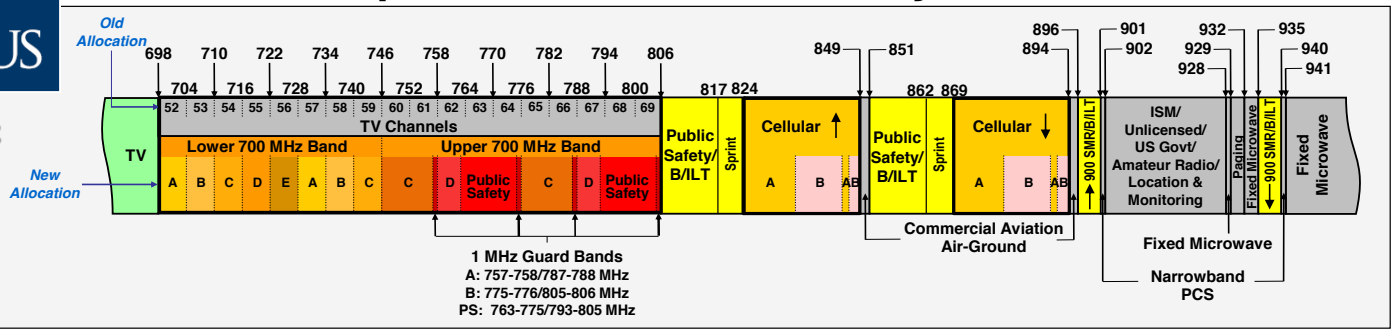
- *Computing system*: dedicated function → OS
  - → abstract into generic components
  - e.g., USB human interface device (HID)
- What are the equivalent sensor and actuator classes?
- *Networks*: generic app protocols
  - request/response → HTTP
  - event notification → SMTP, SIP, XMPP
- *Spectrum*: from new application = new spectrum to generic data transport

STIFEL NICOLAUS

# U.S. Spectrum Allocation of Key Bands

July 14, 2011

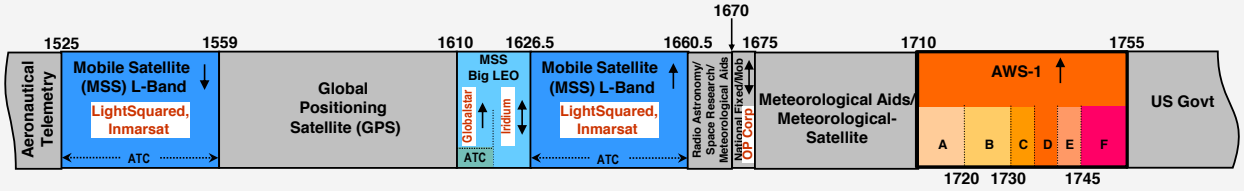
## 700 - 1000 MHz




*IEEE Standard Band Designators*

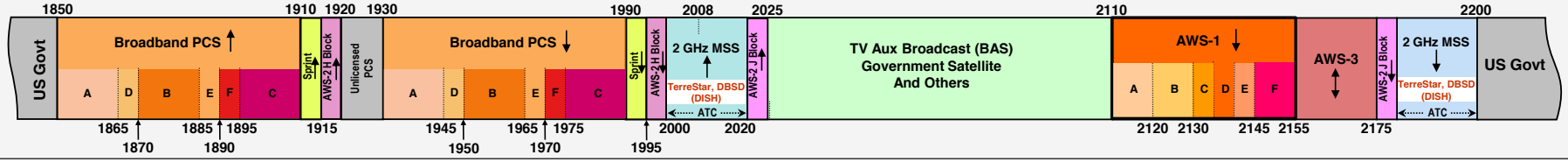
| | |
|---|---|
| HF | 3-30 MHz |
| VHF | 30-300 MHz |
| UHF | 300-1000 MHz |
| L band | 1-2 GHz |
| S band | 2-4 GHz |
| C band | 4-8 GHz |
| X band | 8-12 GHz |
| Ku band | 12-18 GHz |
| K band | 18-27 GHz |
| Ka band | 27-40 GHz |
| V band | 40-75 GHz |
| W band | 75-110 GHz |
| mm wave | 110-300 GHz |

## 1500 - 1800 MHz

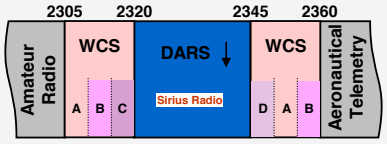


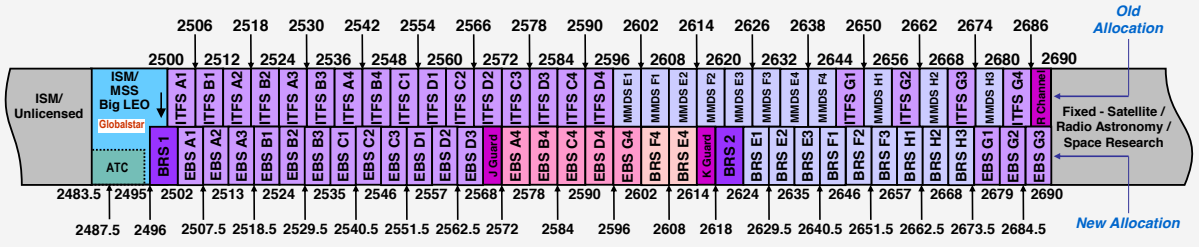

*Legend*
- *Uplink Band*
- *Downlink Band*
- *TDD Band*

## 1800 - 2200 MHz




## 2300 - 2700 MHz




*Source: FCC, Sprint and Stifel Nicolaus Research*

# Post-spectrum world

## Old (pre-2000)

- Mostly single-use, application-specific allocations (“radar”, “LMR”, “paging”)
- Mostly federal OR non-federal use
- Each band its own world
- Static usage
- Limited spectral efficiency concerns
- Go west (up), young application!

## Now

- No more unallocated bands (below 30+ GHz) →multi-use, generic transport
- Shared federal & non-federal use
- Neighbor “issues” (GPS, TV)
- Usage may change (satellite → mobile)
- Spectral efficiency – but how measured? (bits/s/Hz/km$^2$?)
- Limited ability to go to higher frequencies

# Current unlicensed spectrum

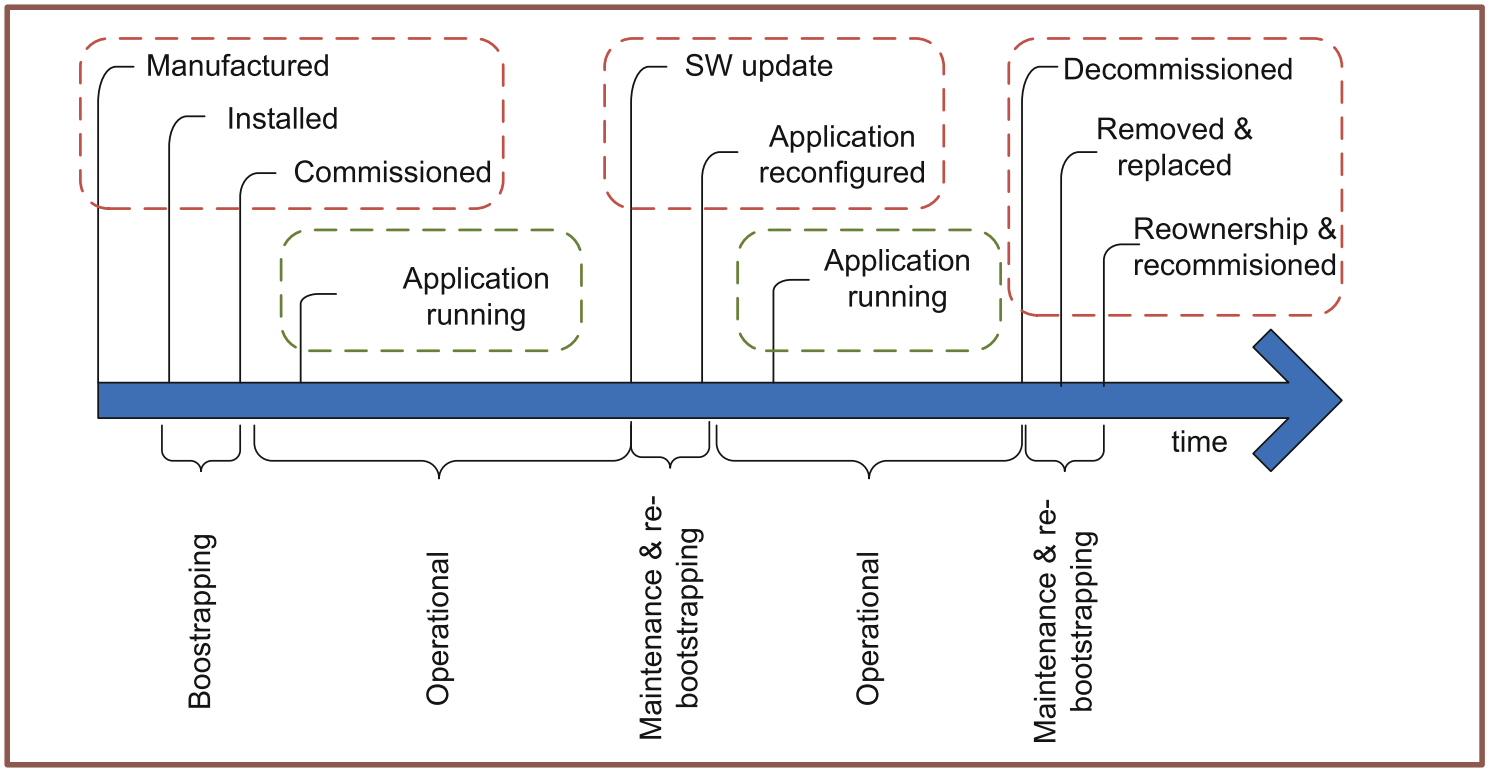
| Frequency range | | Bandwidth | Center frequency | Availability |
|---|---|---|---|---|
| 6.765 MHz | 6.795 MHz | 30 KHz | 6.780 MHz | Subject to local acceptance |
| 13.553 MHz | 13.567 MHz | 14 KHz | 13.560 MHz | |
| 26.957 MHz | 27.283 MHz | 326 KHz | 27.120 MHz | |
| 40.660 MHz | 40.700 MHz | 40 KHz | 40.680 MHz | |
| 433.050 MHz | 434.790 MHz | 1.84 MHz | 433.920 MHz | Region 1 only and subject to local acceptance |
| 902.000 MHz | 928.000 MHz | 26 MHz | 915.000 MHz | Region 2 only |
| 2.400 GHz | 2.500 GHz | 100 MHz | 2.450 GHz | |
| 5.725 GHz | 5.875 GHz | 150 MHz | 5.800 GHz | |
| 24.000 GHz | 24.250 GHz | 250 MHz | 24.125 GHz | |
| 61.000 GHz | 61.500 GHz | 500 MHz | 61.250 GHz | Subject to local acceptance |
| 122.000 GHz | 123.000 GHz | 1 GHz | 122.500 GHz | Subject to local acceptance |
| 244.000 GHz | 246.000 GHz | 2 GHz | 245.000 GHz | Subject to local acceptance |

+ TV white spaces (in 476-692 MHz range) – availability varies

# Challenge: enabling discovery & access control

- Devices should be discoverable & re-usable
  - e.g., provide audio interface to bus display
  - environmental probes (temperature, noise, rain, …)
  - location (iBeacon) → 911
- Layers of functionality
  - anybody in vicinity can read
  - anyone in *family* can change
  - parents can re-program
- Allow delegation
  - grant temporary access to somebody or something else
  - by message or physical proximity
- Currently, all one-off solutions
  - OAuth? NFC?

