Beetle:

Operating System Support for the Internet of Things

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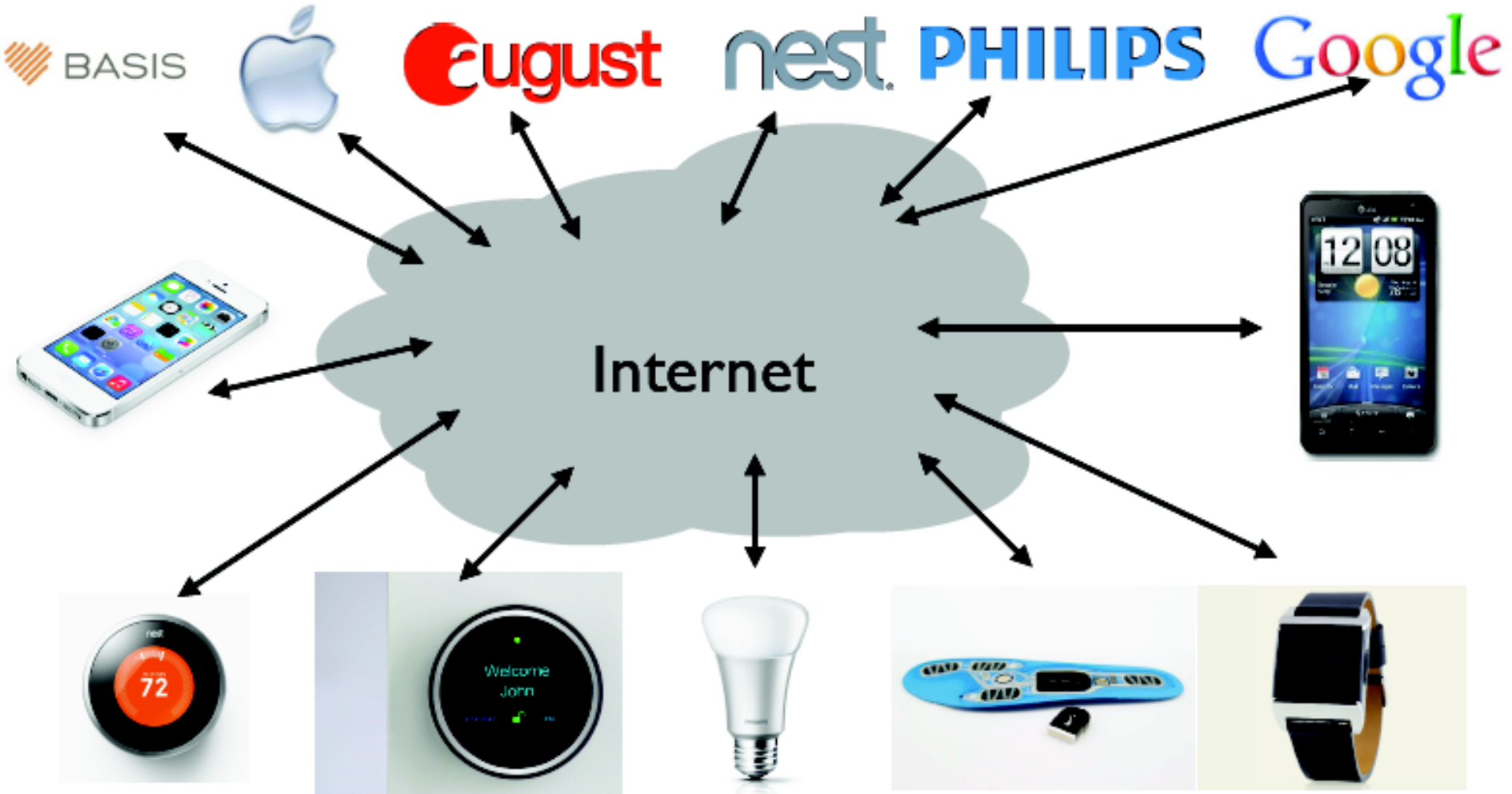
The Internet of Things *Ideal Future*



The Internet of Things *Today*

It's Not An Internet

- Connectivity is poor and constrained
  - Edge devices cannot communicate with each other
  - Edge devices can only communicate with one application
- Vertical integration of peripherals, gateways, and cloud
- Simple, desirable use cases are impossible
  - Monitor battery life of all my devices

Why? Some non-Fundamental Reasons

- Vendors want to “own the user experience”
- Standardization takes time
  - WWW, Z-Wave positive historical examples
  - Messaging probably a negative example

What are the *Fundamental* Reasons?

