Introduction

18-738 Sports Technology

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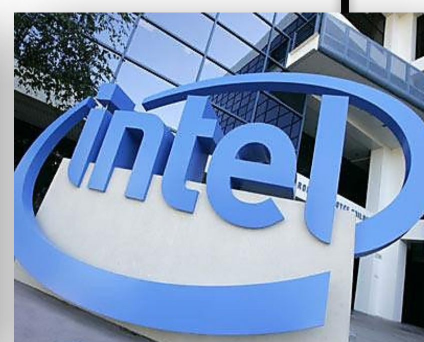


Director, Intel Labs
Pittsburgh

Director, Intel Science
& Tech Center in
Embedded Computing

CEO & Founder, YinzCam, Inc.

My Background

- **At Carnegie Mellon**
  - Faculty in ECE since 2001
  - 18-349 instructor since 2001
  - 18-549 instructor since 2006
- **Industry experience**
  - CEO and Founder, YinzCam, Inc.
  - Founded 2 other startups
  - Director, Intel Labs Pittsburgh
- **Passionate about sports**
  - All aspects
  - Bringing technology to sports
  - Bringing sports into the classroom

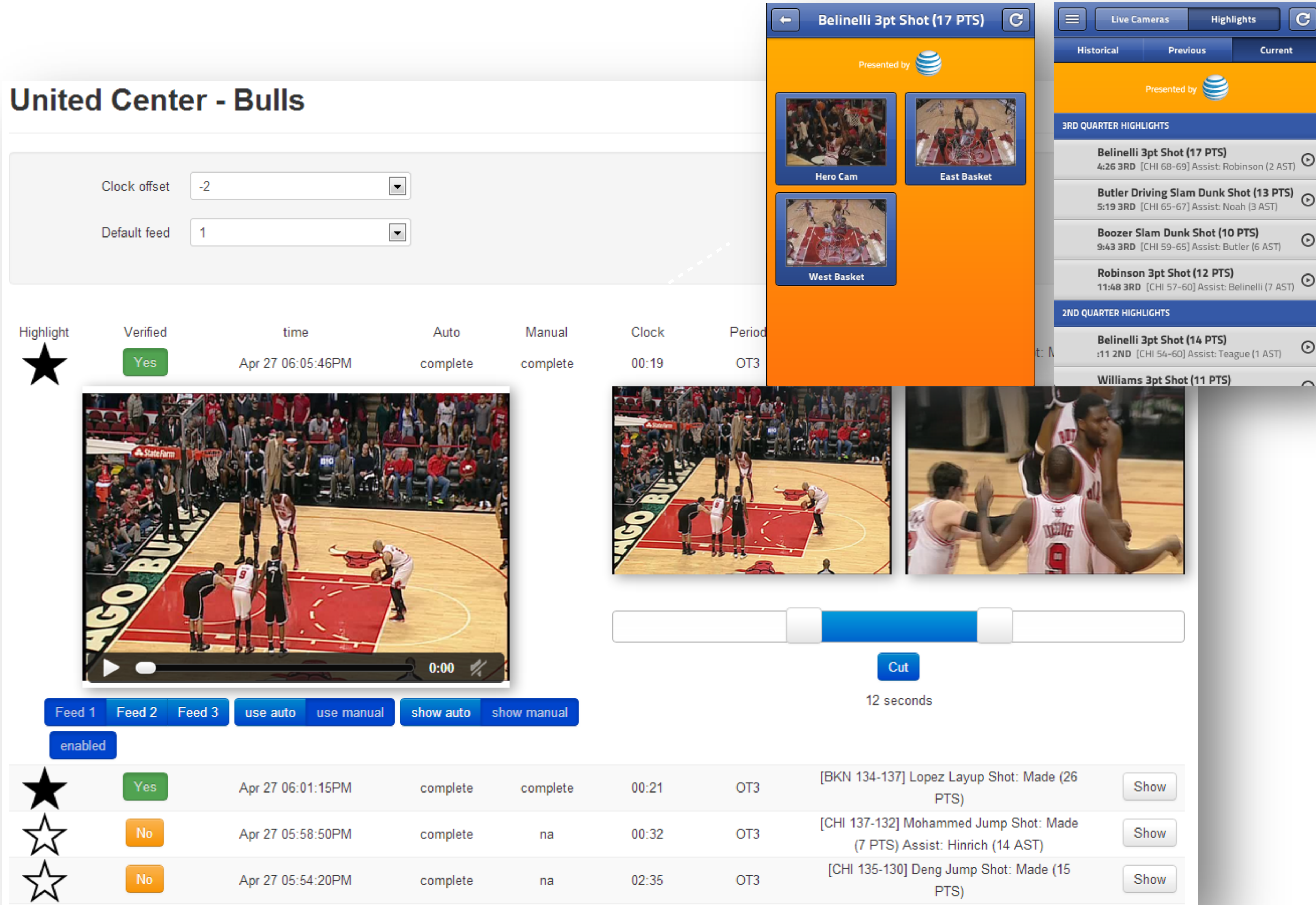
In the beginning .....

The birth of a company


yinzcam

Innovations: At Super Bowl XLIX

YINZCAM



Automation for mobile-highlight creation

Technical Challenges

Broadcast rights. Game footage can never leave the building.

Content rights. Needed for some kinds of content.

Minimal manual intervention. Cannot afford to have humans in the loop, especially for time-sensitive consumption of media.

Scalability. Need to be able to handle dynamic load.

Scalable operations. Need to be able to handle multiple teams and facilities at the same time.

Latency. Need to provide the best quality-of-service for specific kinds of content, e.g., replays

The Roster

NFL Clubs
Pittsburgh Steelers
Buffalo Bills
New England Patriots
New York Giants
New York Jets
Baltimore Ravens
Cincinnati Bengals
Houston Texans
Tennessee Titans
Denver Broncos
Kansas City Chiefs
Dallas Cowboys
Philadelphia Eagles
Chicago Bears
Seattle Seahawks
Detroit Lions
Green Bay Packers
New Orleans Saints
Minnesota Vikings
Carolina Panthers
Tampa Bay Buccaneers
Arizona Cardinals
St. Louis Rams
Oakland Raiders
Cleveland Browns

NBA Teams
Phoenix Suns
Washington Wizards
Charlotte Hornets
Chicago Bulls
Golden State Warriors
Houston Rockets
Memphis Grizzlies
Milwaukee Bucks
New Orleans Pelicans
Oklahoma City Thunder
Philadelphia 76ers
San Antonio Spurs
Cleveland Cavaliers
New York Knicks
Atlanta Hawks
Indiana Pacers
Denver Nuggets
Brooklyn Nets
Los Angeles Lakers
Los Angeles Clippers
Toronto Raptors
Boston Celtics

WNBA Teams
Phoenix Mercury
Washington Mystics
New York Liberty
Minnesota Lynx
Indiana Fever
Dallas Wings
Las Vegas Aces
Connecticut Sun
Chicago Sky

Leagues
La Liga (Spain)
NRL Live (Australia)
Super Netball (Australia)
NBL (Australia)
AFL Women's (Australia)
AFL Under-18 (Australia)
All Blacks / NZR (NZ)
New Zealand Cricket (NZ)
AFL Live for Windows
NBA G-League
Jr. NBA (kids' app)
USA Basketball
NBAmoji
NBA2K (NBA e-League)

Venues
United Center
Gillette Stadium
Verizon Center
Patriot Center
Sports Authority Field
Toyota Center
Soldier Field
CenturyLink Field
Barclays Center
Vodafone Stadium Live
Madison Square Garden
Radio City Music Hall
Beacon Theater
ScotiaBank Arena

La Liga Clubs (Spain)
D. Alavés
Albacete Balompié
AD Alcorcón
UD Almería
Cádiz CF
Cultural
SD Eibar
Elche
Getafe CF
SD Huesca
CD Lugo
Mallorca
Nástic de Tarragona
Numancia
CA Osasuna
Real Oviedo
Rayo Vallecano
Real Sporting de Gijón
CD Tenerife
Real Valladolid
Real Zaragoza

U.K. Clubs
Wolves FC
Blackburn Rovers
Barnsley
Sunderland FC

MLS Clubs
New England Revolution
Toronto FC

AFL Clubs (Australia)
Sydney Swans
Geelong Cats
Hawthorn
GWS Giants
Adelaide Crows
West Coast Eagles
Western Bulldogs
North Melbourne
St. Kilda
Port Adelaide
Melbourne
Collingwood
Richmond
Carlton
Gold Coast Suns
Fremantle
Brisbane Lions
Essendon

NZR (New Zealand)
All Blacks
Vodafone Warriors
New Zealand Cricket

Events
NFL Pro Bowl 2015
NFL Super Bowl XLIX
NBA All-Star 2015
NRL Auckland Nines 2015
Big East Tournament 2015
Breeders Cup 2017
Indian Wells Tennis 2018

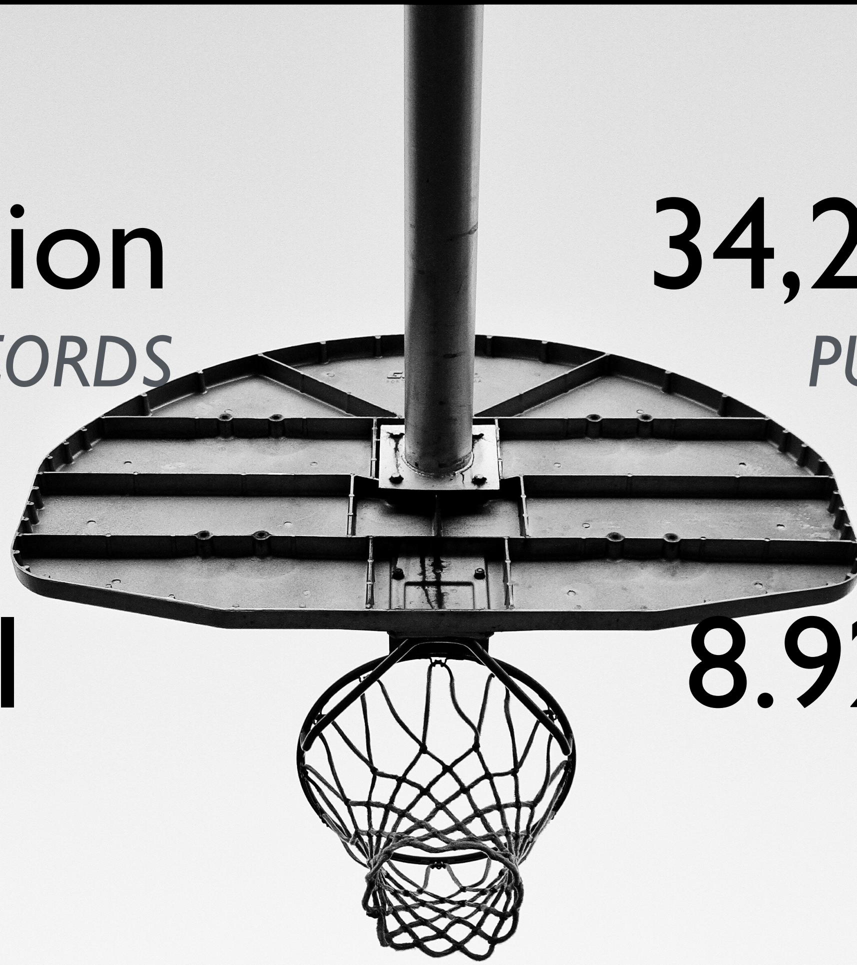
NCAA Colleges
Texas A&M University
Kansas University
Baylor University
University of Wisconsin
Notre Dame University

NHL Clubs
Pittsburgh Penguins
Buffalo Sabres
Toronto MapleLeafs

CFL Clubs (Canadian football)
Calgary Stampeders
Saskatchewan Roughriders
Winnipeg BlueBombers