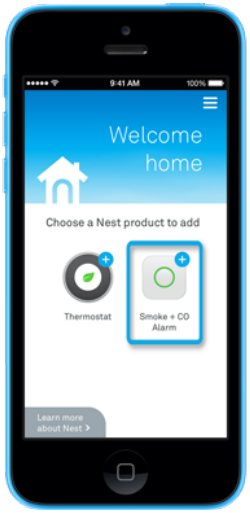
# Device lifecycle



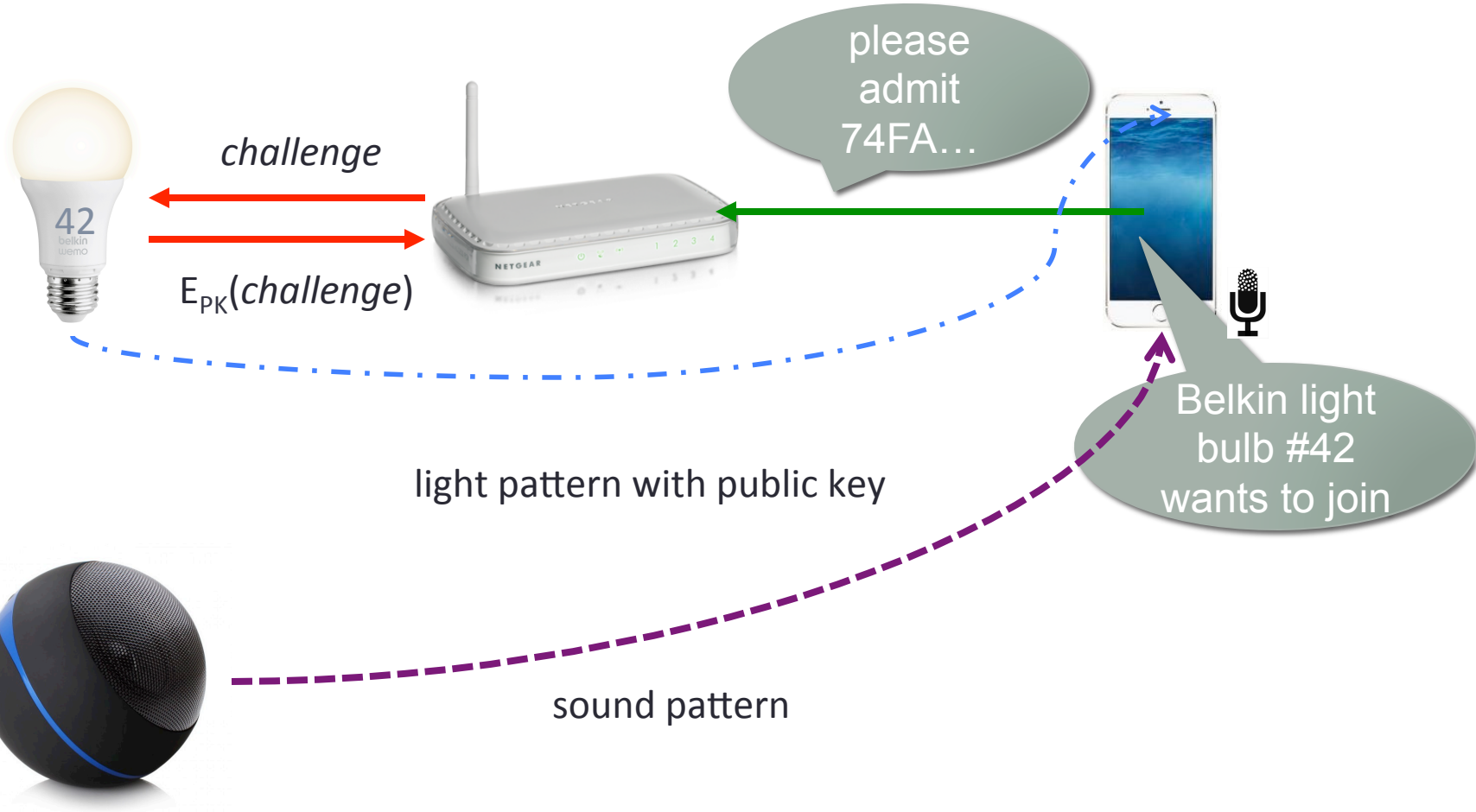

T. Heer et al., “Security Challenges in the IP-based Internet of Things”, 2011.

# Challenge: enrollment

- Commercial buildings → enroll 1,000s of devices at once
- Home → enroll one device at a time
  - current model: one app per device (class)
  - re-do if Wi-Fi password changes
  - common options:
    - QR code
    - P2P Wi-Fi (Wi-Fi Direct)
  - possibilities
    - “hi, I’m a Philips light bulb – add me!” (PKI)

# Other introduction models




Avoid single password → allow device transfer

# IoT good-citizen rules

FCC TAC recommendations +

- Implement current best practices
  - no plain-text data or commands
    - low-power CPUs are no excuse – long-payback or infrequent crypto operations
  - no default passwords
- Do not assume that your (cellular) network is around in > 8 years
  - short-range unlicensed bands more likely a safe harbor
- Update yourself securely
- Don't trust random APs → PassPoint, 802.1x?
  - matters mainly for DNS and denial-of-service
- Go into fail-safe mode if no updates
- Be nice to cellular network (signaling, white spaces, …)
  - and maybe "kill switch" if misbehaving (or stolen!)
- Don't ask for special spectrum
  - except maybe if you're a health-and-safety device (but share nicely)
  - or maybe low-bandwidth narrowband spectrum

Example: SIGFOX (902 MHz, 100 bps) is a connectivity solution that focuses on low throughput devices. On SIGFOX you can send between 0 and 140 messages per day and each message can be up to 12 bytes of actual payload data.

# ShellShock for light switches

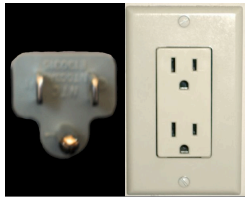

- IoT risks: privacy, DDOS, extortion, …
- *Securely* field updateable or no connection to Internet
  - still vulnerable if malware on home network
- Lifetime of devices > lifetime of company
- Insurance model:
  - source code escrow + maintenance for N years
- UL listing

# Theses: Internet lessons

- The Internet is about more than the Internet protocol
- Reliability multiplies, costs add
- Quality is no substitute for quantity
- Data links layers come & go, IP stays
- The age of application-specific {sensors, spectrum, OS, protocol …} is over
- Protocols matter, but programmability matters more

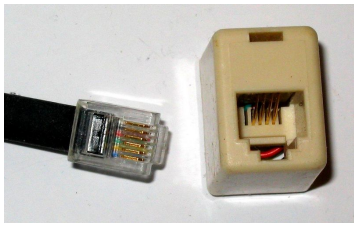
# Technology changes, interfaces are forever

110/220V



1904

1901



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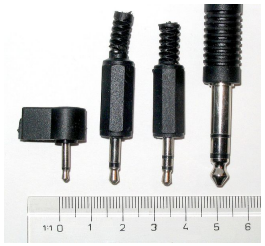


1830

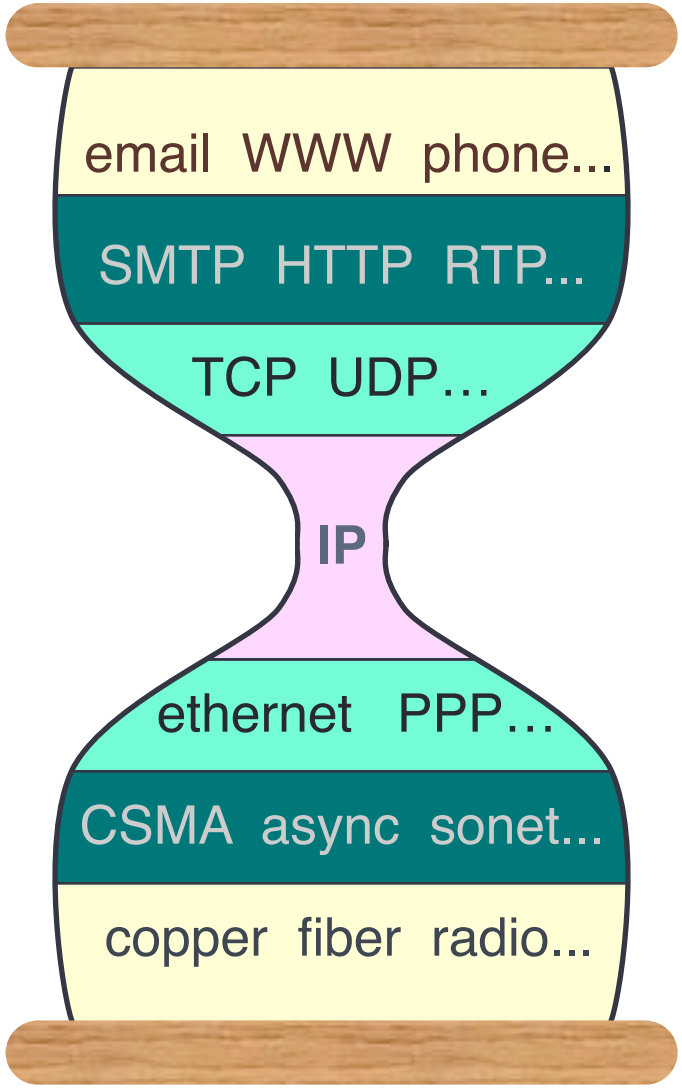

1992


1993

1982

# The Internet is about more than the Internet protocol

- Protocol hour glass
- But ignores important (late) lessons:
  - naming matters: no consumer Internet without DNS
  - support auto-configuration: DHCP, DNS, netconf
  - network management & diagnostics: ICMP, traceroute, SNMP
- Common data coding layers:
  - initially ASN.1
  - then XML
  - now JSON



# Reliability multiplies, cost adds

- Pre-Internet (e.g., phone system):
  - Single switch, 5-nines reliability, $3M dollars
  - mostly hardware
  - specialty components
- Internet:
  - assume that components fail → compensate by redundancy
    - cost for high-reliability components increases >> linear
    - e.g., two paths with 99% reliability each
    - → generic transport (e.g., multiple 4G, fiber, DSL, cable, satellite)
  - build control loops and protocols that expect failure
    - retry, graceful degradation, adaptation, …
    - end-to-end argument
  - as much software as possible → *software-defined networks & infrastructure, IoT*
    - late bindings in functionality