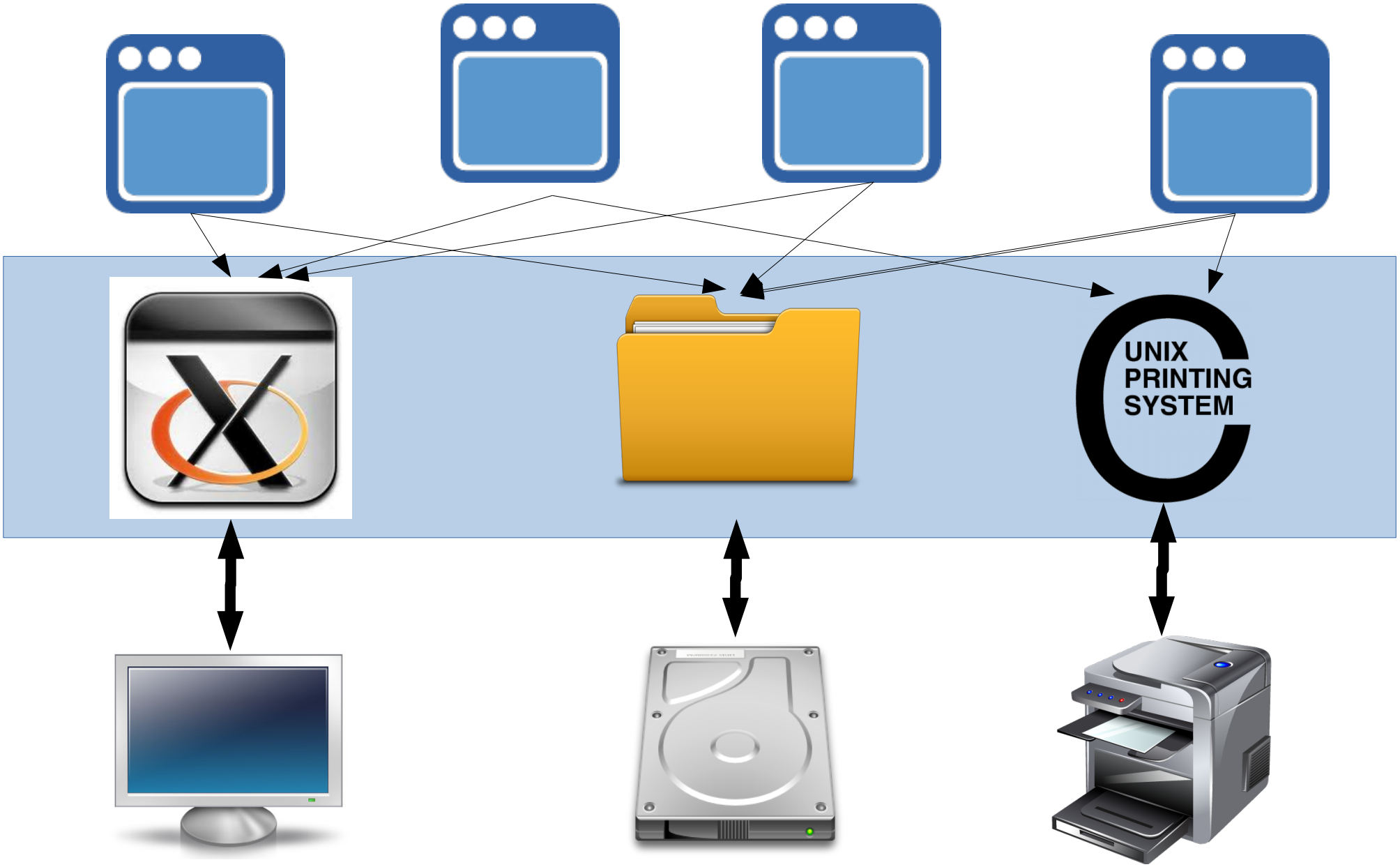

It's the gateway stupid!

“It's the [Gateway] Stupid!”

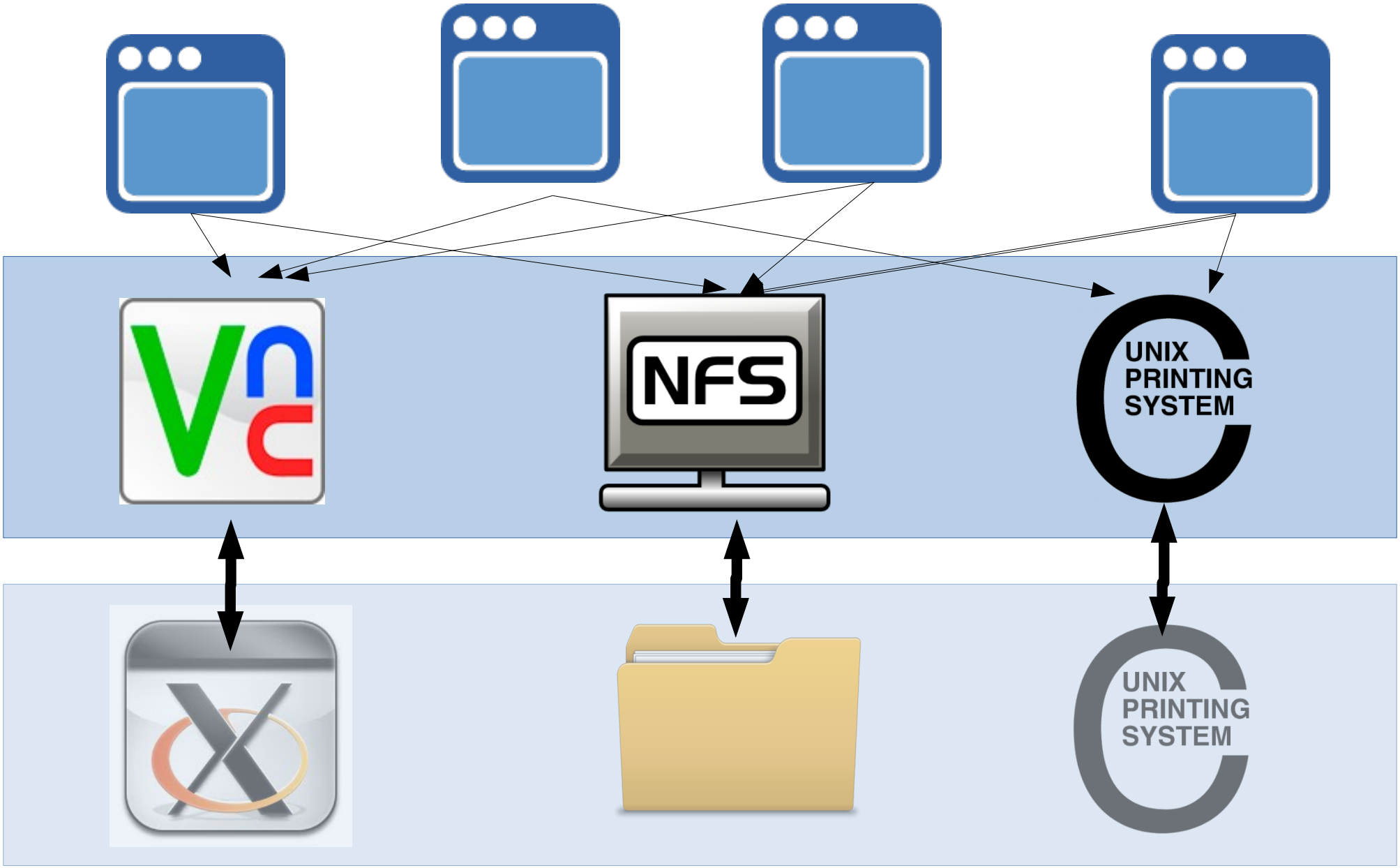
- IoT devices are feable and weak
  - Low power: achieved by being mostly off
  - Simple network protocols: Bluetooth Low Energy et al
- Naming is harder
  - “Honey, what's the toaster's IP address, again?”