AHL Clubs
Lehigh Valley Phantoms
Lake Erie Monsters

YINZCAM



180.38 billion
USER-ACTION RECORDS

34,241,601,697
PUSH NOTIFICATIONS

79,406,781
APP INSTALLS

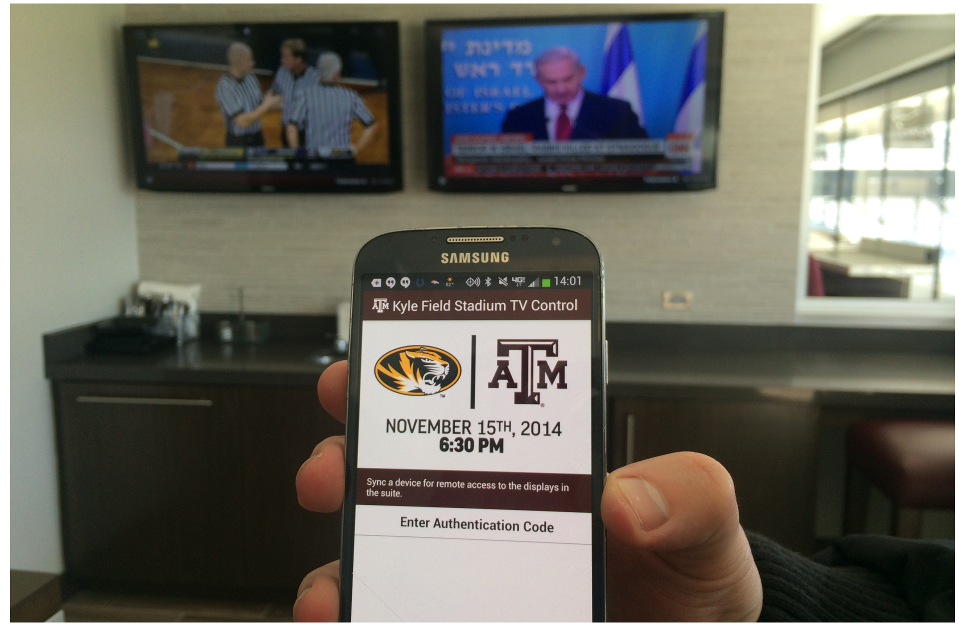
8.92 petabytes
DATA SERVED

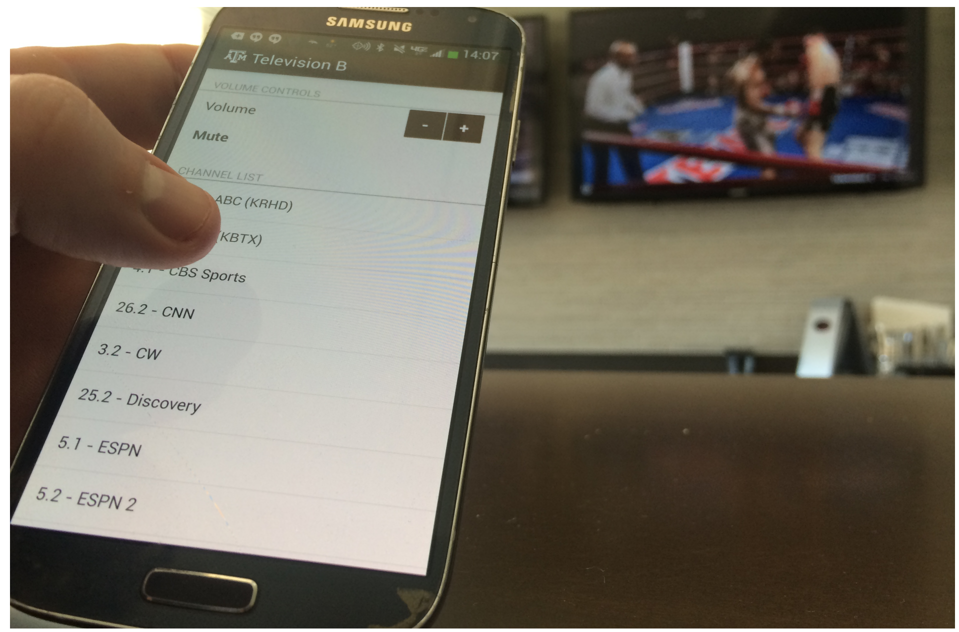
16,912,597,455
PAGE VIEWS

877,774,952,448s
TIME SPENT

YINZCAM

Adding wearable devices to the mix



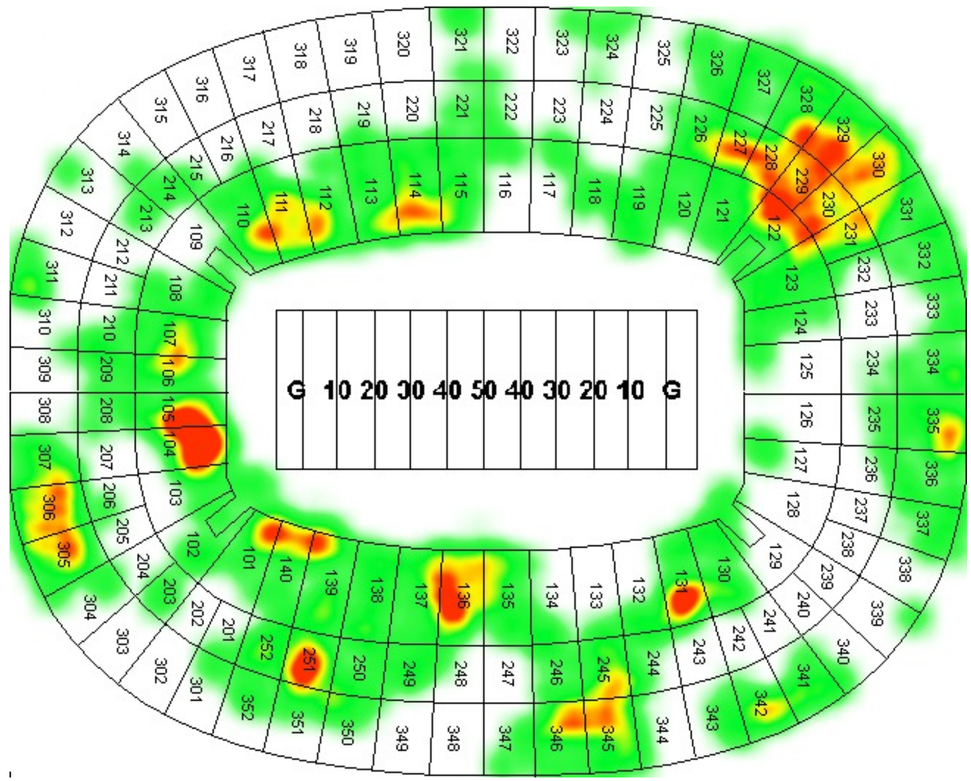


Adding other display devices to the mix

Interfacing with televisions and set-top boxes

Innovations: Wireless Analytics

- **Wireless analytics package**
    - In-seat measurement tool in fans' hands
- **Can measure and report (in real-time)**
    - Signal strength
    - Number of instances of video buffering
    - Number of video interruptions
    - Number of uninterrupted-video sessions
    - Number of failed calls for content
    - Battery life
- **Why?**
    - Measure ROI on wireless investment
    - Shows quality of fan experience
    - Actionable data to improve wireless

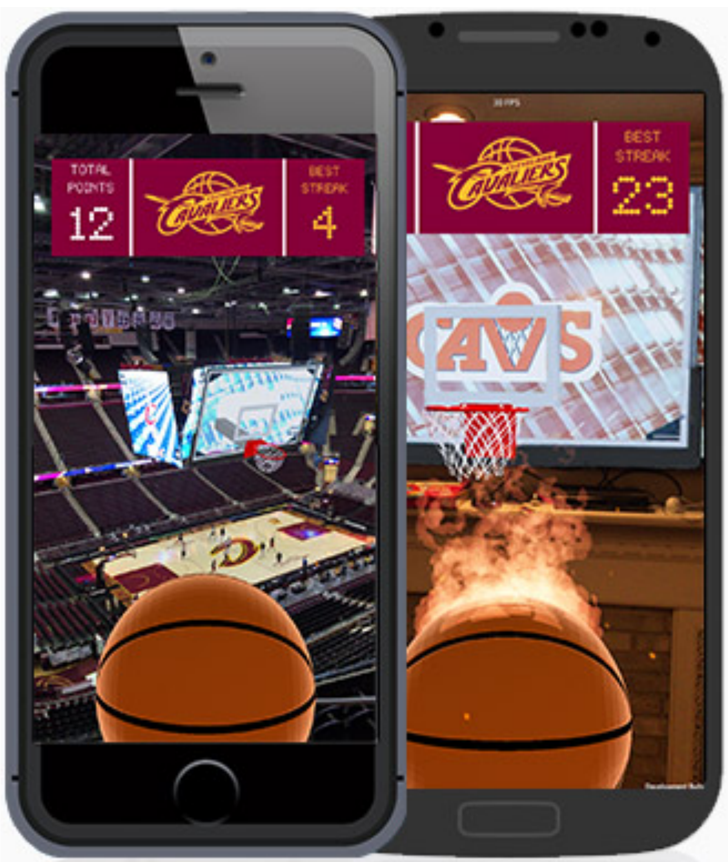


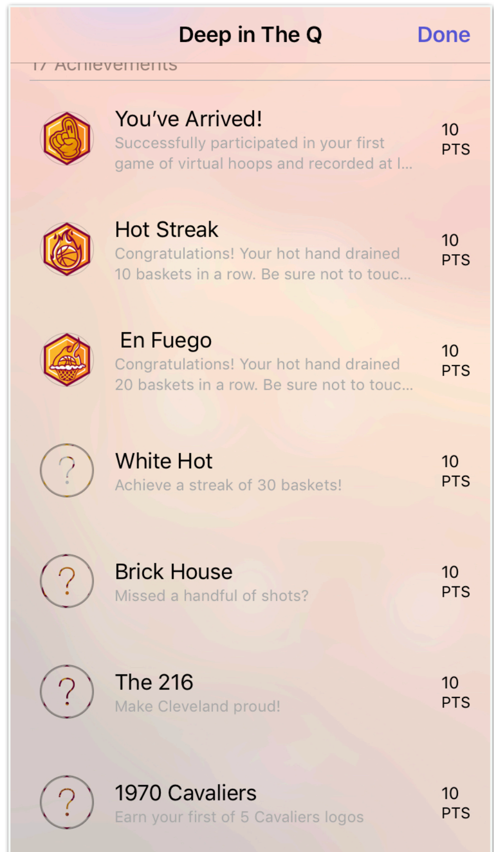
Innovations: Edge Clouds

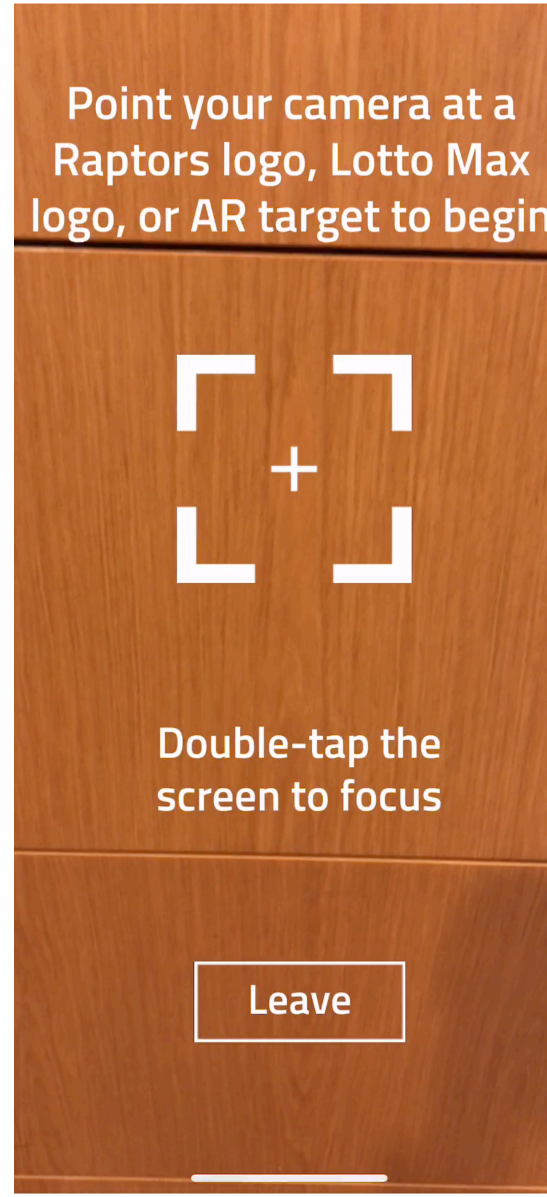
- **Wealth of devices**
  - Number of mobile devices growing
  - Each of them growing in computation
  - Each of them growing in storage, memory
- **What if more devices = better infrastructure?**
  - Crowd-source devices and their computation
  - Run "edge clouds" out of devices alone
  - No access to server infrastructure at all
  - Can help alleviate bandwidth issues
- **Have experimented with edge-clouds**
  - Initial results show great promise
  - Experimentation with stadiums, stores
  - *ACM MobiArch 2015* Best Paper Award
  - *ACM GPCE 2015* keynote