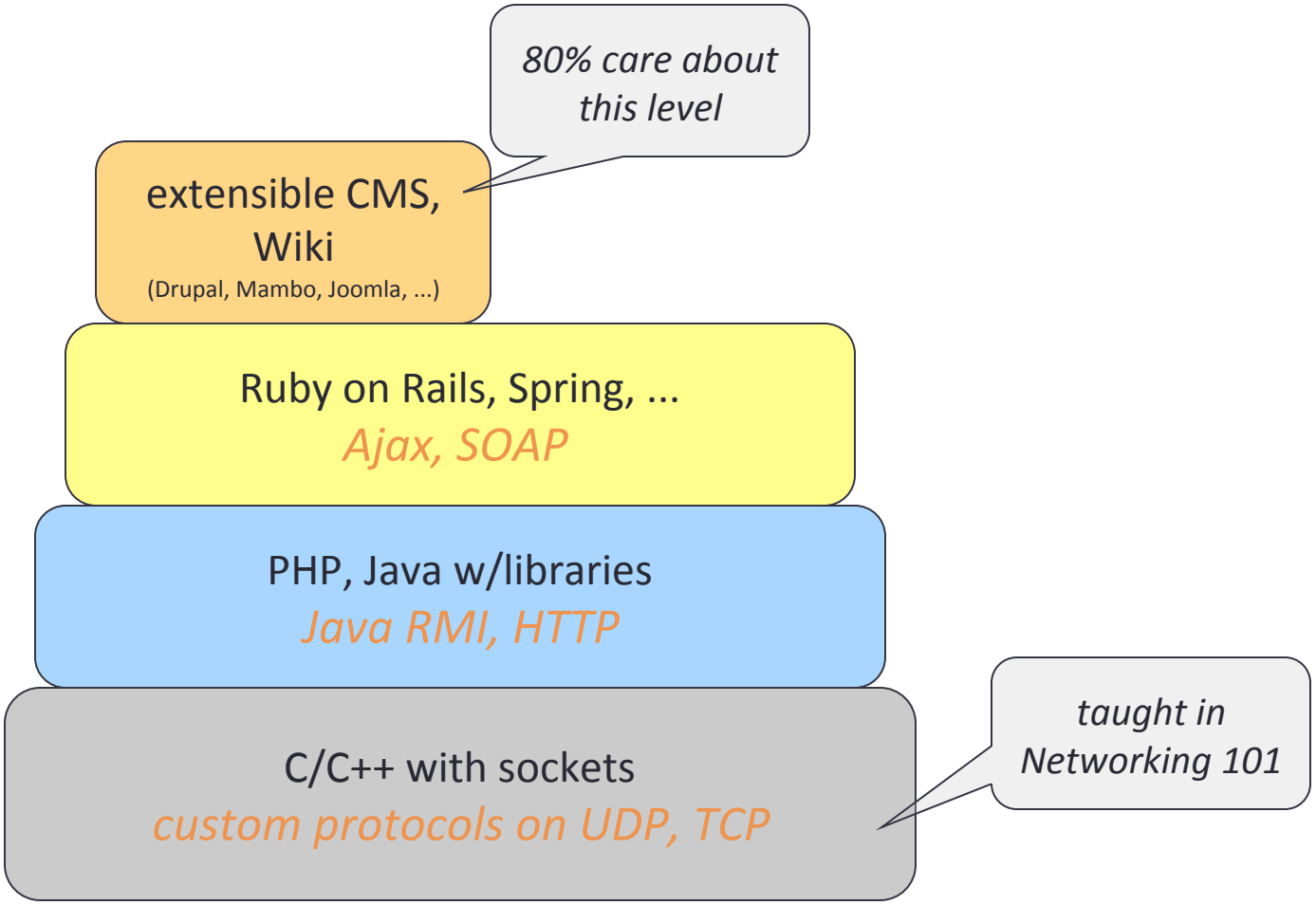

# Quality is no substitute for quantity

- Hypothesis: every new networking area breeds QoS research
- Outcome so far:
  - QoS helps only when the network is *modestly* overloaded
    - but then YouTube doesn't work, either
  - downed trees don't respect reserved resources
  - adds complexity and security vulnerabilities
  - simple priority (e.g., for latency-sensitive applications)
  - → avoid *buffer bloat*
  - shared networks are better → faster links → low queuing delays

# Protocols matter, but programmability matters more

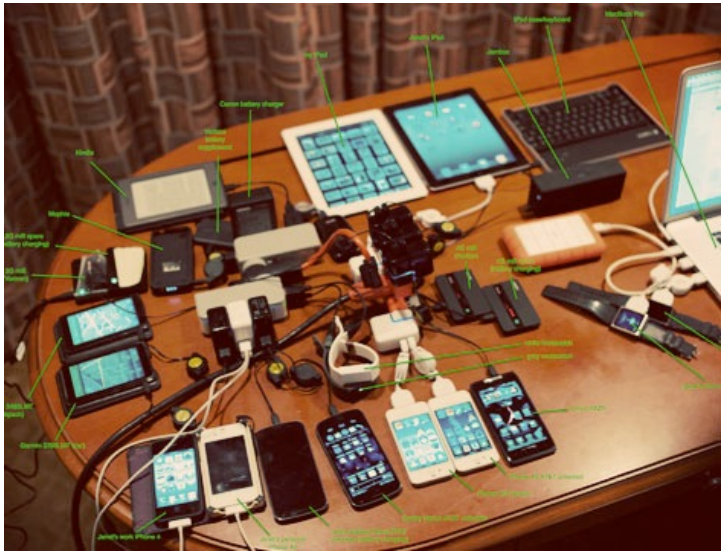
- Nobody wants to program raw protocols
- Most significant network application creation advances:
  - 1983: socket API → abstract data stream or datagram
  - 1998: Java network API → mostly names, HTTP, threads
  - 1998: PHP → network input as script variables
  - 2005: Ruby on Rails → simplify common patterns
- Many fine protocols and frameworks failed the programmer hate test
  - e.g., JAIN for VoIP, SOAP for RPC