It's up to *gateways* to provide:
connectivity, nameing, security...

Operating Systems Today



Operating Systems Today



Operating Systems Today

- Small number of tailored device interfaces
  - Printer
  - File system
  - X Windows
  - HID
  - TCP/IP stack


Linux is not IoT Scale!

Operating Systems Today

- The IoT will have 1,000,000…,000 device types!
- We can't hope to support each type in every OS separately
- For now, instead of safe, shared interfaces we get exclusive streams
  - L2CAP sockets for BLE, serial devices for ZigBee, etc
  - 6lowpan is an exception (sort of)

We need a single OS interface for *all* devices!

Outline

- Looooooong Intro
- Bluetooth LE architecture
- Beetle
  - Network architecture
  - Mechanisms:
    - HAT
    - Virtual devices
    - Service export control

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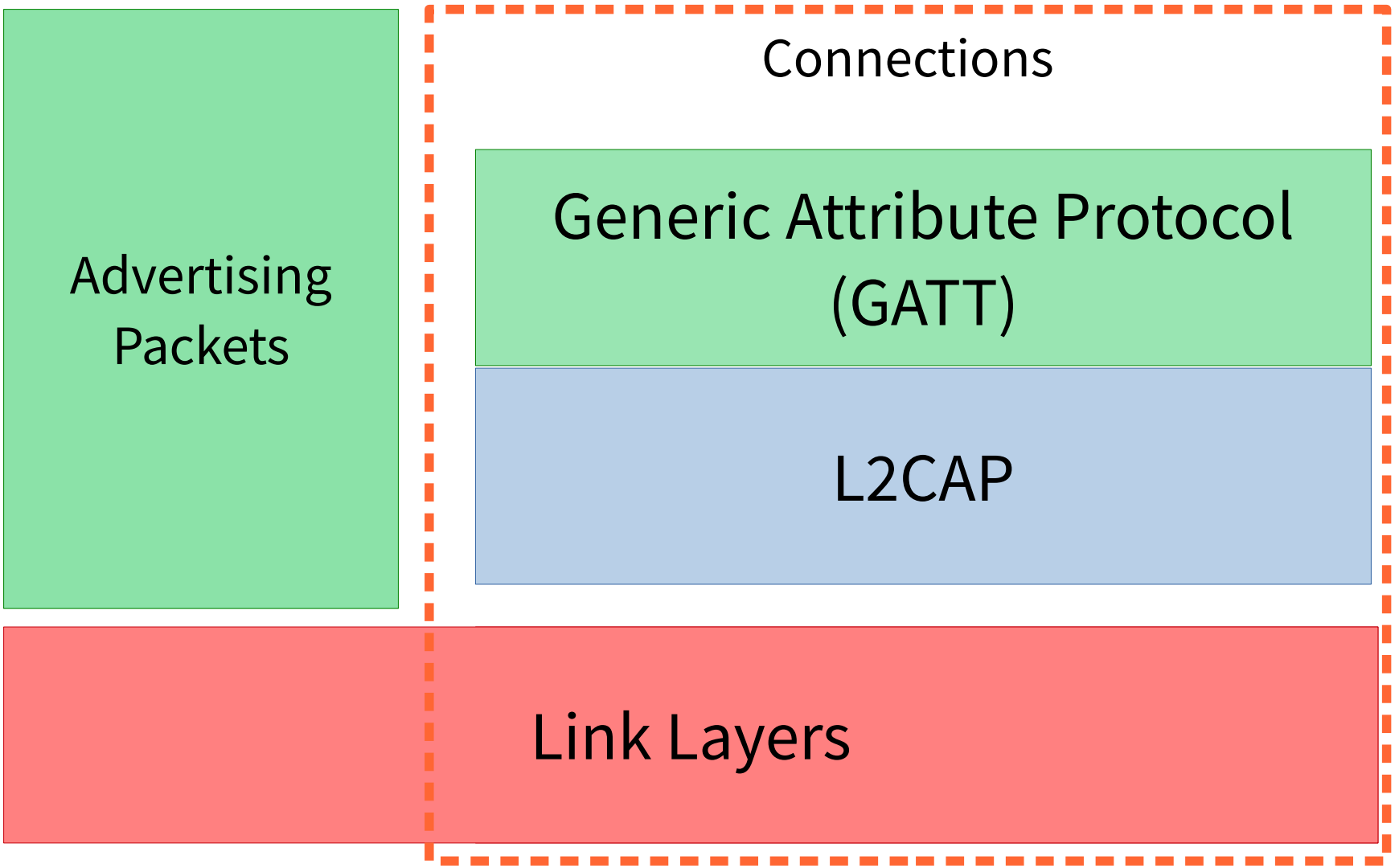
Bluetooth Low Energy

- Single-hop protocol
- Physical, Link and Application layers
- Optimized for small exchanges and low energy:
  - ~24 byte exchanges; infrequently
  - µA power consumtpion
  - Can run for years on coin battery