YINZCAM

Augmented-Reality Work

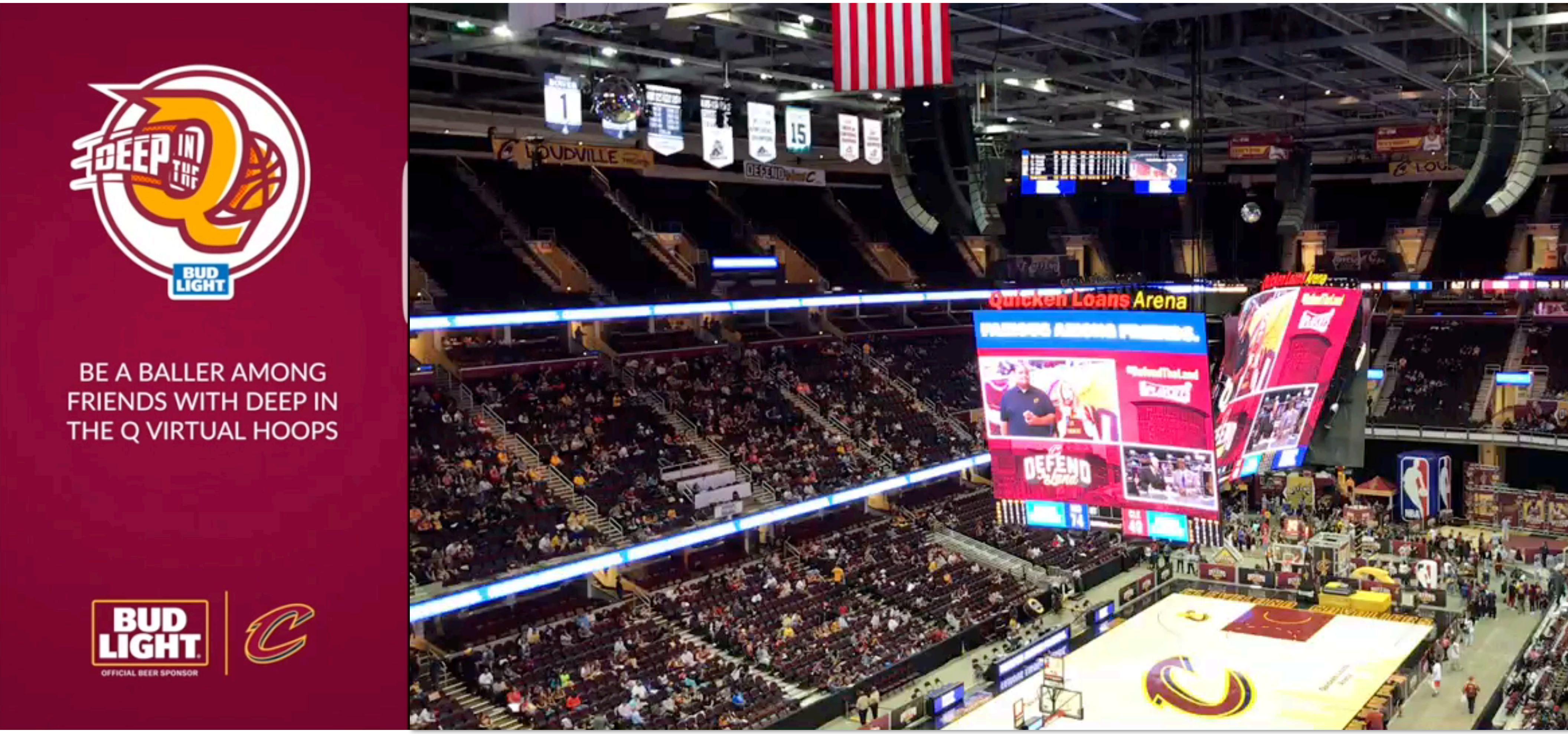


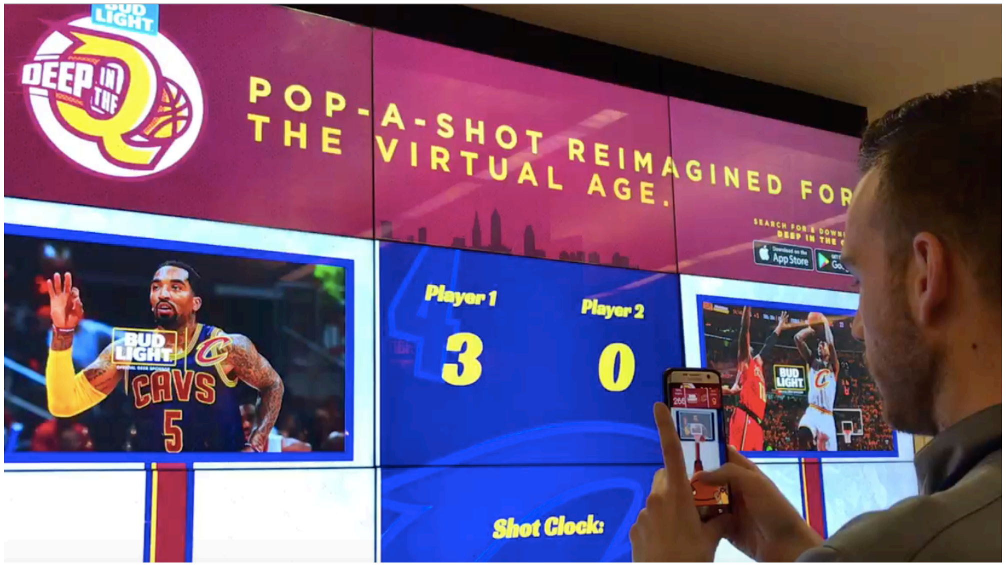




BUD LIGHT
DEEP IN THE Q
POP-A-SHOT REIMAGINED FOR THE VIRTUAL AGE.
App Store
BUD LIGHT
CAVS
5
Player 1
3
Player 2
0
Shot Clock:
26
BUD LIGHT

Example: Interactive In-Arena Game

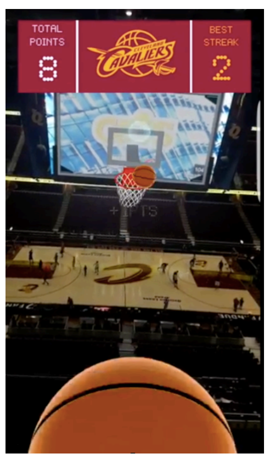


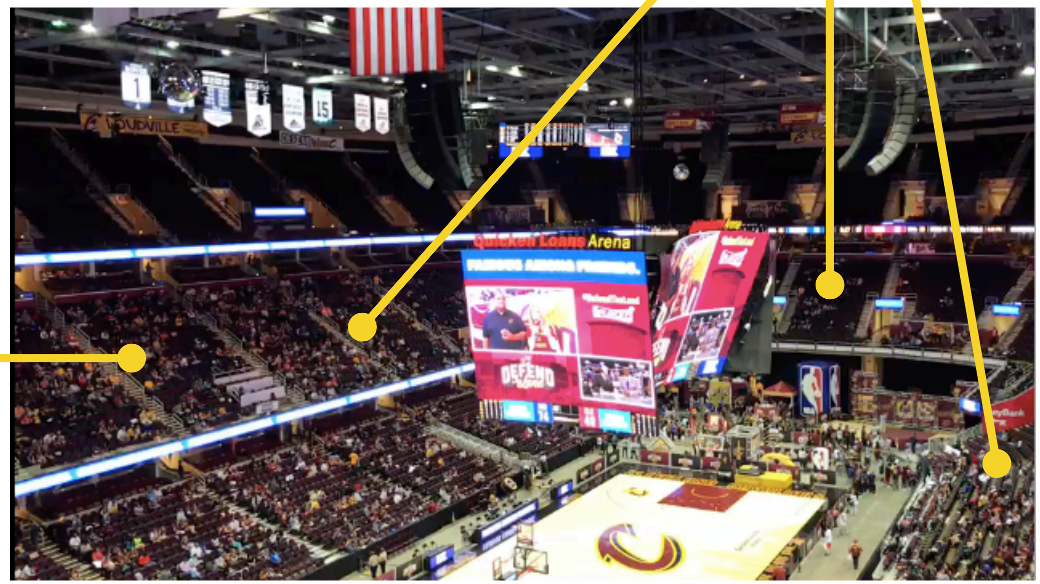


*Fans competing head-to-
head
at a video wall*

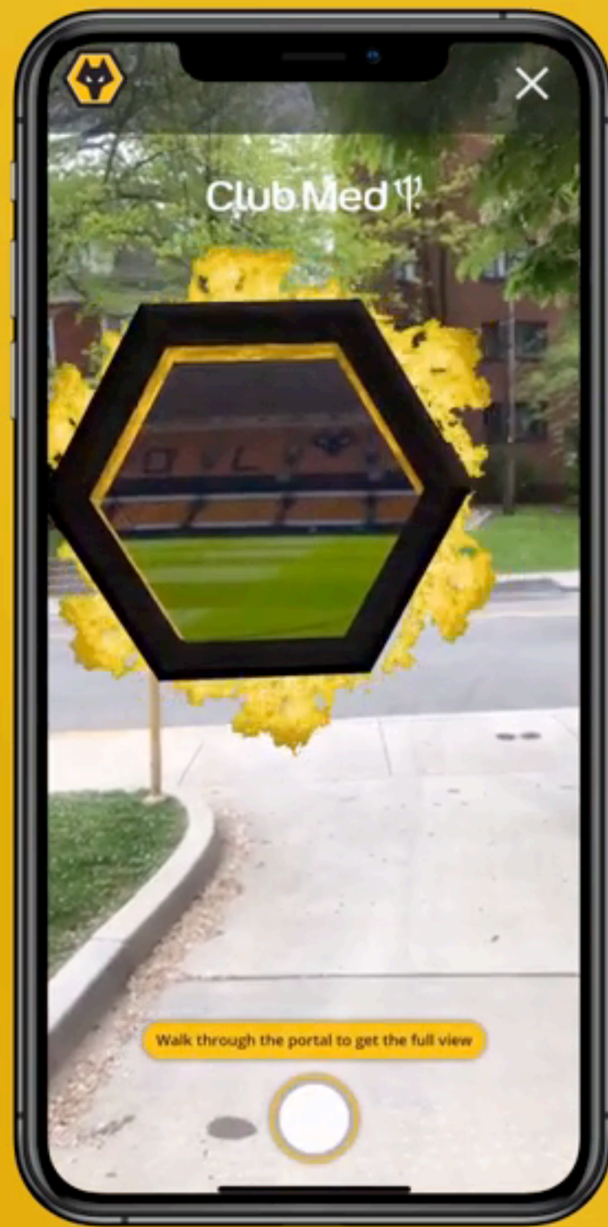
*Fans competing
across sections
by pointing at
the videoboard*