# Building Internet applications

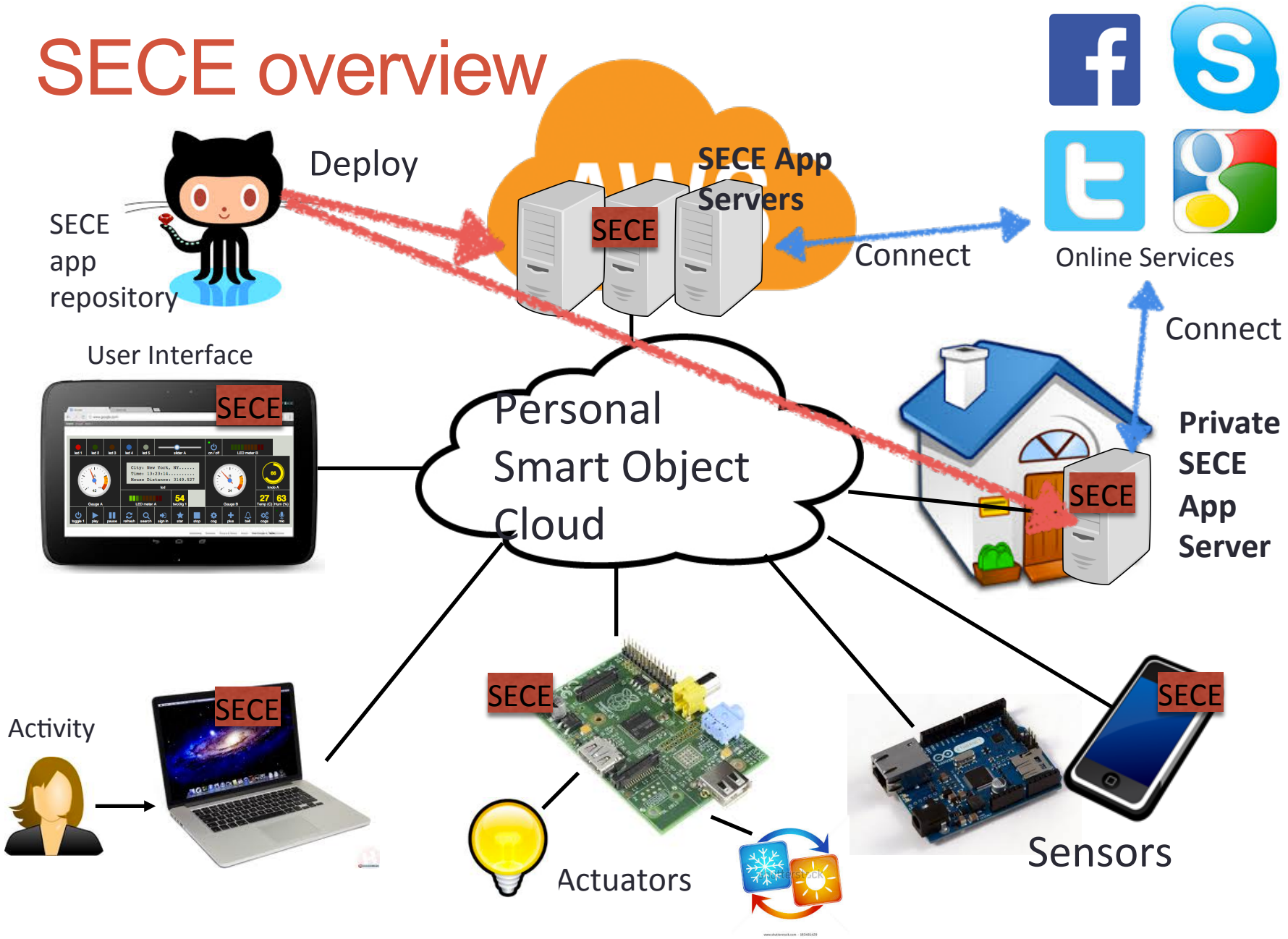


# The IoT integration problem

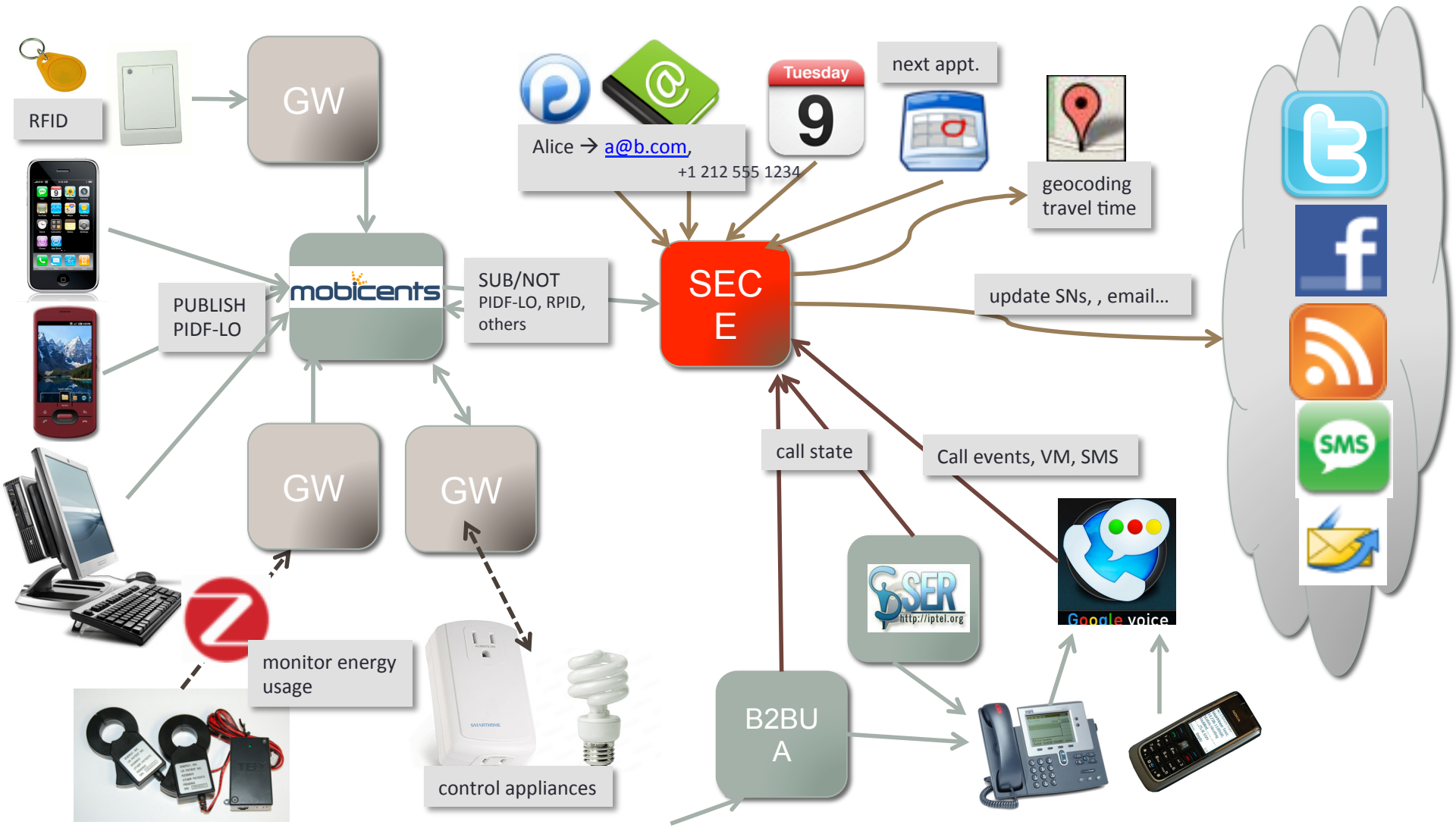
- Too many online services to use
- Too many devices to interact with
- Online and physical worlds disconnected
- M2M communication with a human in the middle
- → SECE (Sense Everything, Control Everything)