Bluetooth Low Energy

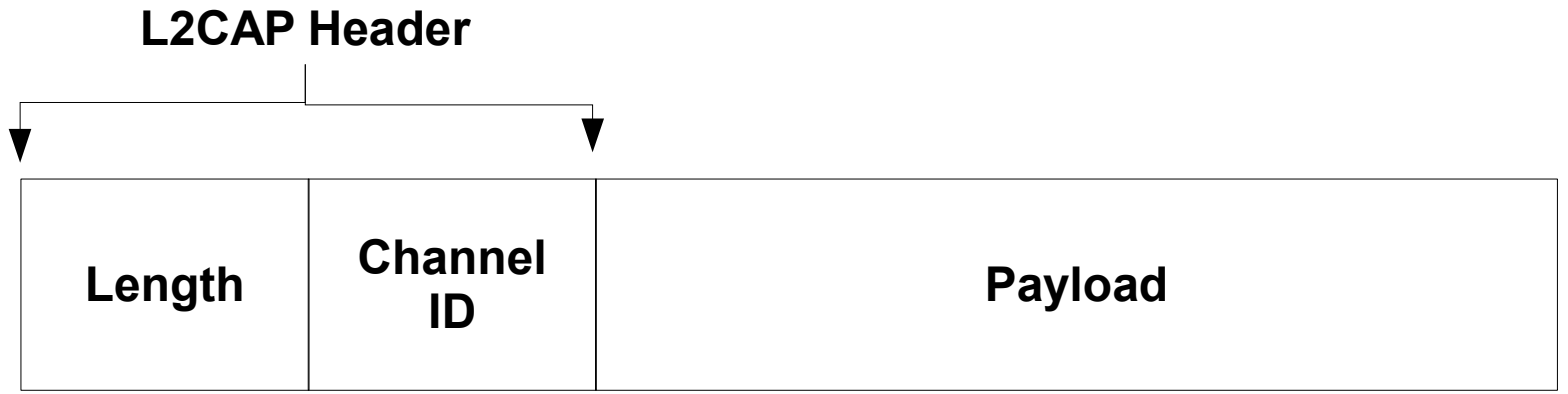


Link Layer

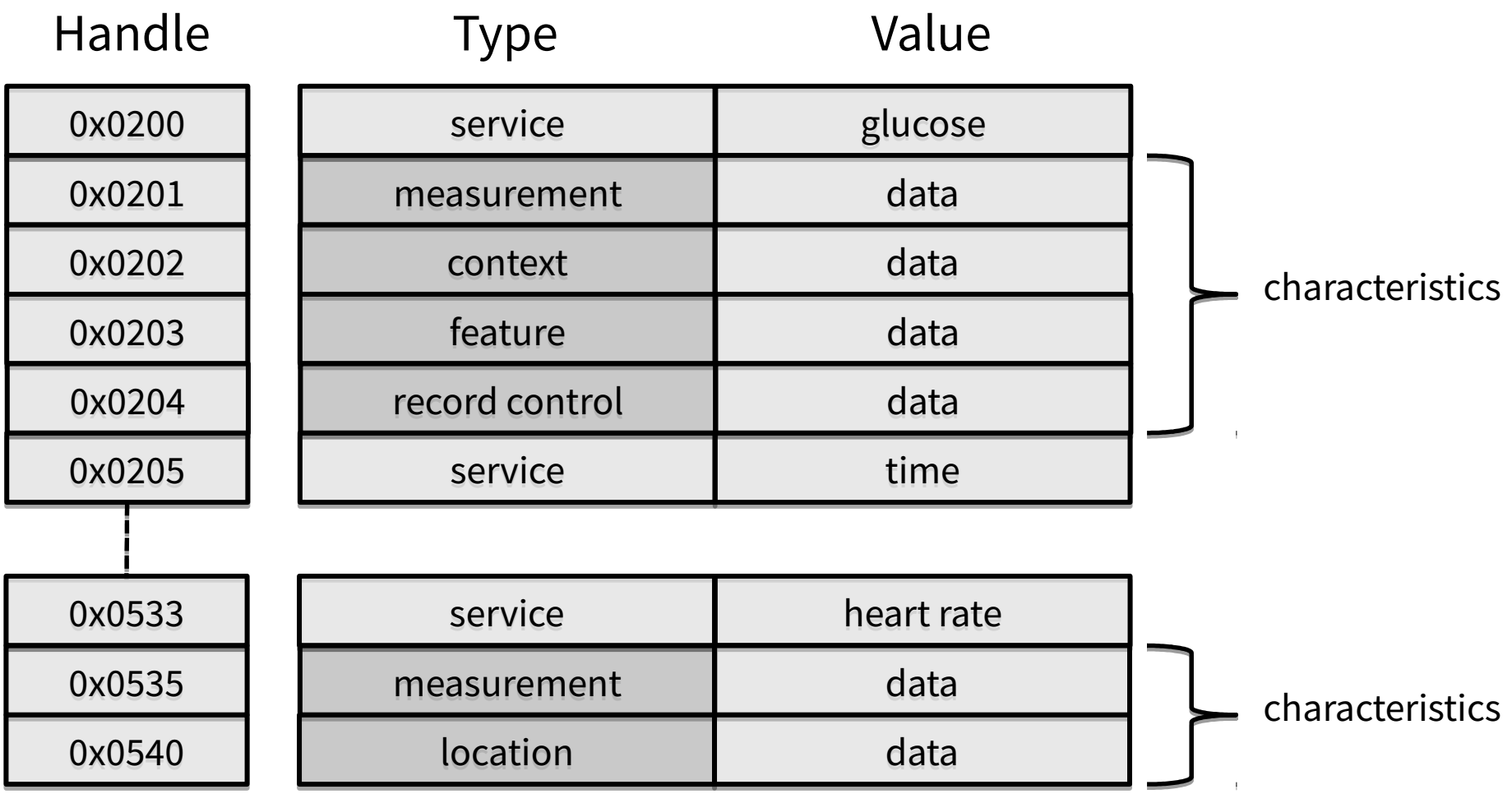
- “Piconet” topology
- Two roles:
  - Peripheral (fitness band, watch, dead-bolt, etc)
  - Central (smart phone, laptop, gateway, etc)
- Centrals manage connections with multiple peripherals
- Peripherals can connect to a *single* central only

L2CAP Channels

- Logical channels over single link
- Reliable
- Some channels reserved (e.g. GATT, signaling)