*Fan points and
shoots at the
video board*





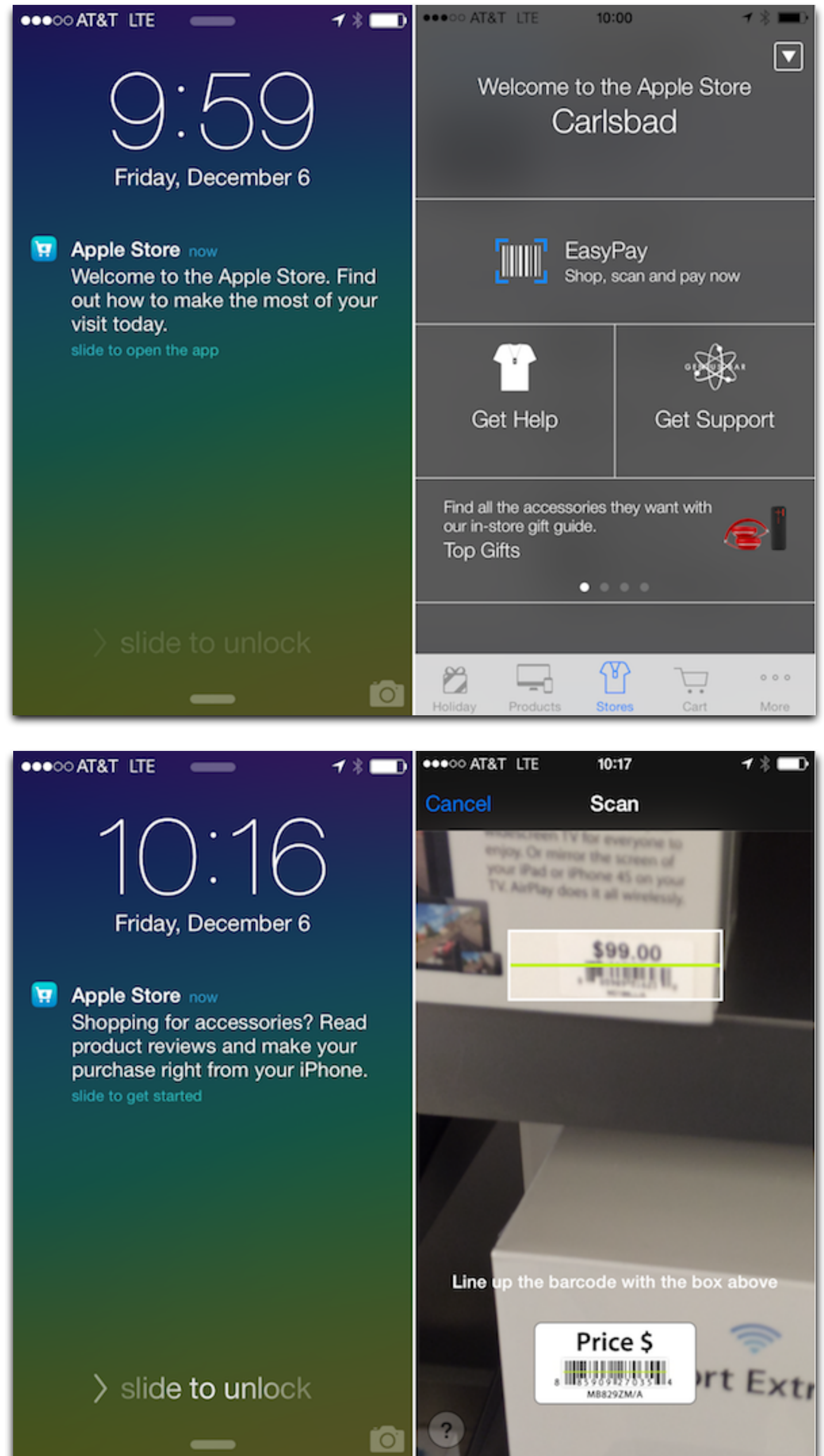
AR PORTAL



Walk through the portal to get the full view
TIM DUNCAN
20
21
HALL OF FAME
H-E-B

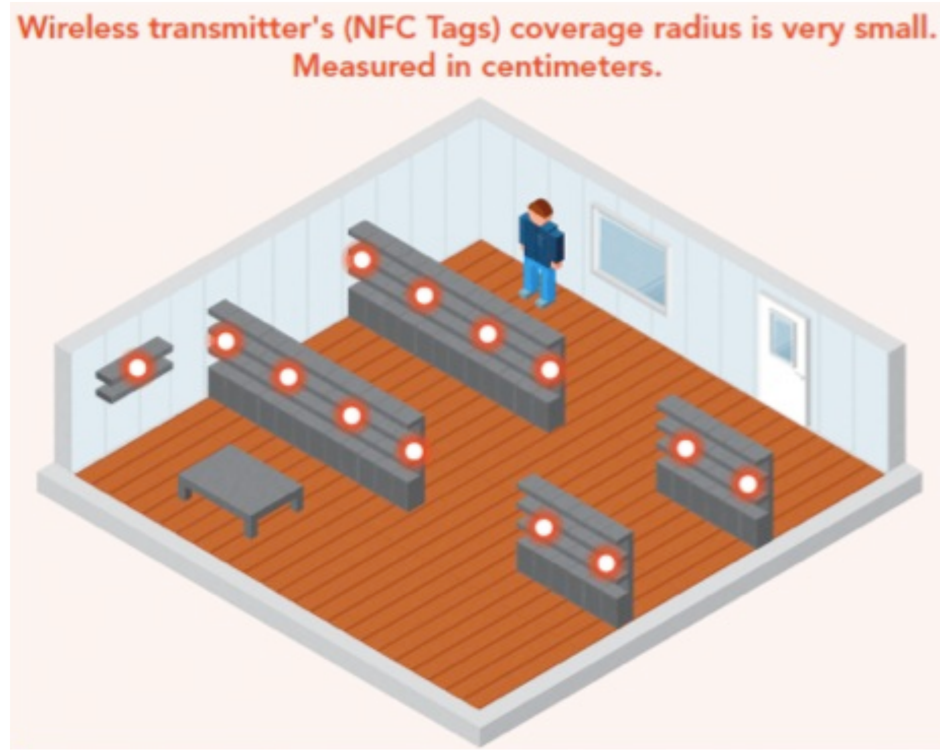
Another Example: iBeacon

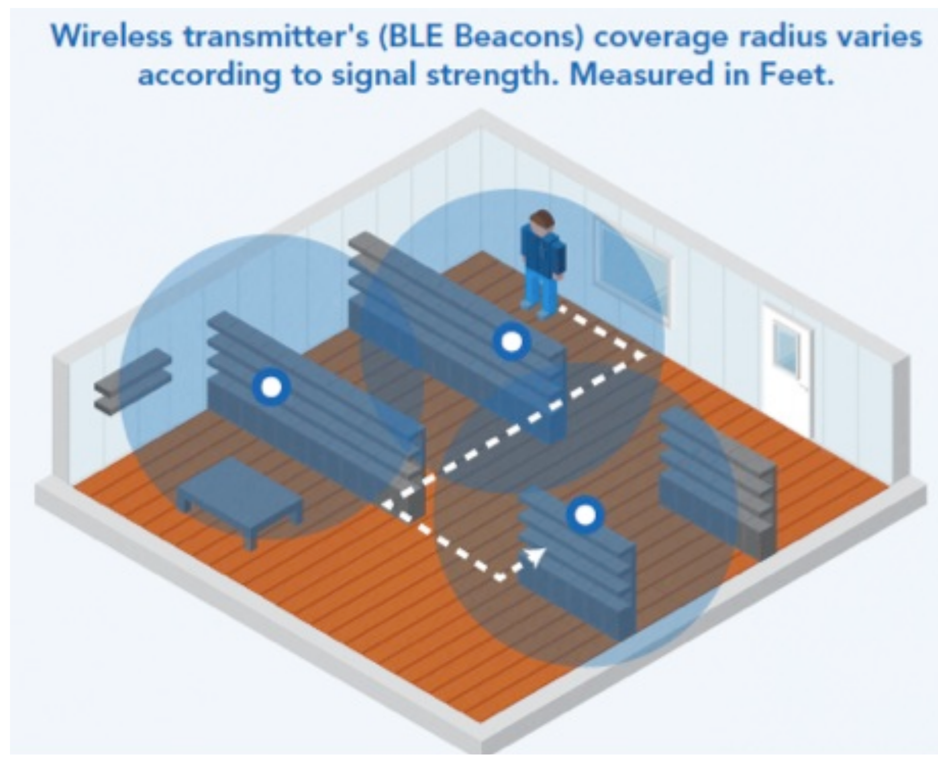
- Announced by Apple in 2013, as a part of iOS7
- Fine-grained location services
- To increase foot traffic to stores
- To reduce showrooming
- Installed in 250+ Apple stores
- To create experiences around physical locations, such as ...



Beacons and NFC

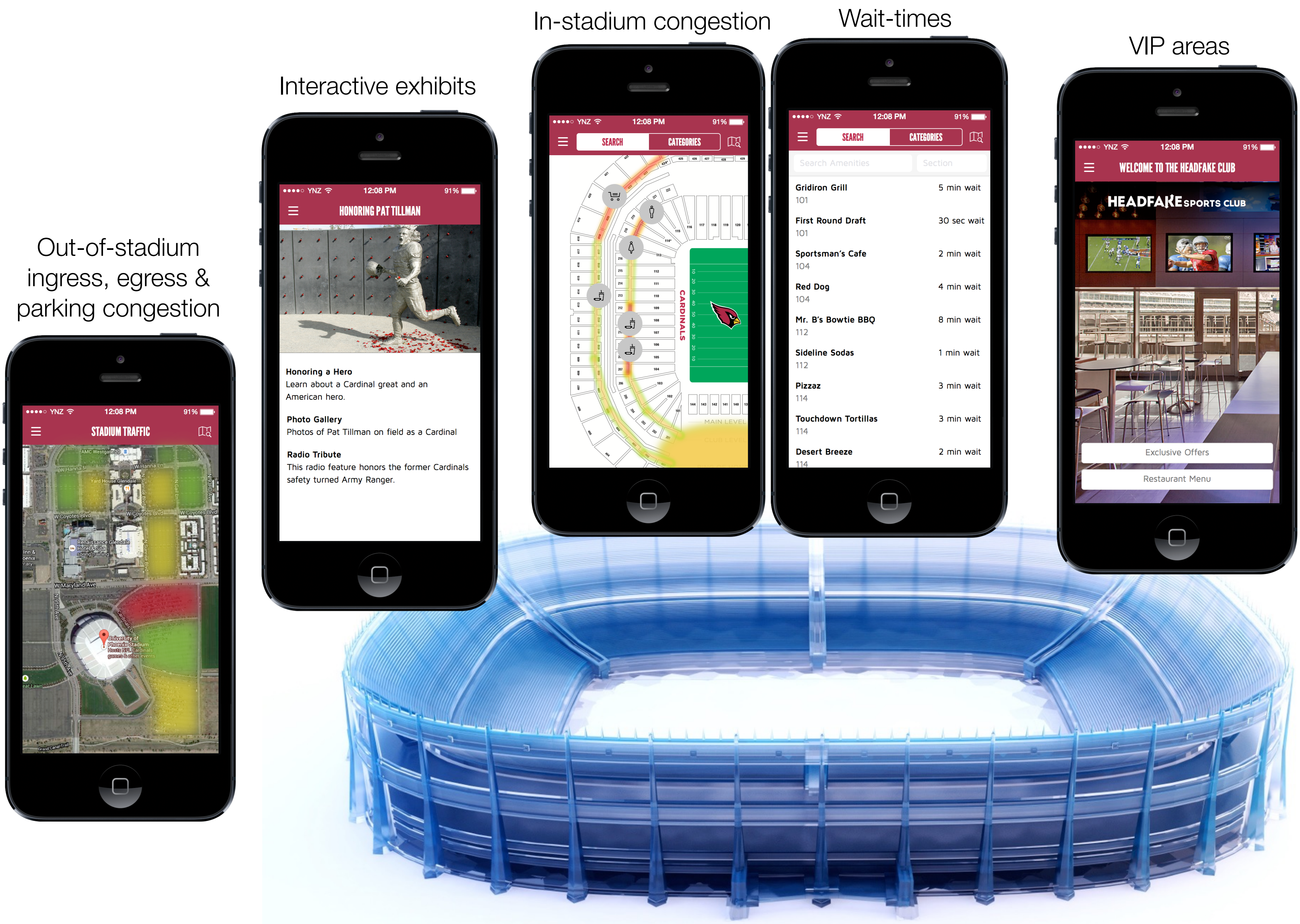
- BLE Beacons continually transmit a discovery signal received by BLE-enabled smartphones
- NFC tags communicate when close to an NFC-enabled smartphone
- BLE beacons' coverage radius can be multiple feet/meters
- NFC tags' coverage radius is centimeters