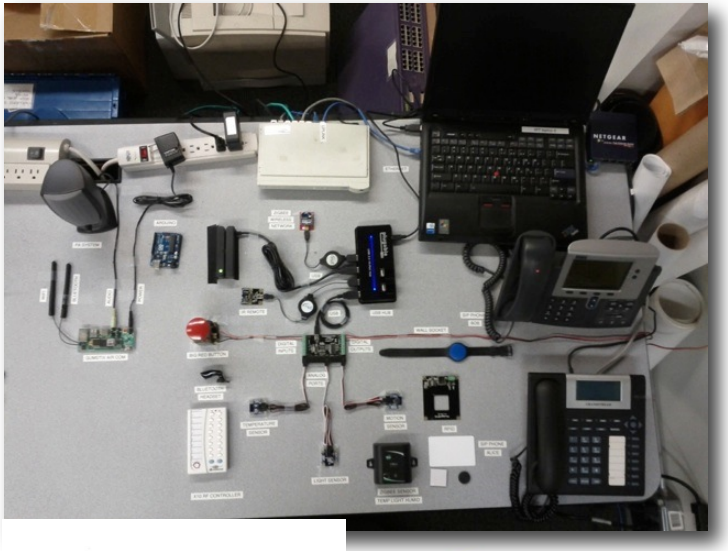
# SECE overview

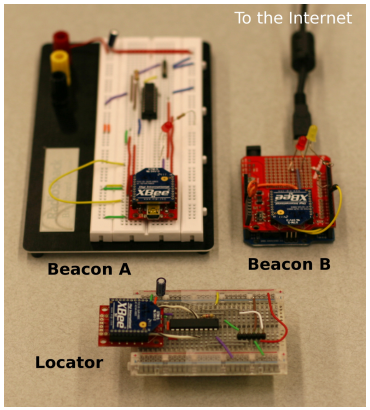


# SECE: The glue for Internet applications

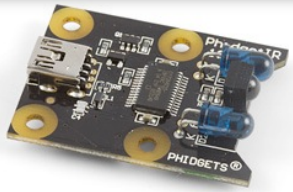


# SECE hardware

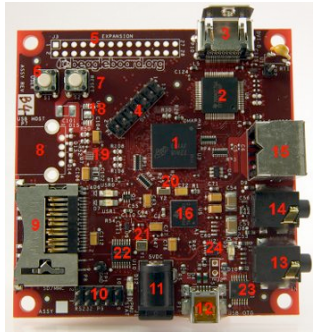




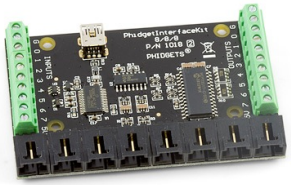

BeagleBoard

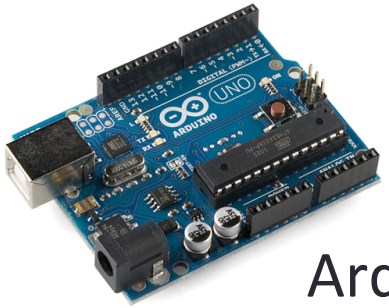




Phidgets

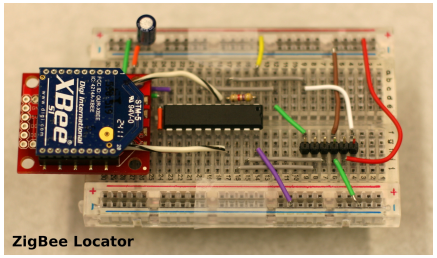


ZigBee

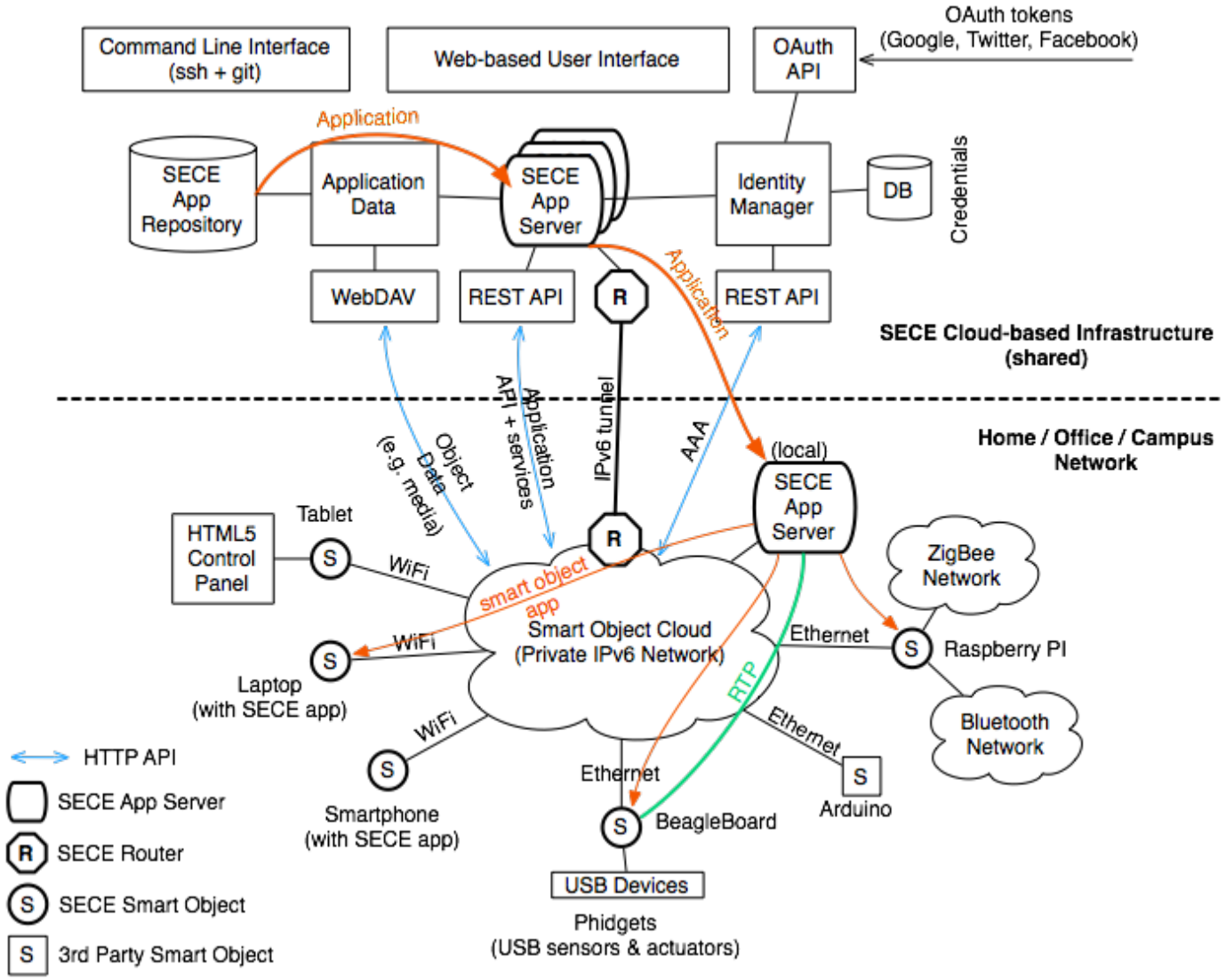





Arduino

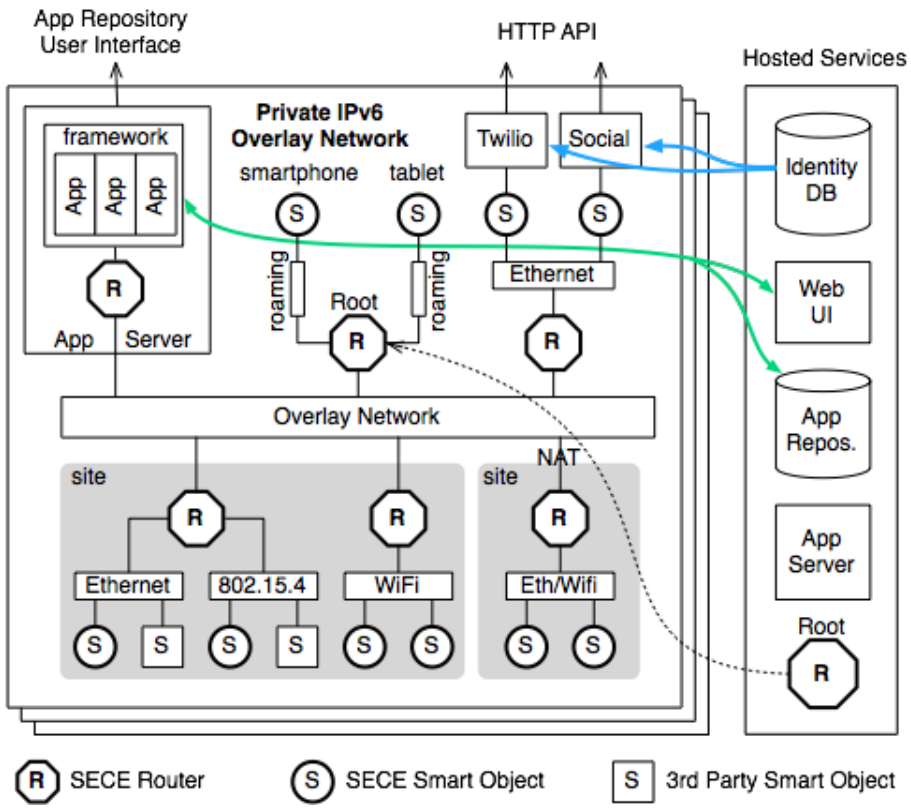



# SECE system architecture

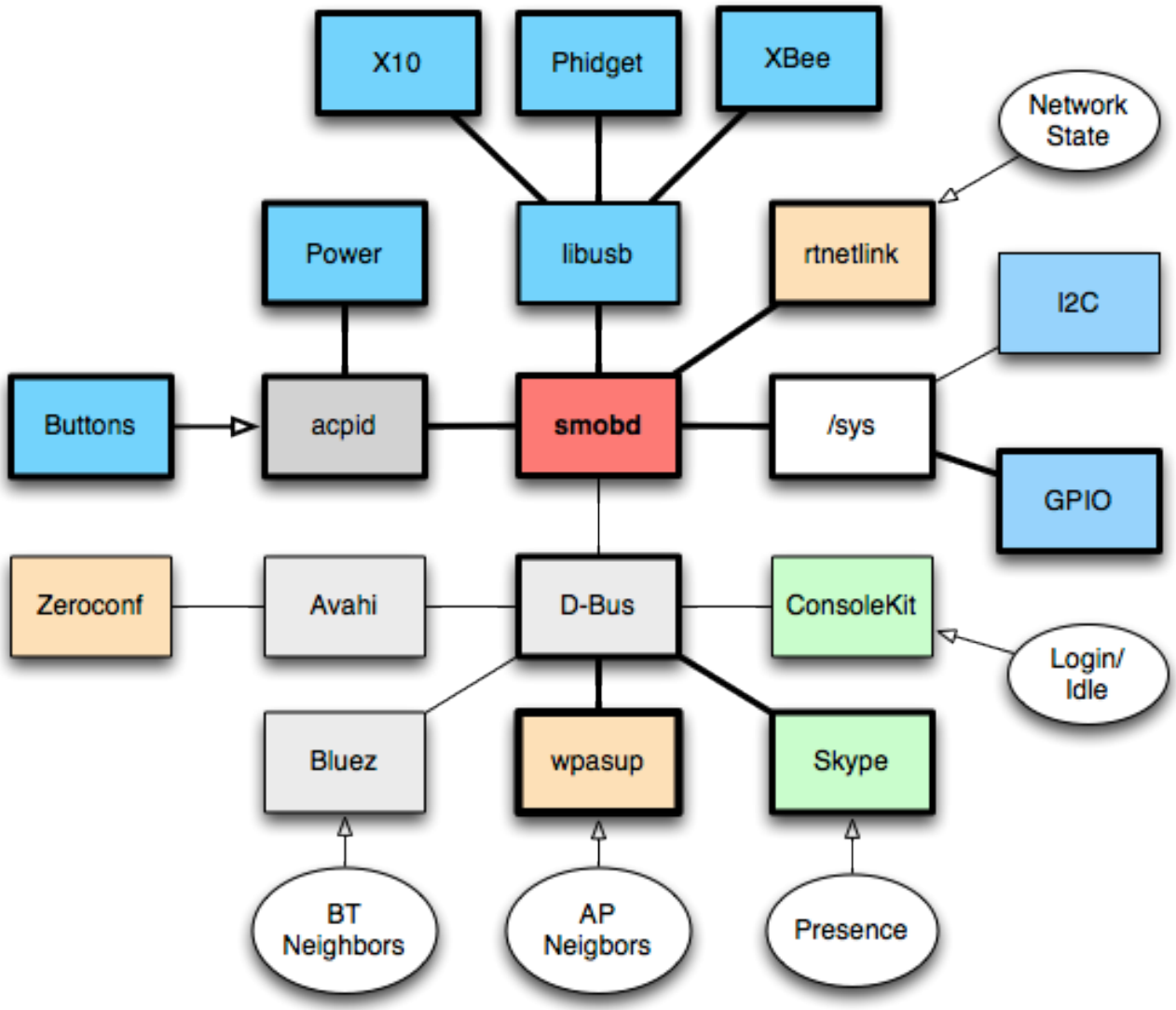


# SECE system architecture

- *Application server*
  - Python + coroutines
  - Custom object model
  - App management via **git**
- *Smart object daemon*
  - time-series data management
  - discovery + configuration
  - network APIs
  - platform drivers (Android, OSX, ZigBee, Phidgets
- *HTML5 user interface*
  - virtual devices
  - visual programming
- Overlay router
  - link setup and management
  - addressing + discovery
- *Semantic naming*
  - knowledge base + query language
- *Service gateways*
  - Facebook, Twilio, Google, Twitter

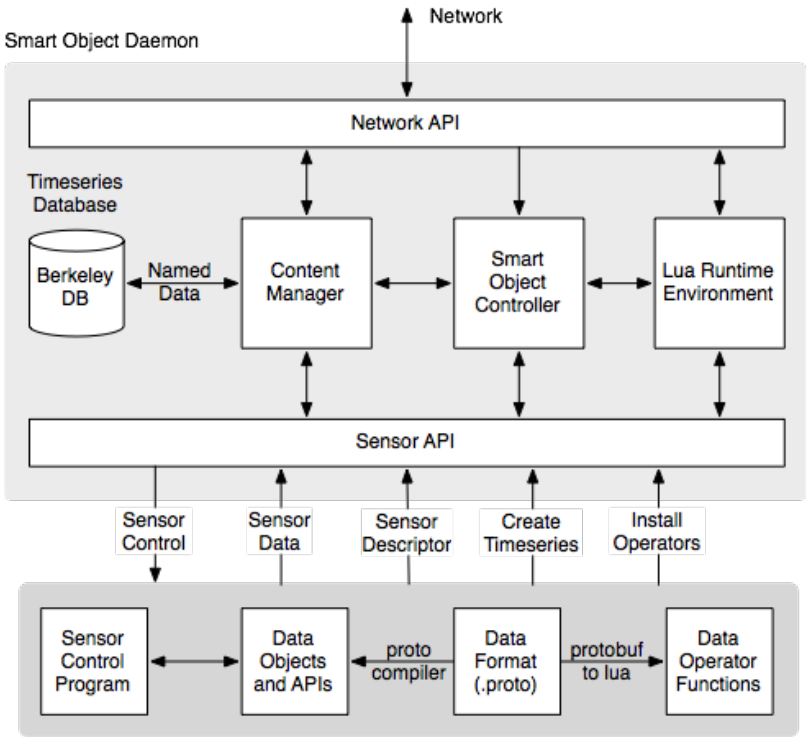


# **smobd**: Subsystems & Interfaces on Linux



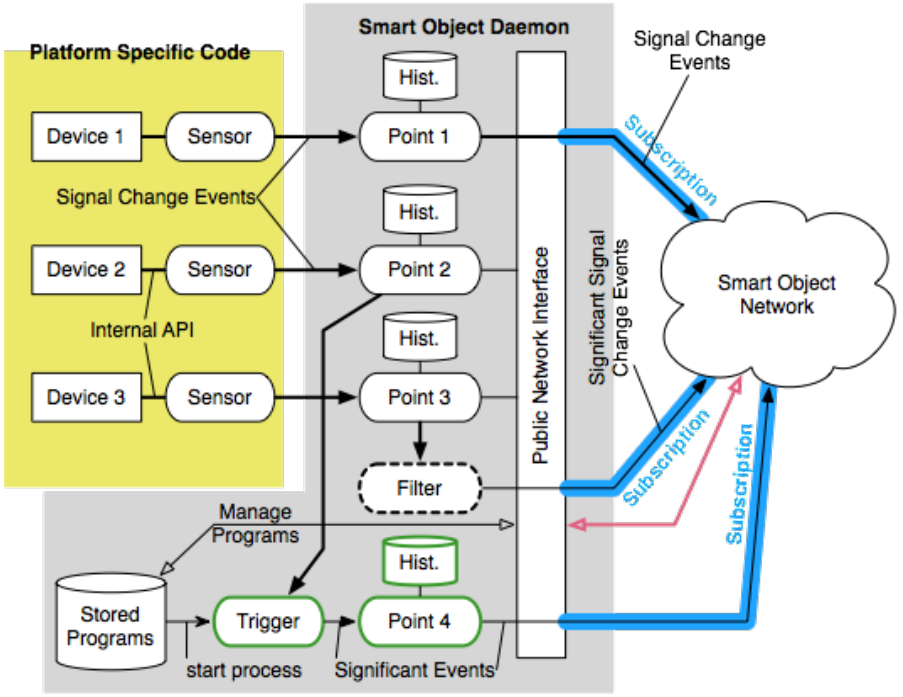
# Smart Object Model

- *Network interface*
  - connects the object to an IP-based overlay network
  - communication protocols and interfaces
  - node discovery, capability negotiation, configuration
- *Data storage*
  - time-series (history) of sensor data
  - collection of named structured documents
  - contents accessible over the network
- *Runtime environment*
  - data processing, programmatic filtering, feedback loops
  - high-level scripting language (Lua, JavaScript)
  - Smart Object Model (SOM) (~ HTML DOM)
- *Sensing and actuation points*
  - addressable components connected via a system bus
  - internal: I2C, SPI, UART (smartphones)
  - external: field bus, BACnet, X-10, XBee, Z-Wave