Generic Attribute Protocol (GATT)



GATT

- Two roles:
  - Server has the attributes
  - Peripherals and Centrals can be both clients and servers simultaneously
- Key/Type/Value store:
  - Read/Write
  - Notify/Indicate
  - Find by type

Opcode	**Handle**	**Opcode parameters (type, value ...)**

GATT: Simple Example

Server

Notify 0x7: 152bpm

Notify every 1 second

Notify 0x7: 154bpm

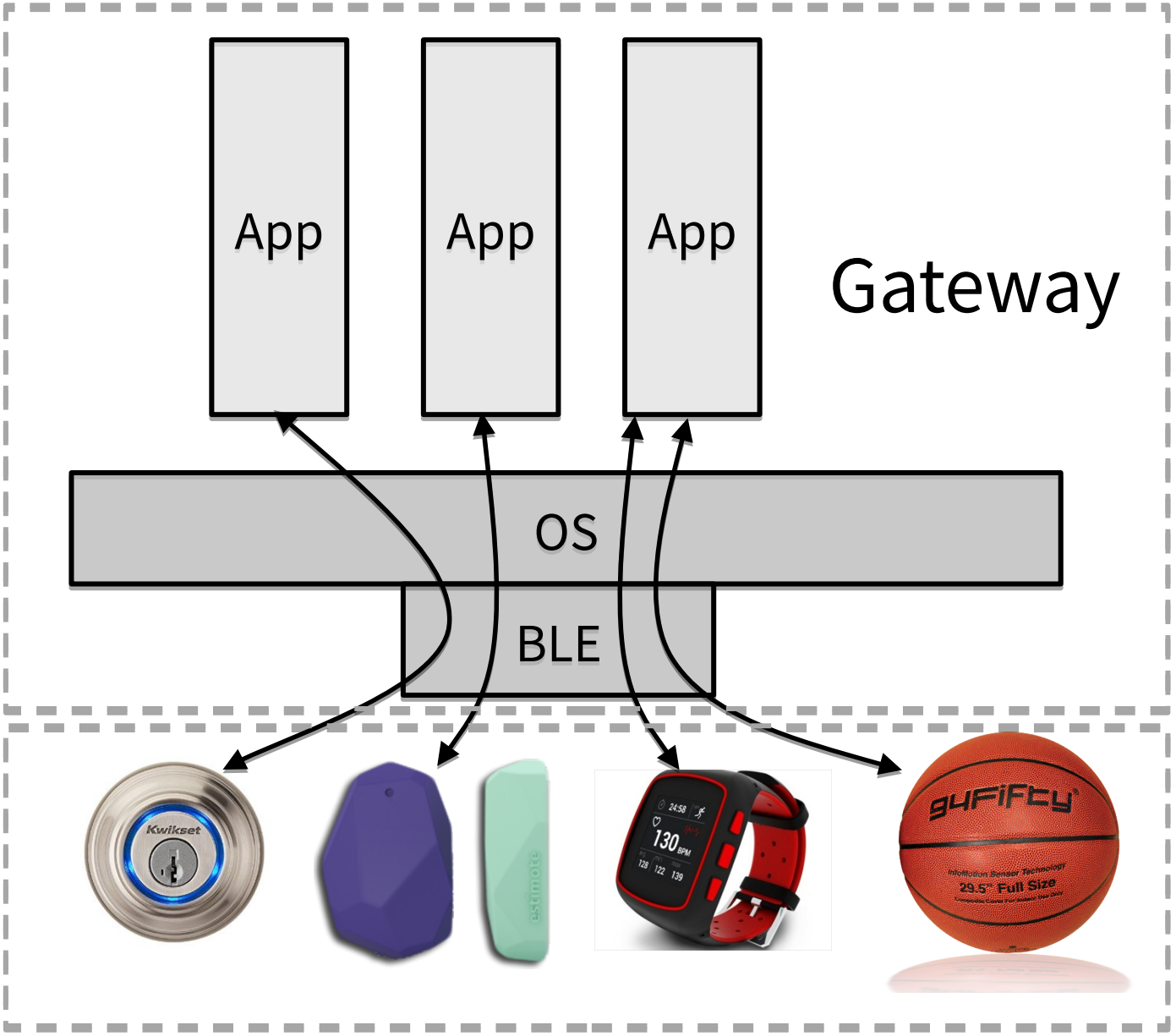
Notify 0x7: 152bpm

Notify 0x7: 157bpm

Client

A peripheral can only maintain one open connection!*

One-to-One Communication



The Internet of Things *Today*

Today: Gateway Interposes on Data

- Each peripheral connects to a single app on the gateway
  - Can only communicate directly with that app
- App consumes GATT data. Mediates only supported interactions:
  - Issue GATT commands to other connected peripherals
  - Proprietary protocol to servers (e.g. over app-specific HTTP)
  - (Limited) Intent-based interface to other apps
- The app doesn't support an interaction you want?
  - Tough luck...

GATT: Three Important Properties

- Self-Describing:
  - Standardized service/characteristic types
  - Incorporates service discovery
- Transactional
  - Only onle outstanding command per connections in each direction
- High level
  - Application-level transactions == protocol transactions

Outline

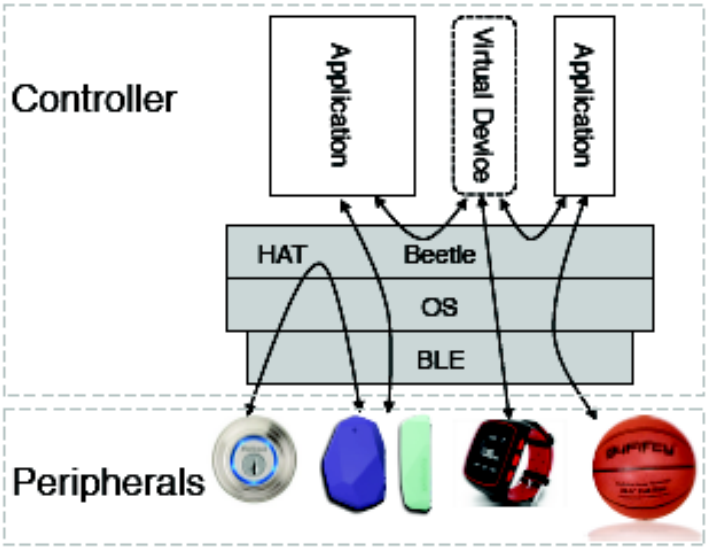
- Looooooong Intro
- Bluetooth LE architecture
- Beetle
  - Network architecture
  - Mechanisms:
    - HAT
    - Virtual devices
    - Service export control