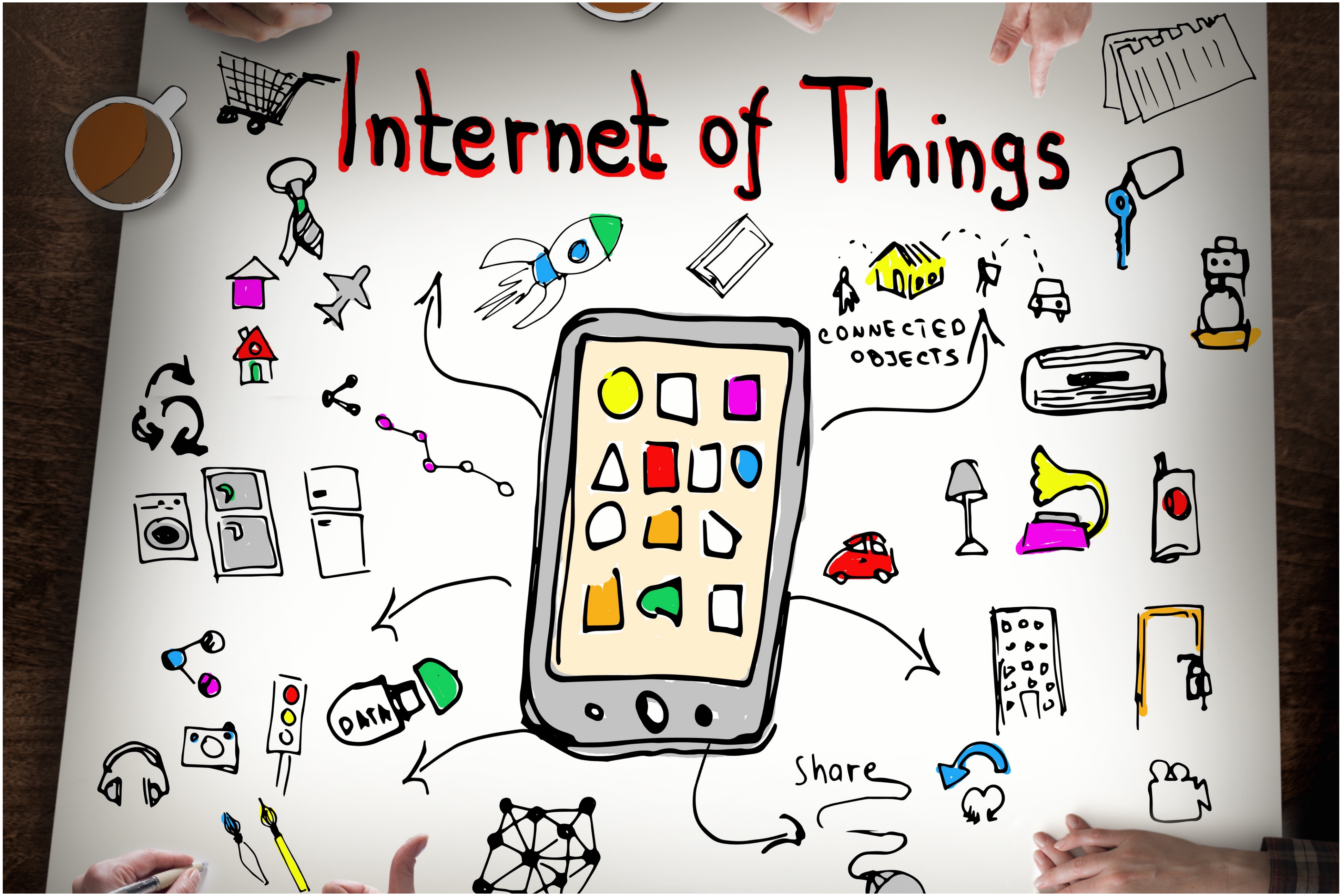
Sports Industry

- Beacons installed in several stadiums and venues
- Works with the venue/team/league app
- Experiences associated with physical artifacts (hall of fame)
- Loyalty programs, season-ticket holder experiences



Beacon-Activated Fan Journey

It’s amazing what a group of Carnegie Mellon students can do!



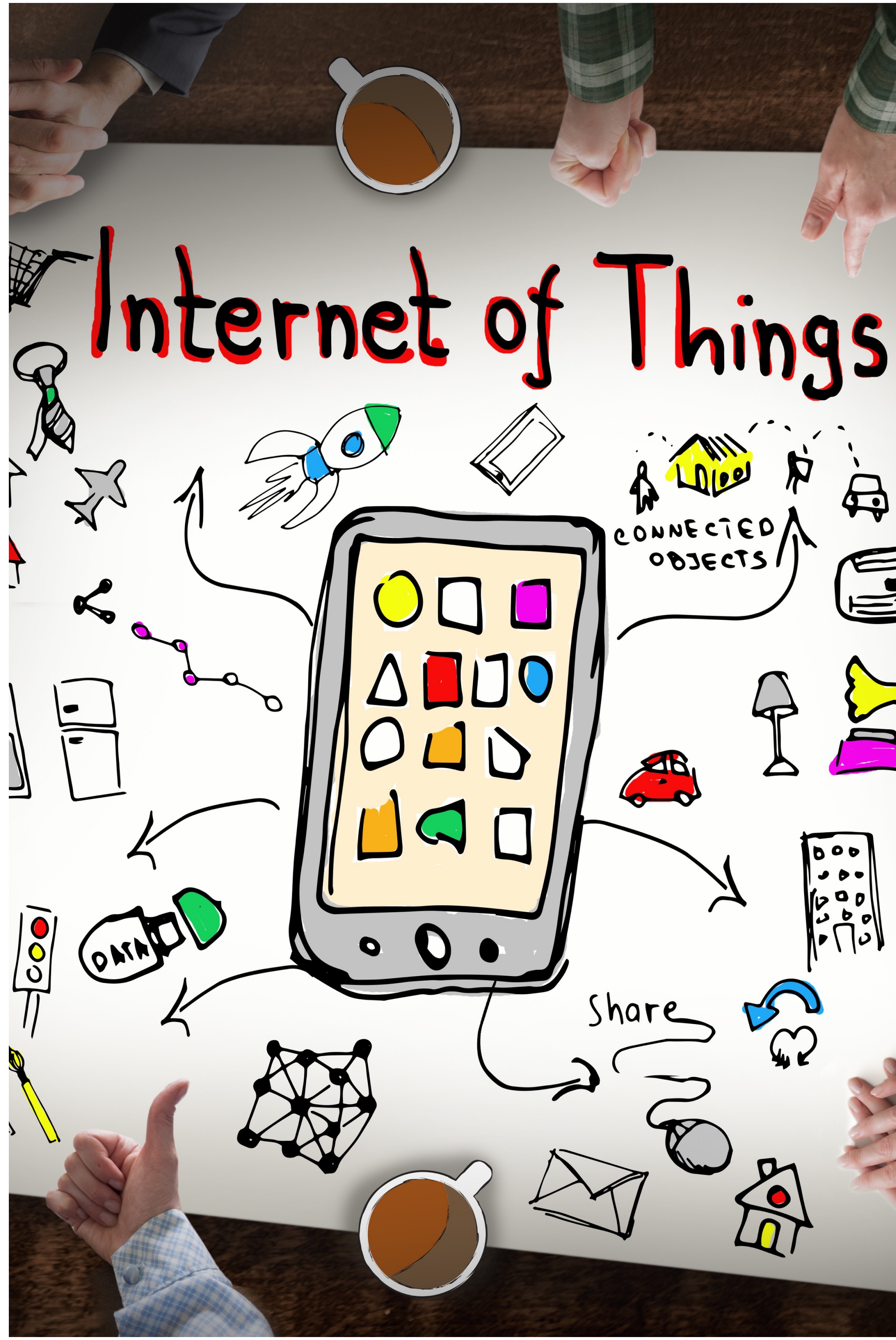
What is the Internet of Things?

What is IoT?

- **Network of physical objects**
  - Each being uniquely addressable
  - Each with some kind of “smarts”
  - Each built to sense/react/interact
  - Each possibly purpose-built
  - People can be objects, too
- **What emerges if**
  - You put them together?
  - They communicate with each other?
  - New capabilities could emerge?
- **Massive network of**
  - Deeply-embedded devices+people

Trends & Predictions

- **Gartner's 2013 report predicts**
  - 26B IoT "things" by 2020
  - (Only 7.3B phones/PCs/tablets)
  - $300B IoT-traceable added revenue
  - Every device born with connectivity
- **What the future will bring**
  - New business models
  - Example: Usage-based insurance
- **Will affect every aspect of our life**
  - Work, home, play, family, travel



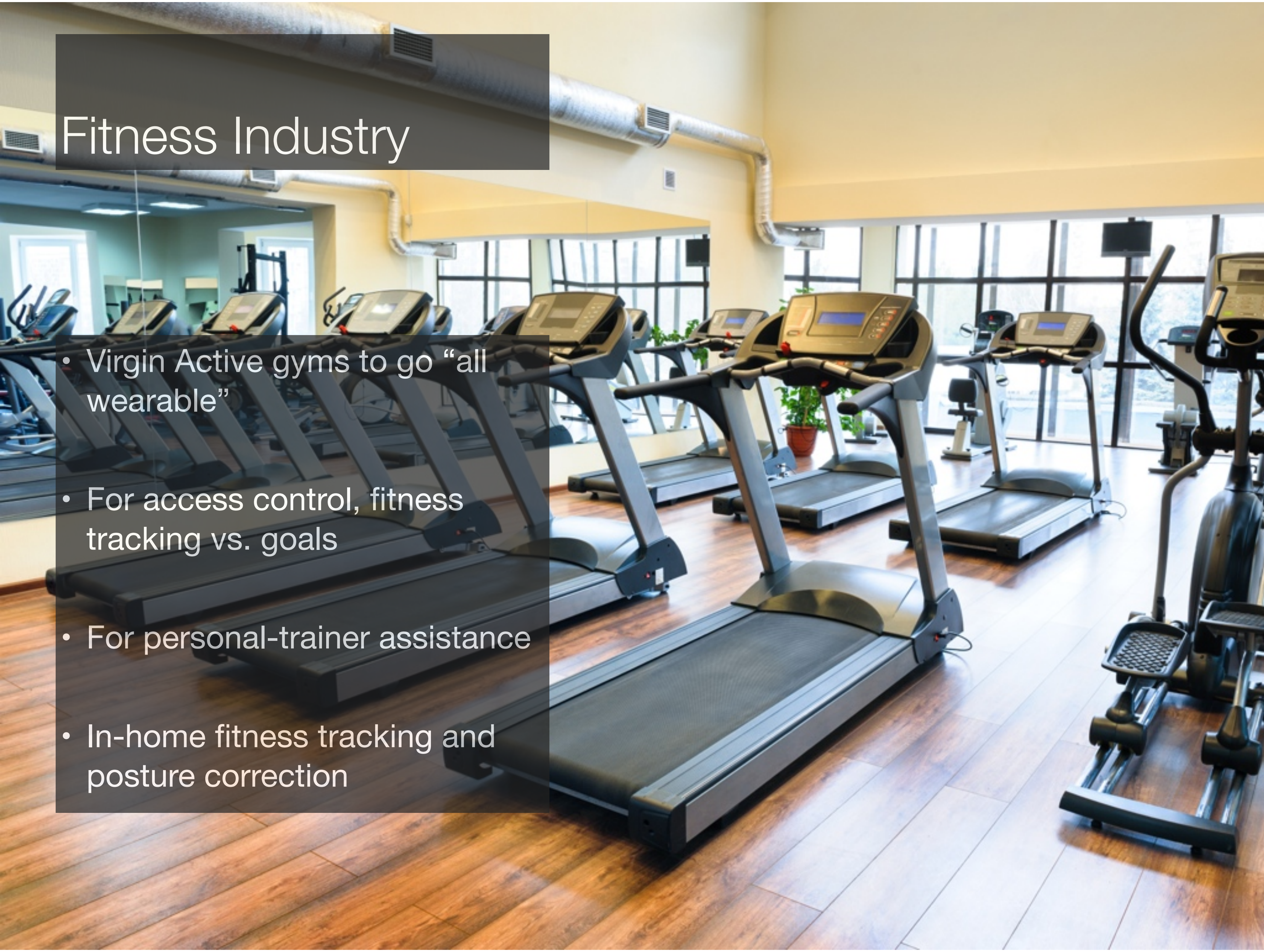
Domains (Verticals)