# Smart object runtime environment

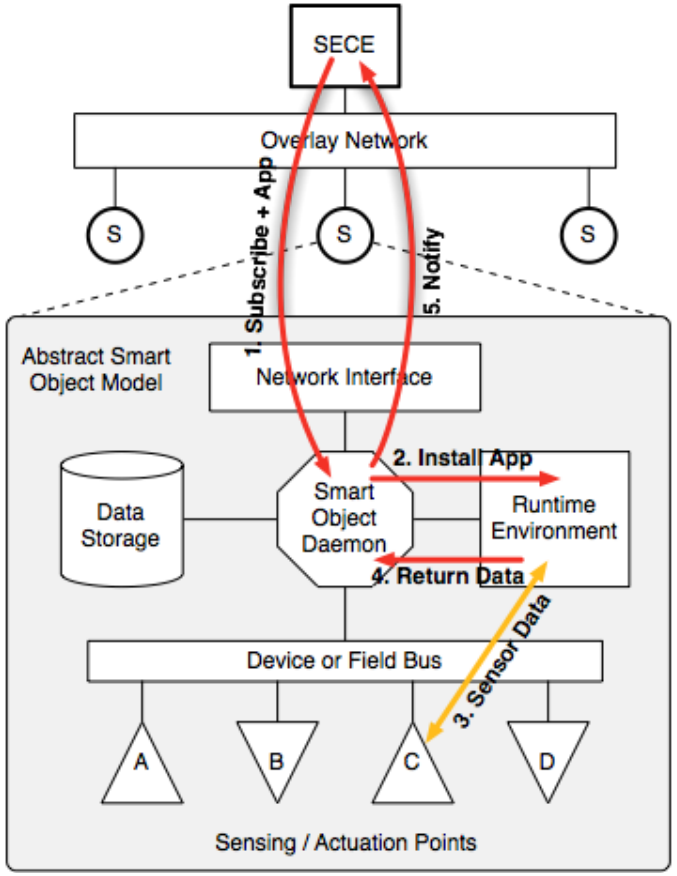
- A built-in framework for **end-device programmability**
- Programs installed over-the-network by a cloud application
- Application domains: signal processing, control loops, distributed control, programmatic notification filtering
- Application model: Lightweight cooperative processes in a sandbox
- Network Interface:
  - Manage program life cycle (install, start, stop, uninstall)
  - Subscribe-notify interface to program output
- Internal APIs:
  - **Smart Object Model (SOM)**, inspired by HTML DOM access to sensors and actuators
  - Setup RTP session
  - Push / pull data transfer to / from other smart objects
- Prototype implementation:
  - Embedded devices: Lua coroutines
  - Android: JavaScript sandbox



# Programmatic notification filters

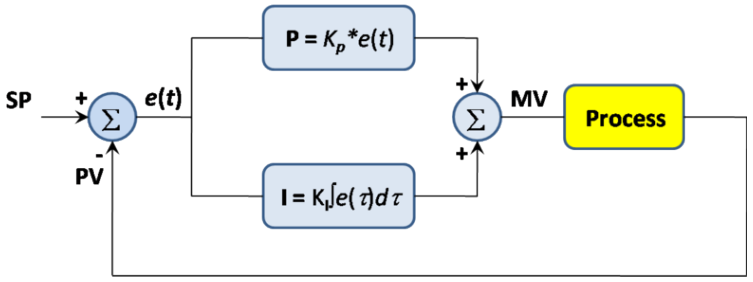
Goal: "Notify when edge(ewma(sensorC, coeff) > threshold)"

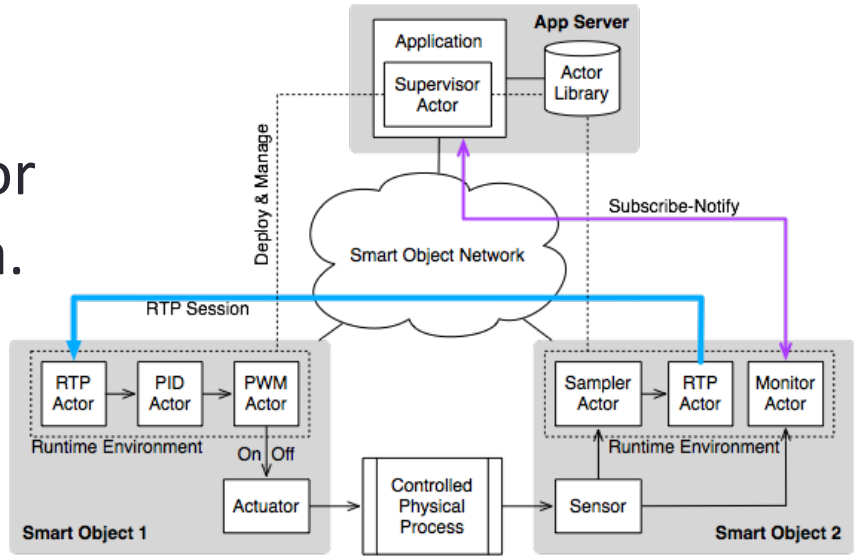
1. SECE app subscribes to sensor data
2. Smart object installs included program
3. Program setups callbacks for sensor updates
4. Program generates notifications on significant events only (received by SECE app)
5. Program is automatically uninstalled when subscription terminates



# PLC: Internet style

1. PID controller implemented on a programmable smart object
   - JavaScript / Lua application installed by SECE
2. SECE requests persistent app installation on smart object
3. Smart object returns app URI
4. App continuously adjusts actuator based on history and sensor data.
5. The app keeps running until explicitly uninstalled

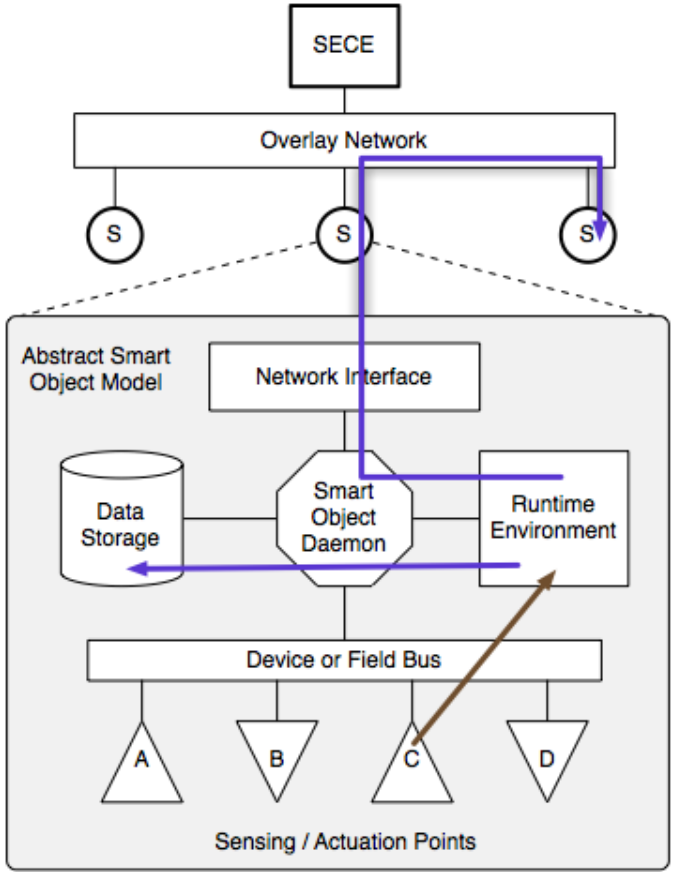


# Direct Object-to-object communication

Goal: "object1.actuatorB = avg(object2.sensorC)"

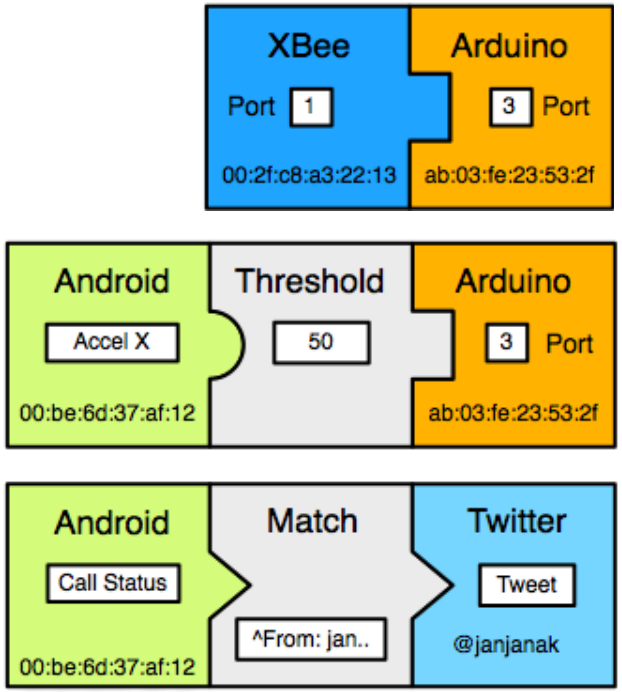
1. SECE install a JS/Lua app into a smart object
2. The app requests access to the network
3. The app initiates a pull session, pushing sensor data to a remote smart object
4. Runs until explicitly uninstalled
5. Once installed, the system requires no central entity