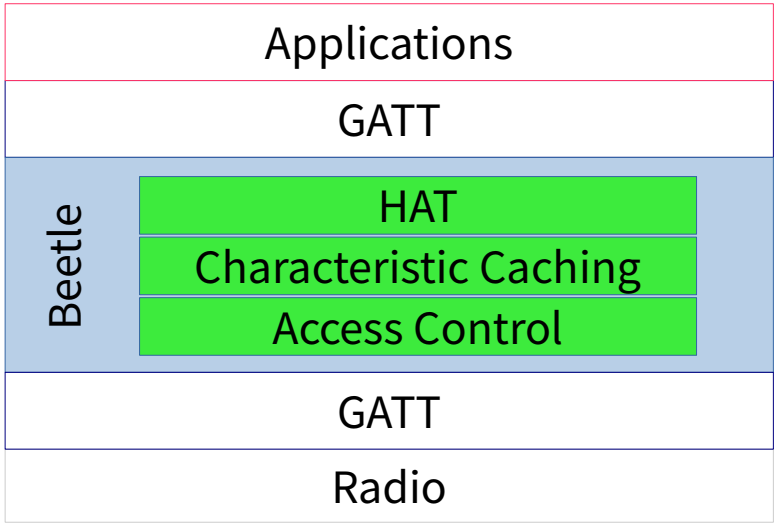
Beetle

- Builds a *network* out of BLE
- A software layer that runs on your gateway
  - Device-to-device communication
  - ***Safe*** multi-app communication, locally or over Internet
  - Fine grained access control
- Completely backwards compatible with existing BLE devices

Beetle: Design Overview

- Privileged user-space process on Linux and Android
- Provides networking to BLE devices
- Gateway *routes* between peripherals, apps and cloud
- Leverage richer user-interface on gateway





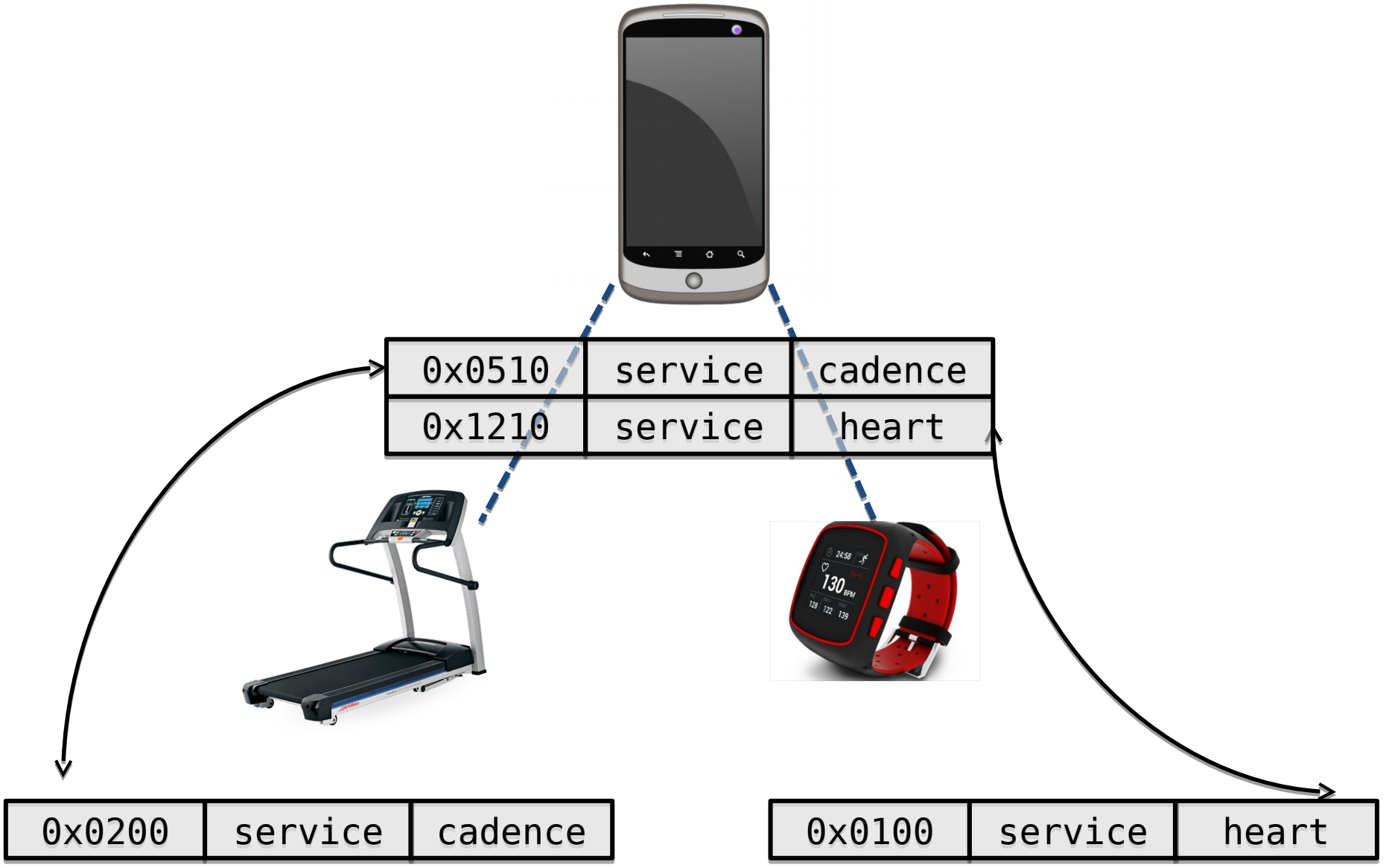
Beetle: Gateway Mechanisms

- Handle address translation (HAT)
  - Multi-link networking
- Virtual devices
  - Software connectivity
  - Interface with other protocols (e.g. HTTP, Intents)
- Service export control
  - Fined-grained security policies
  - Naming