- **Healthcare**
  - In-home patient monitoring
  - In-hospital improved service
  - Tracking of blood, instruments
- **Retail**
  - Improved inventory management
  - In-store customer service
  - Goods across the supply-chain
- **City/Transportation**
  - Improved congestion/traffic flow
  - Improved maintenance of assets
  - Reduced costs, higher efficiency


This is already happening
FUTURE

Fitness Industry

- Virgin Active gyms to go “all wearable”
- For access control, fitness tracking vs. goals
- For personal-trainer assistance
- In-home fitness tracking and posture correction



Mobile Payments

- Paypal beacons installed in stores, restaurants
- Works with the PayPal smartphone app
- Seamless, location-aware payments
- No card, no cash, no contact

Retail Industry

- Shelves have sensors embedded in them to track movement of products
- Warehouses have robots for restocking and sensors
- Store personnel wear devices for detecting posture and fatigue

Smart Cities

- Beacons installed in cities, e.g., New York City
- Sensors on snow plows
- Sensors on bridges
- Analysis of real-time video from moving and stationary cameras

Focus of this Course

- **Learn about IoT**
  - Platforms (hardware, software)
  - Standards
  - Services (security, dependability)
  - Domains of application
- **Emphasis on IoT-enabled domains**
  - Improving refereeing
  - Improving player performance
  - Improving the fan experience
  - Improving the patient experience
  - Improving the stadiums of the future
  - Improving the hospitals of the future
  - Seeing this in action

Entrepreneurship

- **Applying IoT to new products**
  - Opportunities for products
  - Commercialization practices
  - Product management in industry
- **Emphasis on entrepreneurship**
  - Market surveys and studies
  - Understanding ROI
  - Intellectual property
  - How to think about productization

Lecture Coverage

Logistics

- **Project (Number of team members TBD)**
  - 30% of your grade
  - Propose an IoT-enabled sports technology
  - Must involve hardware
  - 4-page paper + working prototype + demo
- **Mid-term exam (Individual)**
  - 30% of your grade
- **Final exam (Individual)**
  - 30% of your grade
- **In-class talk on IoT sports topic (Individual)**
  - 10% of your grade

How about the Project?

Project: Presentation (Feb 17-18, in class)

- First in-class team presentation
  - All team members to present jointly
  - Concept, motivation, market, competitive analysis
  - Initial requirements, initial list of parts
- Next few milestones
  - Form teams of four people: 28 January
  - Review your project concepts with me: 4 February
  - Get sign-off on your project idea: 11 February
  - Present your project in class: 17-18 February
  - All parts in hand:15 February

Project Phases and Expectations

- Concept
- Requirements
- Specification
- Design, architecture, hardware, software, interfaces
- Prototyping – iterative
- Quality assurance (testing, empirical evaluation)
- Packaging and demonstration
- We will cover project expectations every week in class

Project: Grading

- Project counts for 30% of your overall grade

- Grading-related milestones
  - In-class presentation, project proposal — 3% of grade
  - Alpha demo to Priya — 5% of grade
  - Beta demo to Priya — 7% of grade
  - Final demo to Priya — 15% of grade

The Lightning Talk

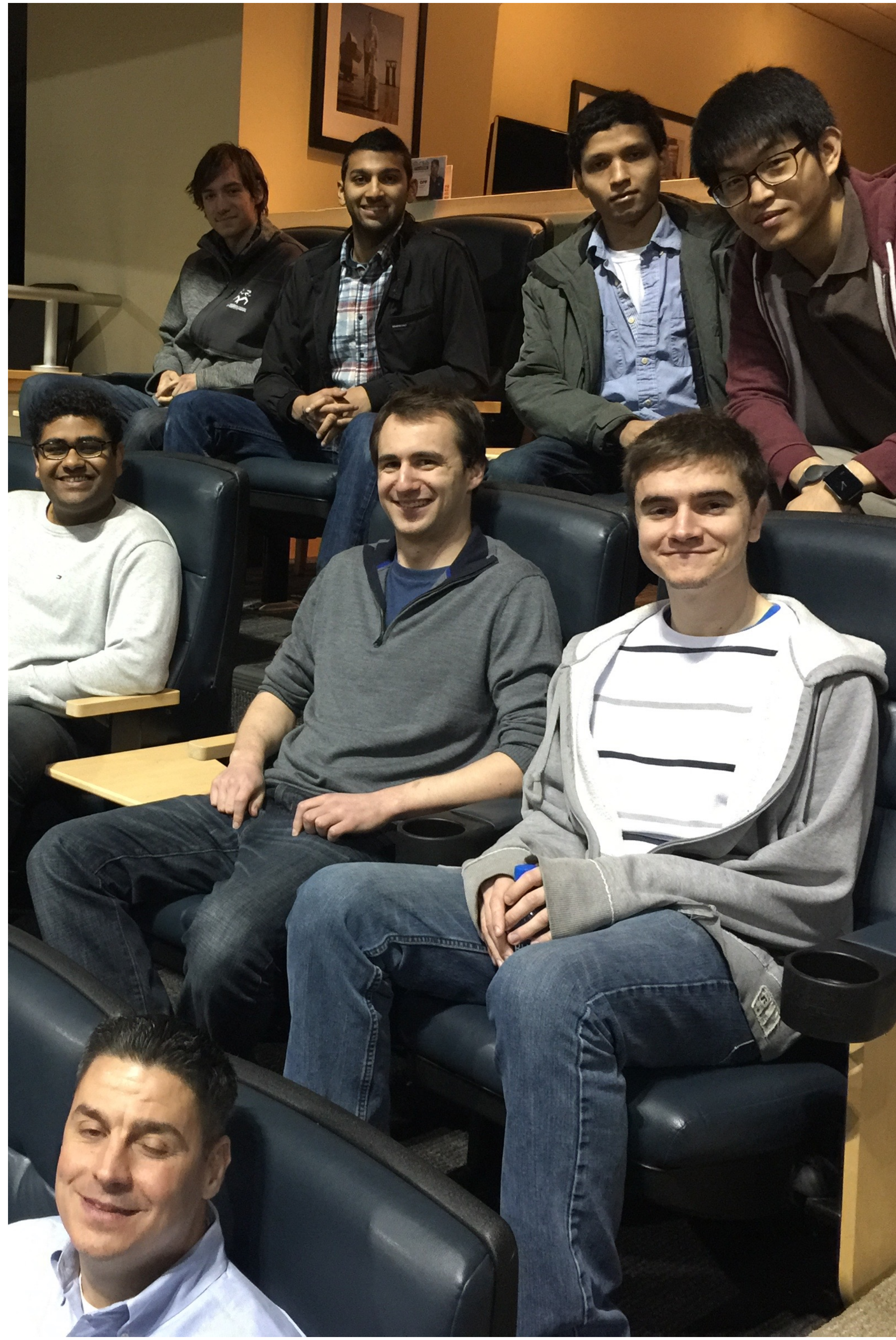
Individual Lightning Talk counts for 10% of your overall grade

What you need to do for the 10% of your grade

- Do a 15-20 minute talk
- Work with me to refine the talk to present in class
- Pick a topic you are passionate about
- The topic should be in IoT and sports

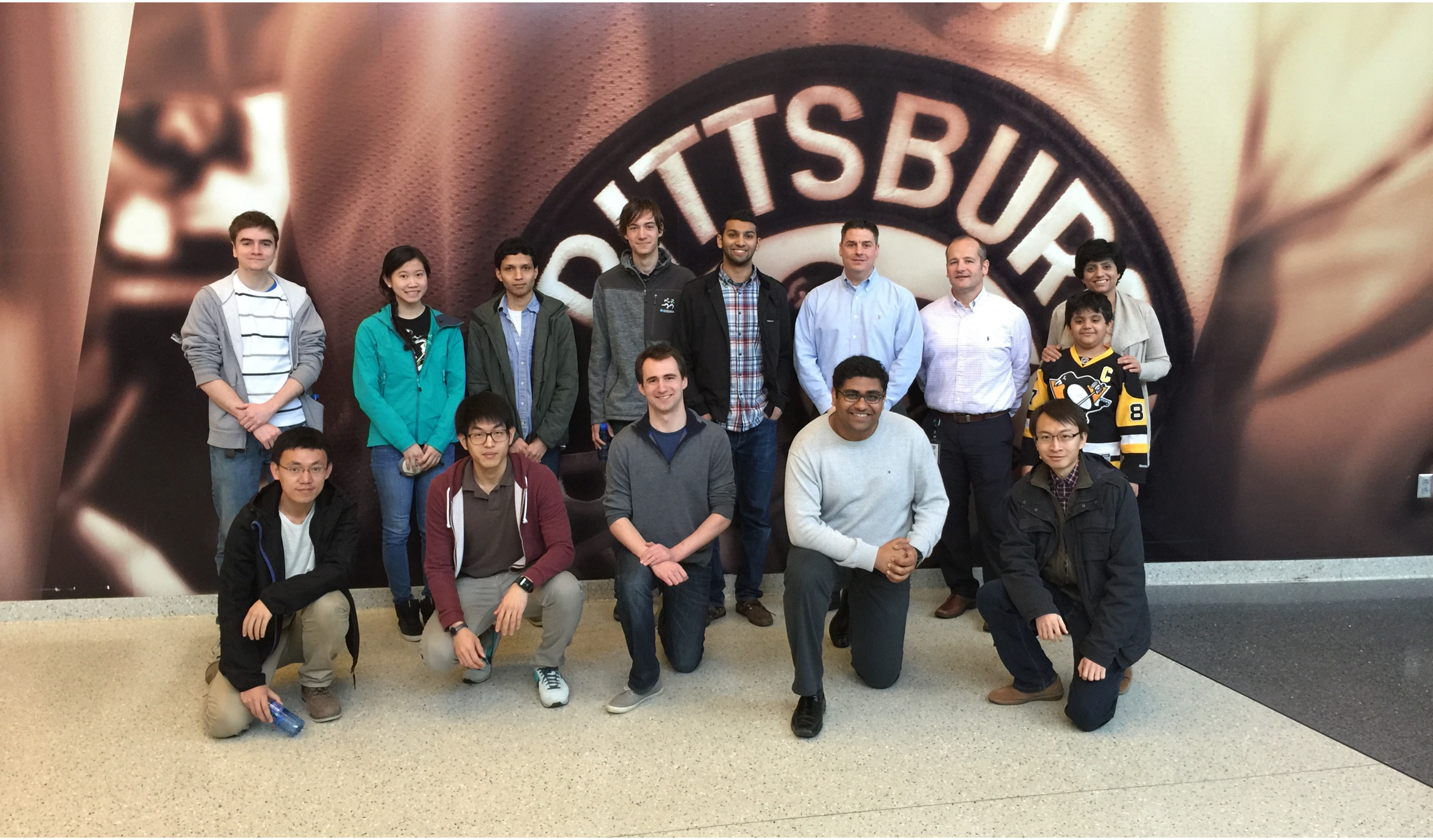
Past Projects

- **Previous projects**
  - Visual pacing system
  - Wait-times in stadiums
  - Smart soccer cleats
  - Virtual-reality basketball trainer
  - Smart beverage cup
  - Chucking detection in cricket
  - Anti-theft for bicycles
- **Feel free to propose ideas**
  - You can pick a domain
  - You can pick the problem
  - We will shepherd you to success



What you should do **NOW**

- Form a group, and start brainstorming
  - What problem are you solving?
  - What is the solution/product that you are proposing?
  - What sport does it work for?
  - Who is the user? Athlete? Coach? Parent? Referee?
  - Who is your competition?
  - In what way is your solution/product/approach novel, or different?
  - What types of components/parts do you need?
  - What do you expect to be able to demo in 10 weeks?