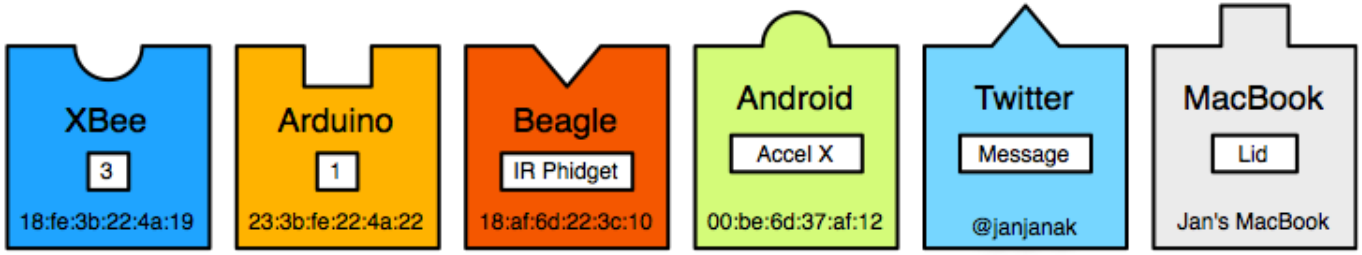


# SECE UI: Visual programming

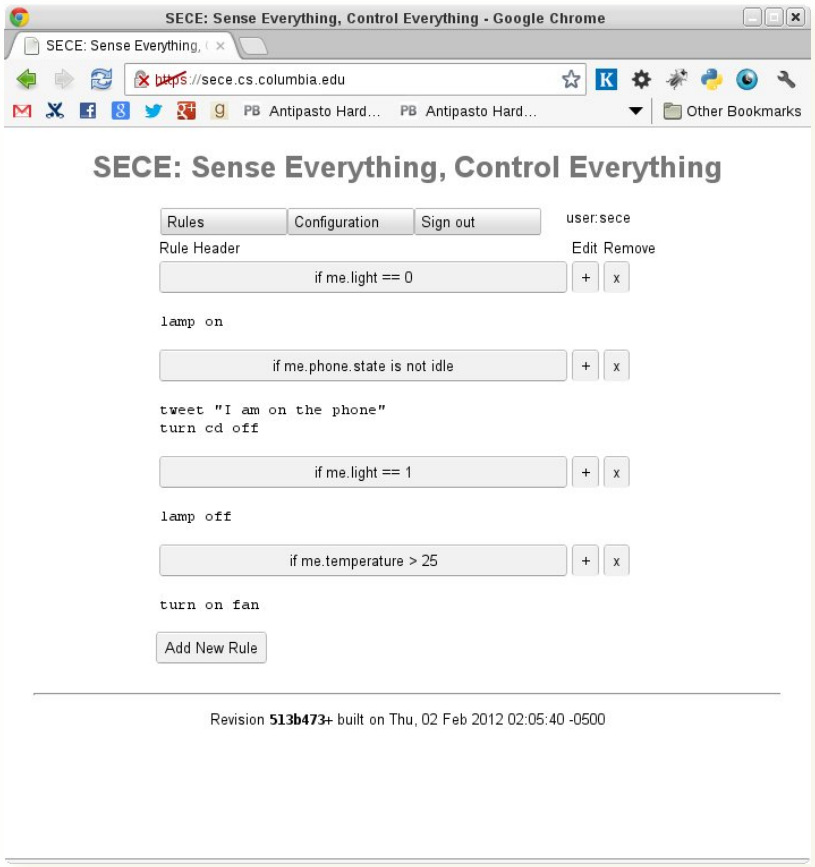
in progress

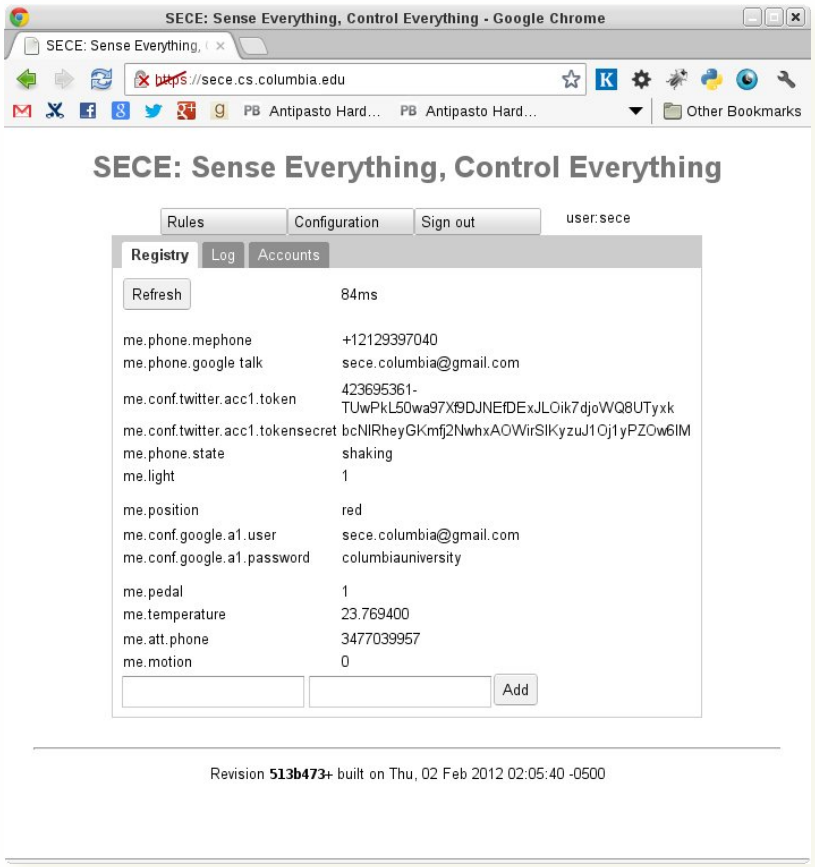
- User-friendly UI for programming smart objects
- Inspired by MIT Scratch
- Blocks represent devices or programs on an application server
- Different latch-socket shapes represent different types of data
- Drag&drop HTML UI
- Suitable for simple add-hoc applications



# SECE UI: web


SECE: Sense Everything, Control Everything - Google Chrome
https://sece.cs.columbia.edu
Other Bookmarks
SECE: Sense Everything, Control Everything
Rules
Configuration
Sign out
user:sece
Rule Header
Edit Remove
if me.light == 0
lamp on
if me.phone.state is not idle
tweet "I am on the phone"
turn cd off
if me.light == 1
lamp off
if me.temperature > 25
turn on fan
Add New Rule
Revision 513b473+ built on Thu, 02 Feb 2012 02:05:40 -0500


SECE: Sense Everything, Control Everything - Google Chrome
https://sece.cs.columbia.edu
Other Bookmarks
SECE: Sense Everything, Control Everything
Rules
Configuration
Sign out
user:sece
Registry
Log
Accounts
Refresh
84ms
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me.light 1
me.position red
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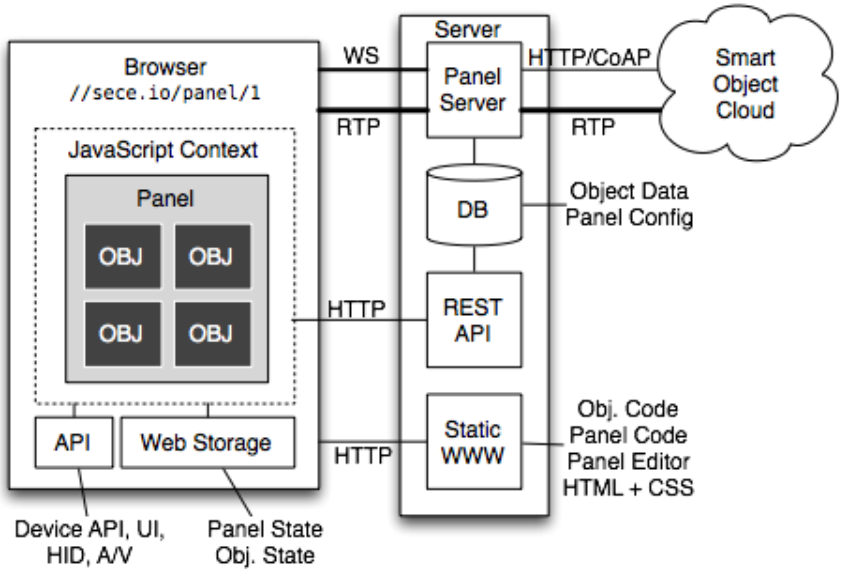
me.conf.google.a1.password columbiauniversity
me.pedal 1
me.temperature 23.769400
me.att.phone 3477039957
me.motion 0
Add
Revision 513b473+ built on Thu, 02 Feb 2012 02:05:40 -0500

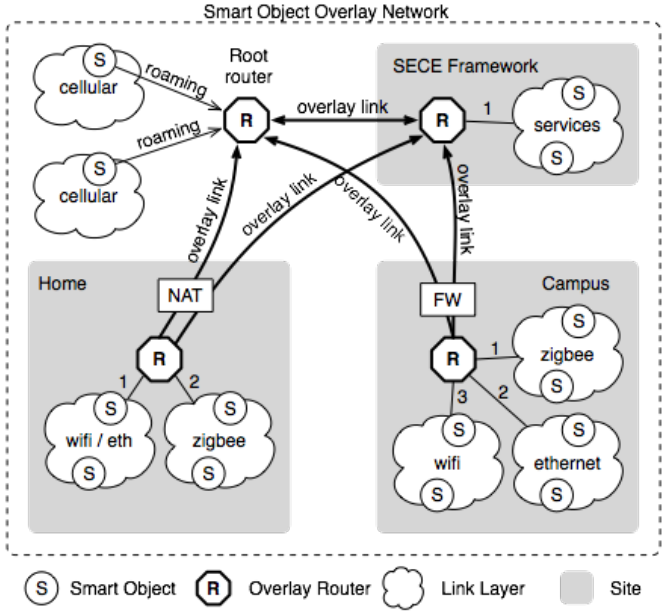
# SECE UI: Programmable control panel

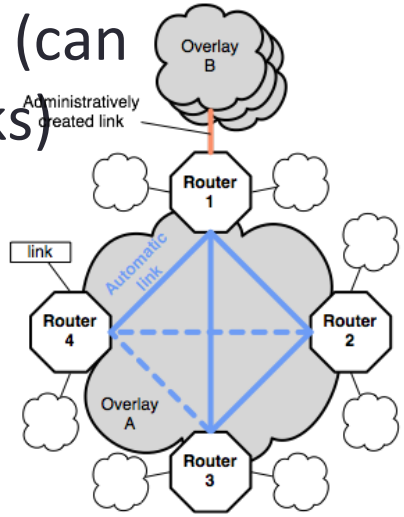
- Virtual JavaScript smart objects
- Emulate physical devices in browser (buttons, LEDs, switches, gauges)
- Create via drag&drop
- Customizable IoT control panels
- Programmable in JavaScript

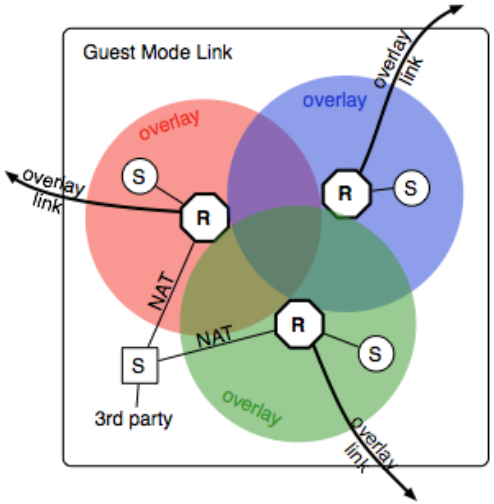



# SECE smart object cloud

- IPv6 overlay network architecture
- Automatic tunnel links setup by router nodes
- Spans multiple networks and sites of a SECE user (home office)
- Supports shared local links (can coexist with other networks)
- Similar to an IPv6 VPN