Handle Address Translation (HAT)

- Re-export peripheral services as gateway services
- Proxied attributes on the gateway
  - Associated with a remote attribute on a peripheral
  - Beetle routes messages to proxied attributes to the appropriate peripherals
- Translate peripherals handles into gateway address space
  - Similar role to NAT in TCP/IP world

Handle Address Translation (HAT)



HAT: Discovery

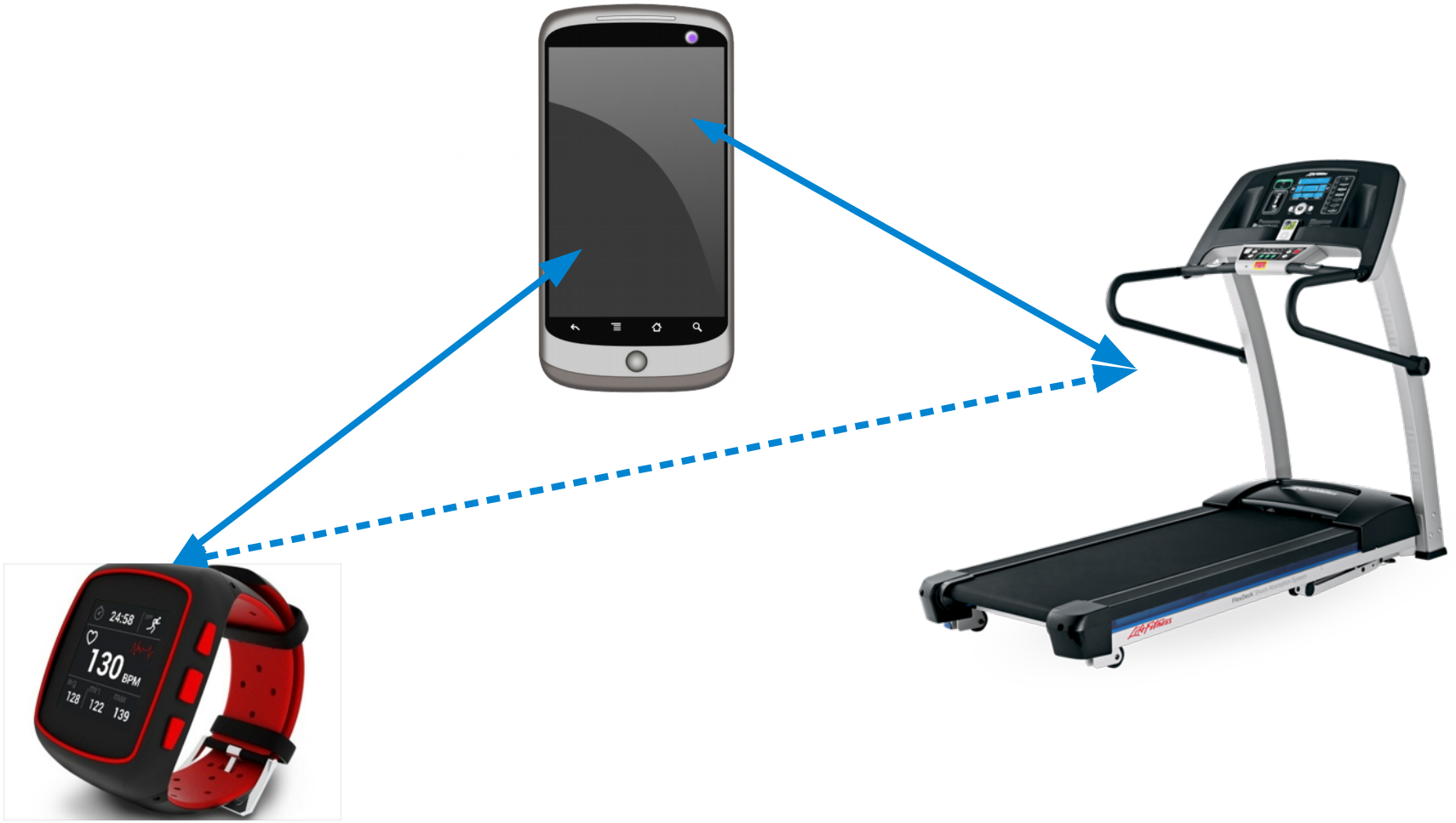
- Typical BLE connection has fixed set of services
- In Beetle, new services appear as more peripherals connect or policy is changed
- Take advantage of “Service Changed” characteristic
  - Notifies client when new set of services changes
  - Provides a range of affected handles
- Keep track of which peripherals might notice the service has changed to minimize noise
  - If a peripheral never asks for a service, it shouldn't matter

HAT: Notifications

- GATT notifications are a two-step process:
  - *Subscribe/unsubscribe* to notification by writing 1 or 0 to an attribute
  - Server begins notifying when value changes
- Cannot re-expose subscription attribute directly
- Instead:
  - Maintain a subscription set for every server notification source
  - Intercept *subscribe* and *unsubscribe* messages
  - Only forward first *subscribe* or last *unsubscribe* to server

HAT Creates a *Network*

- Re-exporting attributes on gateway enables peripheral-to-peripheral communication
- Aggregating attributes from multiple servers allows many-to-many peripheral communication
- HAT must maintain app-level protocol semantic
- Leverage knowledge of app-level protocol semantics to retain reasonable performance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130 BPM
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122
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Demo: Lights and Switches