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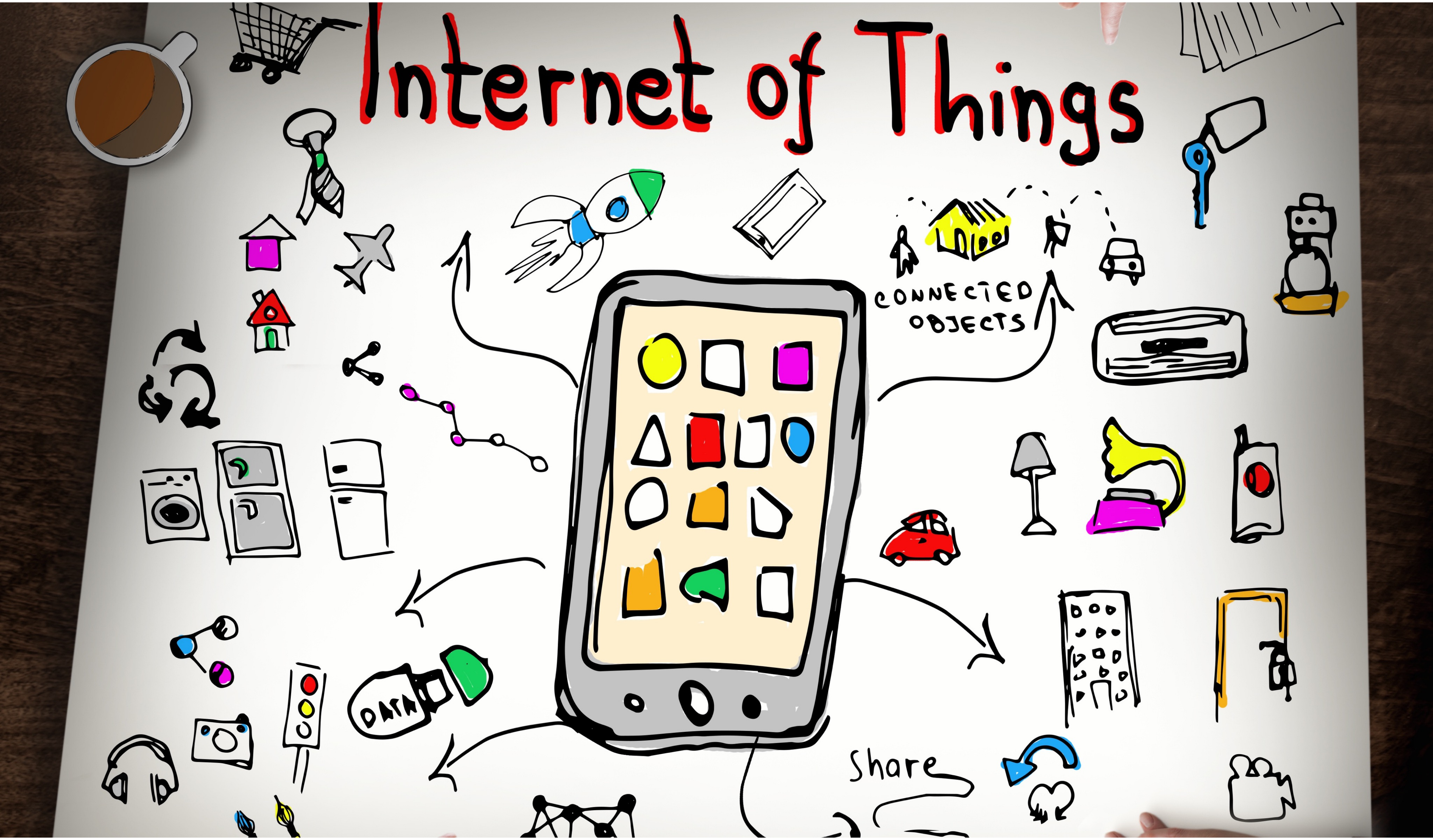

Officiating Technologies in Sports

18-738 Sports Technology

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Overview

- Evolution of officiating technologies
- Electronic line-judge
- Hawk-Eye
- Hot Spot
- Snickometer
- Adidas’ Cairos goal-line
- Research at Carnegie Mellon

Technology for Officiating

Electronic Line-Judge Experimentation

- Technology introduced in early 1970s to improve officiating in tennis
- Used to detect where a ball has landed on the tennis court
- Goals
  - Detect whether the ball was inside/outside the boundary lines
- Original version (1974) was the Grant-Nicks pressure-sensor system
  - Grant was a keen tennis player and Nicks was an electronic engineer
- Thin mylar conductive plastic pressure sensors beneath court surface
- Could differentiate between a player's foot vs. the ball
  - Signature of a ball's millisecond bounce vs. human footfall's duration
  - Normal player movements couldn't accidentally trigger the system
- "In" and "Out" sensors on the boundary lines of the court

Tennis Rules

Electronic Line-Judge Experimentation

- Added objectives
  - Make decisions on foot-faults and service net-cord legal serves
- Required additional sensors to be incorporated
  - Directional microphones to detect a player's racquet striking the ball
  - Synchronized with player's foot triggering the "In" boundary-line sensor
  - Net-cord with piezoelectric sensor (a guitar pick) to detect touching of net
- Interesting combination of number of sensors working together
  - Service-line sensor + net-cord sensor + foot-fault sensor + microphone
  - Turned "on" together when a player served the ball
  - Turned "off" as opponent returned the ball

Electronic Line-Judge Experimentation

- Inaugural Grant-Hicks prototypes demonstrated in 1974
  - Service lines: Men’s World Championships, Dallas, 1974
  - + Net calls, all lines: Ladies’ Virginia Slims Championships, L.A., 1975
- Additional system demonstrated by David Lyle in Edinburgh, 1977
- **Neither Grant-Hicks’ or Lyle’s systems made it into commercial products**

Cyclops: Commercial Line-Judge System

- Invented by Bill Carlton and Margaret Parnis England
  - Focus only on service-line calls, but commercially successful
  - Introduced at Wimbledon Championships (1980), U.S. Open (1981)
- Different from the early experimental prototypes
  - Service-line judge turns the system “on” before each serve
  - Array of 5-6 horizontal infra-red beams, 1cm above ground
  - Loud beep noise whenever ball breaks beams beyond service line
  - False alarms due to insects flying in front of beams at times
- Moment of notoriety
  - Ilie Nastase, Wimbledon 1980
  - Went down on his knees to Cyclops to argue call

Cyclops

- Control box with service-line umpire
- Audible beep when serve was long
- Phantom beeps at times

“*I don’t want to sound paranoid, but that machine knows who I am*.”

John McEnroe to an umpire

Hawk-Eye

Hawk-Eye

- Invented by Dr. Paul Hawkins
    - System to track the real-time trajectory of a moving ball
    - Objective to display its most likely path as a moving image
    - Introduced for television viewing for cricket in 2001
- More of a computer-vision-based system
    - System of 6-7 high-performance cameras placed high above the court
    - Cameras track the players and the ball
    - Video data from the cameras is processed by computers
    - Video combined to create a 3D representation of ball trajectory
    - Processing takes into account player skid and ball compression
    - Accurate to within 5 mm

Hawk-Eye: Commercial Use

- Used in many sports
  - Since 2006 in tennis
  - Since 2009 in cricket (Umpire Decision Review System)
  - In 2013-2014 for the Premier League (goal-line technology)
  - In 2007 for snooker
  - In 2014 for the Australian Football League
  - In 2011 for the Gaelic Games
- The French Open is the only Grand Slam not to use Hawk-Eye

Hawk-Eye: Statistics

Inside Hawk-Eye

Hawk-Eye: Issues

- Computer vision is not without its challenges
- Indian Wells 2009
  - Quarterfinal between Ivan Ljubicic and Andy Murray
  - Hawk-Eye incorrectly called a Murray shot to be “in”
  - Turned out later that it had accidentally taken image of a second bounce
- Australia 2009
  - Match between Roger Federer and Tomas Berdych
  - Berdych challenged an “out” call
  - But Hawk-Eye did not work due to large shadow on the court

Not everyone is a fan

Yup, not everyone is a fan

Yup, not everyone is a fan

Hawk-Eye in Soccer

Cricket rules

A specific rule in cricket: LBW

Snickometer

- Invented by Alan Plaskett in mid-1990s
    - Snick = fine noise (sound made by a ball striking a bat, for instance)
    - Used by Channel 4 in the U.K. in 1999
- Sound-based system to determine if the ball has struck the bat
    - Record of sound and movement (video)
    - Graphical analysis of the sound and video combined
    - Humans listen to, and view, the recorded sound-wave shape
    - Different sound signatures for ball striking bat, ball striking batsman, etc.
    - Friction elevates local temperature and can be detected on a thermal map
- Used extensively in cricket, until replaced by Hot Spot

Snickometer

Hot Spot

- Invented by Nicholas Bion
    - Originally developed in the military for tank and fighter-jet tracking
    - Used first in the 2006-7 Ashes Test Match at The Gabba, Australia
- Infra-red system to determine if the ball has struck the ball, batsman or pad
    - System of 2 IR cameras on opposite sides of the ground above play
    - Continuously recording the images
    - Relies on the fact that the point of contact generates friction
    - Friction elevates local temperature and can be detected on a thermal map
- Important for specific play calls in cricket
    - Where a determination is made for LBW or player being dismissed

Overview of Technologies Used in Cricket

Umpire Decision Review System (UDRS)

- Introduced by the International Cricket Council
  - Introduced at an India vs. Sri Lanka game in 2008
  - Used to determine whether a batsman should be dismissed
- Three components in UDRS
  - Hawk-Eye
  - Hot Spot
  - Real-time Snickometer
- Typically, a non-match umpire sits separately and reviews all plays
  - Using the combined information from all components of the UDRS

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    - Using the combined information from all components of the UDRS

Hawk-Eye: Cricket vs. Tennis

In **cricket**, the system automatically calculates the following information:

- The speed of the ball leaving the bowler’s hand.
- The swing of the ball from the bowler’s hand to its ‘pitch’, or bounce
- How much the ball has bounced
- How much the ball spun sideways off the wicket
- A prediction of where the ball would have passed the stumps

In **tennis**:

- Hawk-Eye cameras are placed high above the court to track the ‘trajectory’ (or path) of the ball.
- It can point out the bounce of the ball up to the precision of 3.6mm.
- The cameras record the movement of ball at the rate of 100 frames per second.
- The Hawk-Eye System can incorporate more video replay cameras for analysis from different angles, which can be controlled remotely.