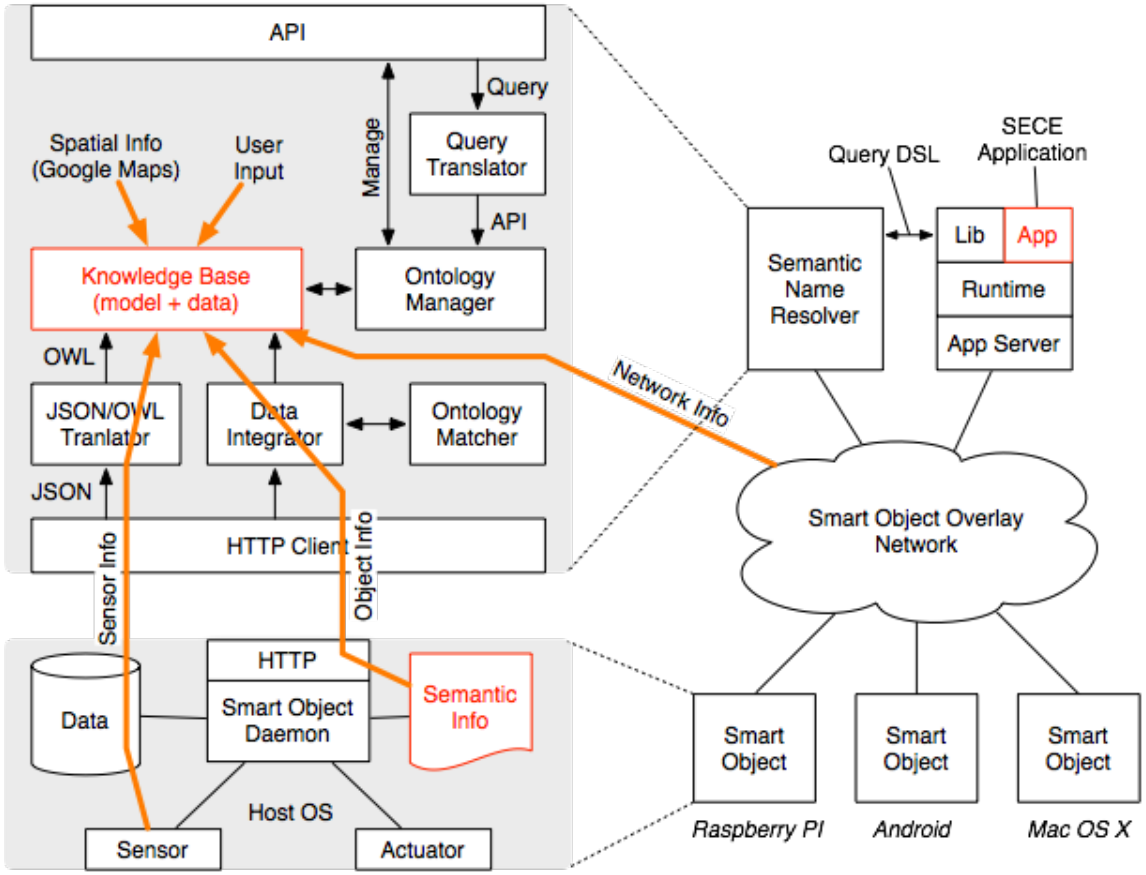


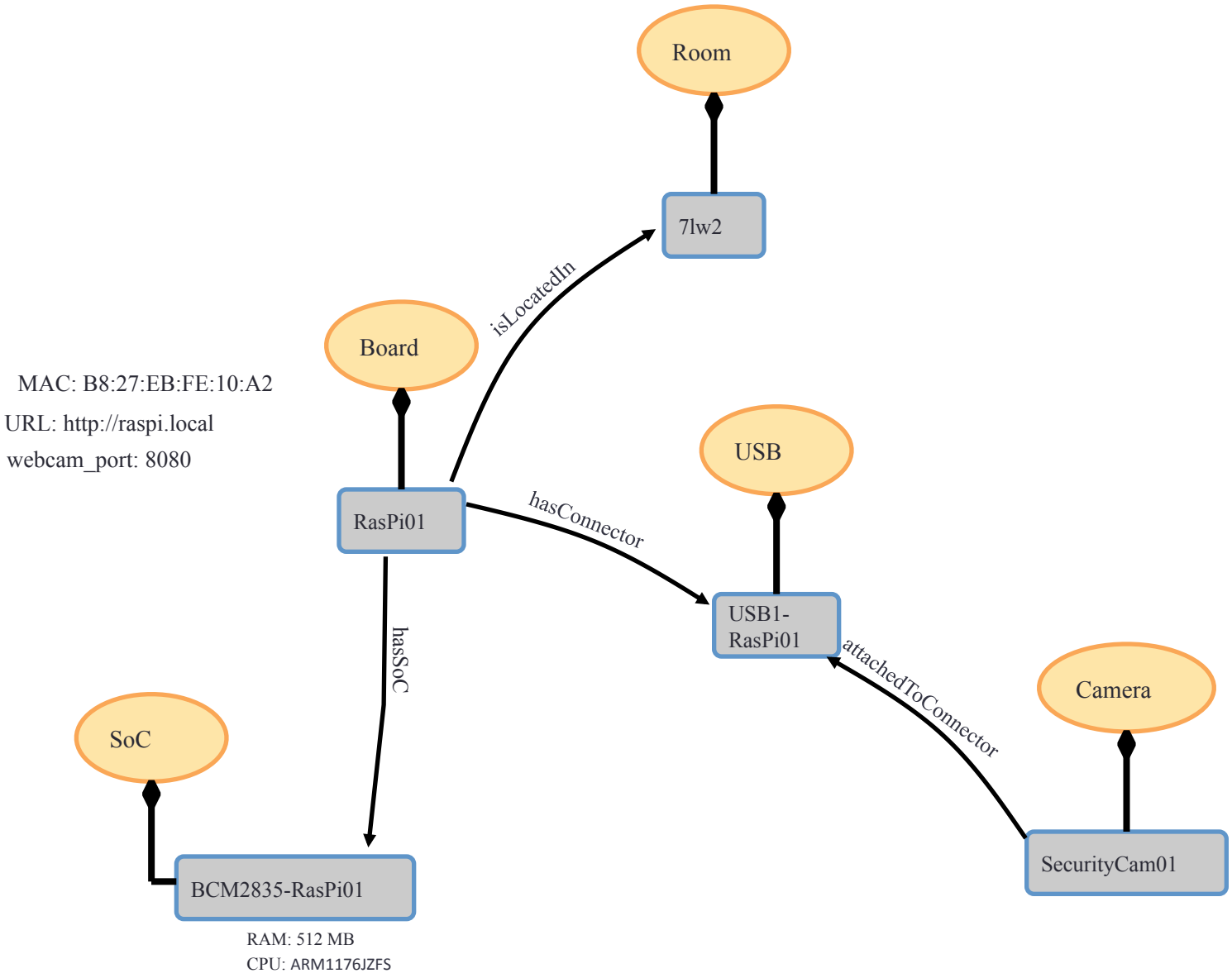



# Semantic naming

- Knowledge base
  - abstract representations of objects
    - sensors, actuators, appliances
  - through human readable query language
- Objects can be referenced
  - through unique IDs
  - properties or context (e.g., location, point of network attachment)
- Unlike SQL, semantic name resolver can infer new information
  - queries return results incorporating the inferred information

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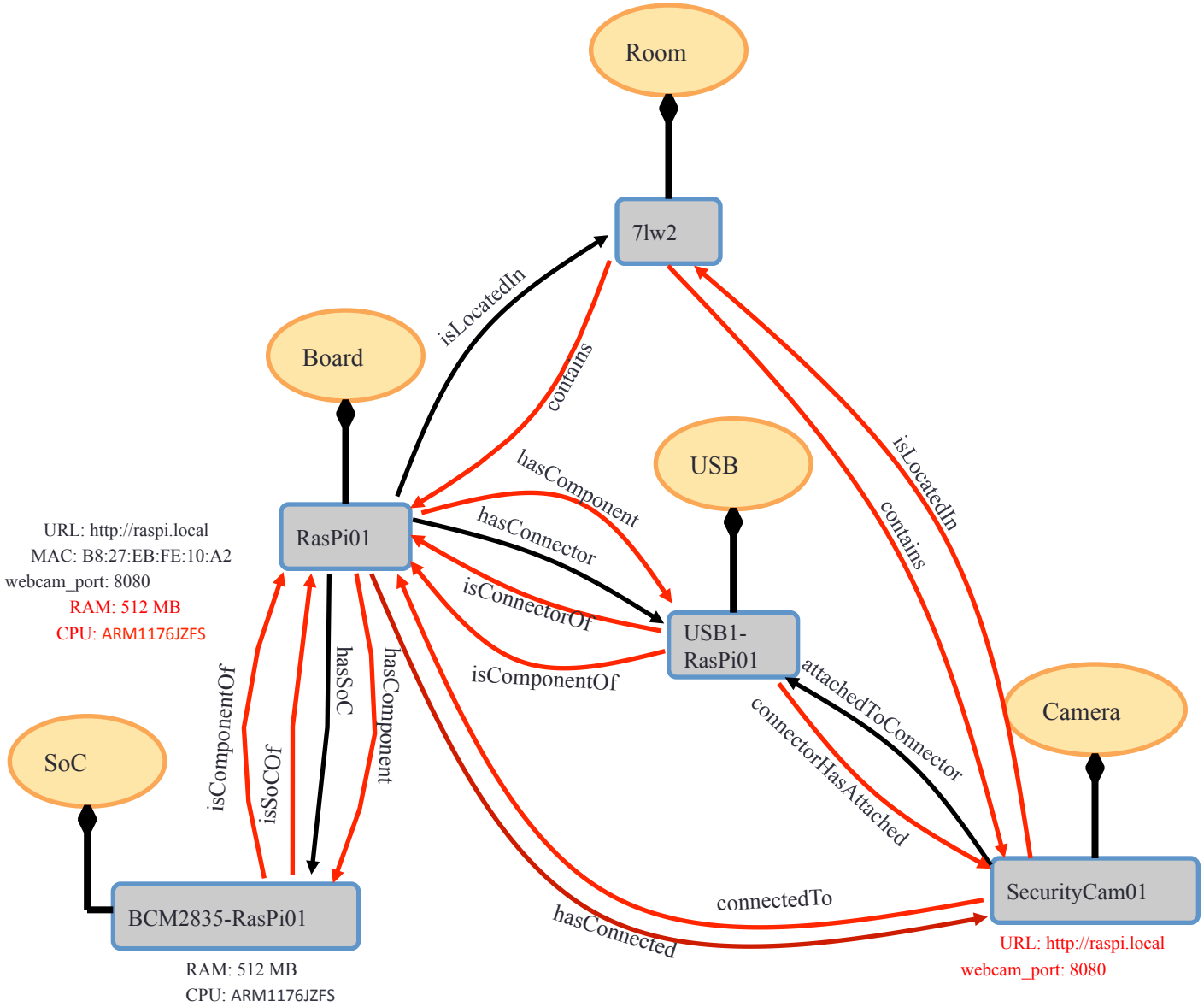
7lw2
isLocatedIn
Board
MAC: B8:27:EB:FE:10:A2
URL: http://raspi.local
webcam_port: 8080
USB
RasPi01
hasConnector
USB1-
RasPi01
attachedToConnector
Camera
hasSoC
SoC
SecurityCam01
BCM2835-RasPi01
RAM: 512 MB
CPU: ARM1176JZFS


Room
7lw2
Board
isLocatedIn
contains
hasComponent
hasConnector
isConnectorOf
isComponentOf
USB
isLocatedIn
contains
RasPi01
URL: http://raspi.local
MAC: B8:27:EB:FE:10:A2
webcam_port: 8080
RAM: 512 MB
CPU: ARM1176JZFS
USB1-
RasPi01
attachedToConnector
connectorHasAttached
Camera
SoC
isComponentOf
isSoCOf
hasSoC
hasComponent
BCM2835-RasPi01
RAM: 512 MB
CPU: ARM1176JZFS
connectedTo
hasConnected
SecurityCam01
URL: http://raspi.local
webcam_port: 8080

# Conclusion

- IoT of things as natural progression
  - but limited mainstream in-home applications so far
  - boring commercial applications!
- Network is (relatively) easy, security and software are much harder
- Reaching beyond connectivity and software islands
  - plug-and-program