Virtual Devices

- Virtual devices speak GATT for non-BLE links:
  - IPC, TCP/IP, USB, etc
- Provide access to non BLE services
  - GPS
  - Emulated device with test data
  - Legacy Internet services (e.g. HTTP)
- Complexity handled by HAT

Virtual Devices: Local

- A user-level process that speaks GATT
- Access to Beetle over IPC (e.g. UNIX domain sockets)
- Similar to programming an app now (identical on Android)
- Very useful:
  - Multiple user apps
  - Expose local, non-BLE, sensors
  - Prototyping hardware
  - Custom multiplexing

Virtual Devices: Network Services

- Virtual devices can exist on the Internet
  - In the cloud, local area network
- Scenario 1: Internet service supports Beetle
  - Beetle OS service connects directly over TCP
  - Don't need to write a tailored app
- Scenario 2: Legacy Internet service (e.g. HTTP/REST)
  - A local virtual device exports data over the legacy protocol


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130 BPM
128
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Service Export Control

- So much connectivity!!
- Need a way to control who sees what
  - Strava shouldn't only see my current heart rate when I allow it
- Routing at app-level protocol gives us more flexibility
- Many possible criteria for access control
  - Physical location
  - Identity
  - Pre-established trust
  - Out-of-band authentication (e.g. user login)

Beetle

- Gateway should route communication but not mediate application data
- Beetle is an OS service on the gateway that creates a network from BLE
- Three key mechanisms:
  - HAT for peripheral communication
  - Virtual devices for multiple-apps, device emulation and connecting other networks
  - Service export control pushes policies to more featureful gateway devices
- Completely backwards compatible with existing BLE devices


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august
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NIKE
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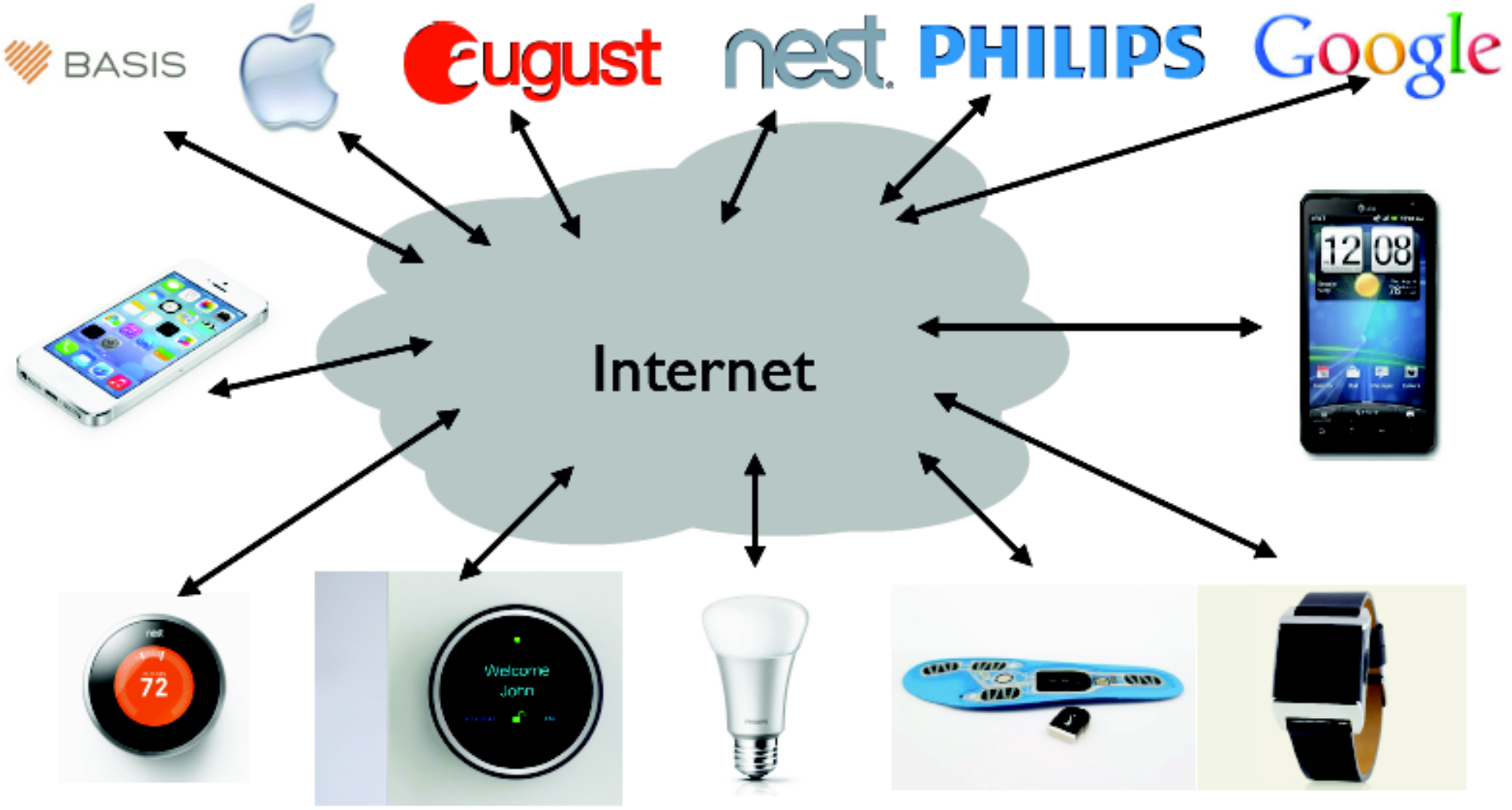
Welcome
John

Questions?


BASIS
august
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Welcome
John

Beetle Linux Implementation

- Linux user-level process
- ~1300 lines of code (in Go)
- No changes to Kernel
  - Although could be useful
- Global handle address space
- Virtual devices over UNIX domain sockets

Peripheral-to-Peripheral RTT