Hawk-Eye in Cricket

Soccer Goal-Line Technology

- July 2011, FIFA decided to test 9 different goal-line technologies
- FIFA President Sepp Blattner reversed his opposition to goal-line technology
    - After 2010 World Cup, 2nd-round, England vs. Germany
    - When Frank Lampard had a clear goal disallowed
- FIFA requirements
    - Recognition of free-shots on goal with 100% accuracy
    - Match referee must know within 1 second if a goal has been scored
    - Message must be relayed to referee’s watch
    - Message must be in the form of a vibration and a visual signal
    - Message must be received wherever the referee is in the field of play
    - System must work in daylight and floodlit conditions

FIFA and Soccer Goal-Line Technology

- FIFA has granted goal-line technology license to some of the technologies

- Adidas Cairos GLT
- Hawk-Eye
- GoalRef

Adidas’ Cairos Goal-Line Technology (GLT)

- Smart ball, i.e., sensor embedded inside a soccer ball
- Chip held in the middle of the ball via mechanical supports

Adidas' Cairos GLT

- Uses a magnetic field to track the ball
- Cables with electric current buried in the penalty box and behind goal-line
- Cables form a grid
- Ball sensor senses and measures the magnetic grid
- Ball sensor relays the data to a computer that processes the data
- Computer declares whether ball has crossed the goal-line
- Some interesting issues
  - Ball sensor suspended to withstand impact of kicking
- Cairos GLT got its license from FIFA in February 2013
  - Allowing this technology to be provided at FIFA competitions

Inside Cairos

GoalRef

- Developed by Fraunhofer Institute for Integrated Circuits IIS
- System based on a smart ball and a magnetic field
    - Passive electronic circuit embedded in the ball
    - Magnetic field around the goal (coils embedded in the goal frame)
    - Any change in the magnetic field is detected by the coils
    - When the ball completely crosses the goal-line, magnetic field changes

FIFA tests Goal-Line Technology

Goalminder

- Developed by two football fans, Harry Barnes and Dave Parden
    - Passionate about their team, the Bolton Wanderers
    - Conceived of the system after their team was wrongly disallowed a goal
- Focuses on providing better visual evidence
    - High-speed cameras built into the goal posts and cross bar
    - Records images at 2000 frames/second
    - Delivers visual evidence to the referee within 5 seconds
    - No calibration, no automated judgement, just better evidence
- Some advantages
    - Field does not need to be dug up
    - Cameras are getting cheaper and smaller

Inspiration for Research

- Pittsburgh vs. Indianapolis playoff game (January 2006)
- With just under five and a half minutes left in the game
- Steelers' safety Polamalu picked off Colts' quarterback Peyton Manning
  - Polamalu fumbled the ball and then recovered it
  - Referee Pete Morelli ruled that Polamalu never had control of the ball
  - Ball stayed in possession of the Colts
  - Colts continued, to score a touchdown
- The NFL later said that Morelli made a bad call

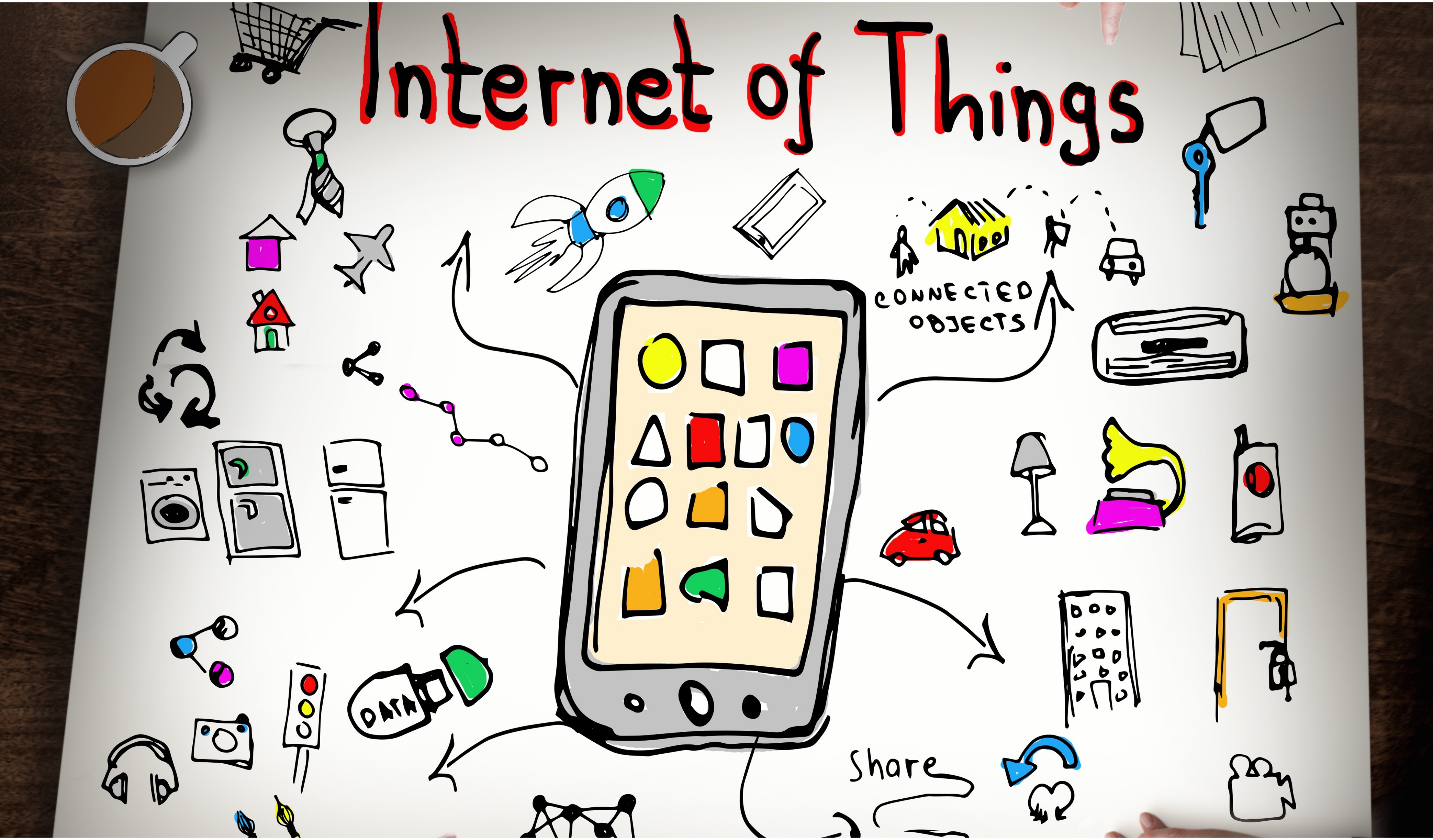
A Virtual Referee for (American) Football

- Concept
  - Using a collection of embedded devices
  - Including possibly ones mounted on the football itself
  - Possibly those mounted on players' uniforms or knee pads
  - Possibly on different yard lines and markers on the field

- Objectives
  - Can we tell when the ball "crosses the plane" for a touchdown?
  - Can we tell when the player "does not have full control of the ball"?
  - Can we tell the difference between "4th and inches" vs. a "1st down"?

A Virtual Referee for (American) Football

- What kinds of sensors do we need?
- RFID tags? GPS devices on helmets? Accelerometers on football?
- Where do we place the sensors?
  - On the field? If so, where?
  - On the players? If so, where?
  - On the football to create an “electronic pigskin”? If so, where?
- Localization algorithms that are accurate enough to
  - Identify the location and trajectory of the football with respect to field
  - Must have sufficient resolution to pick out the football vs. players
- Ensuring the torque and weight of the football is not impacted
- Environmental conditions and their impact on the system



Officiating Technologies in Sports

18-738 Sports Technology

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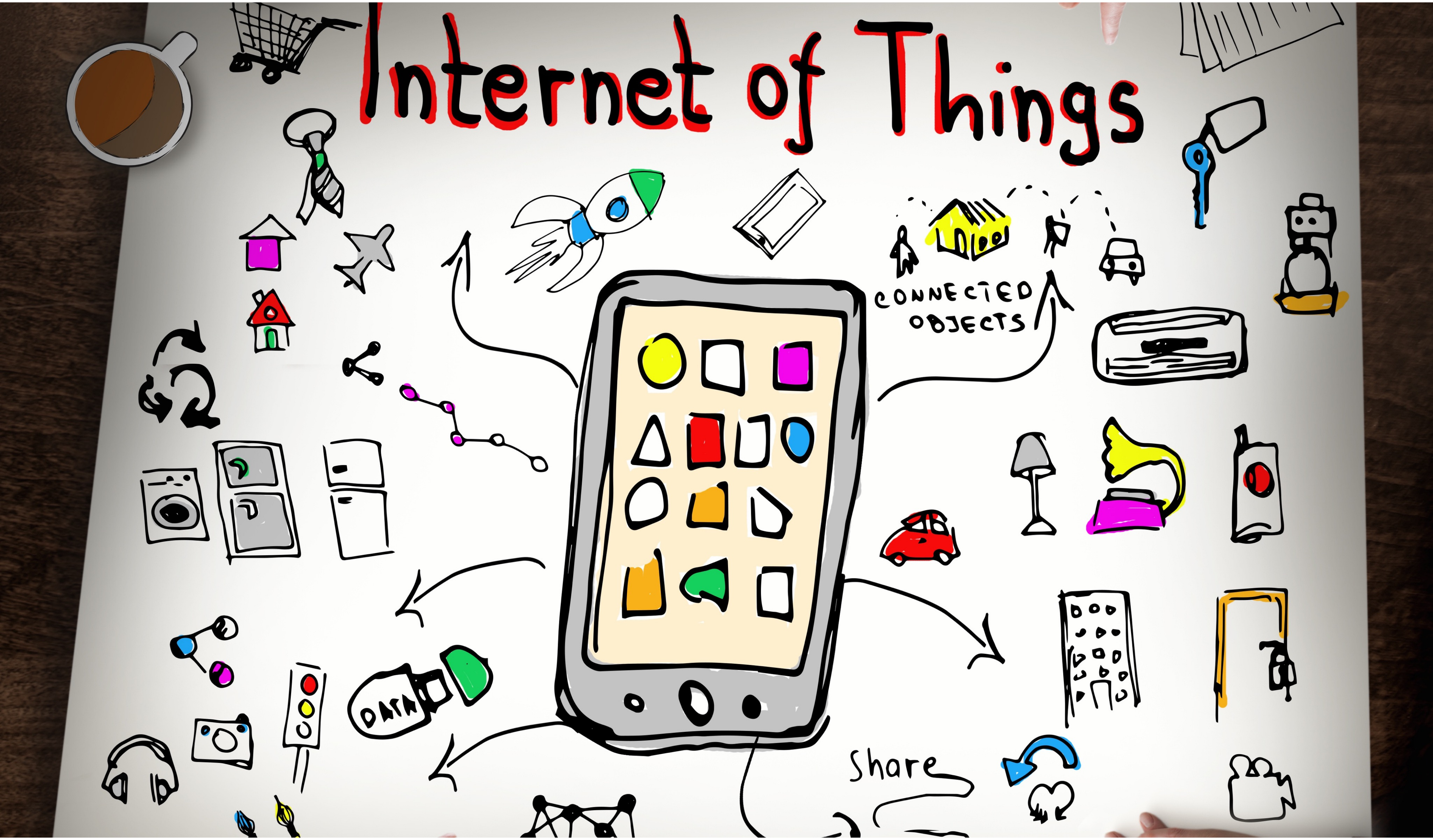

Safety and Performance

18-738 Sports Technology

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Overview

- Evolution of technologies for performance and safety
- Concussion and sideline testing
- Riddell’s smart helmet
- Reebook’s Checklight system
- Smart mouthguards
- Other efforts
- Research at Carnegie Mellon

Technology for Player Safety

Concussions (1)

- Most common type of mild traumatic brain injury (MTBI)
  - Head injury with temporary cognitive impairment, loss of brain function
  - Latin concutere = “to shake violently”
  - Latin concussus = “action of striking together”
- Causes
  - Blow to the head
  - Sports injuries
  - Car/bicycle accidents
  - Falls
  - Acceleration forces without direct impact (explosion nearby)

Concussions (2)

- Grades of concussion
  - Whether post-traumatic amnesia exists
  - Whether there is loss of consciousness
  - Whether subject exhibits confusion
  - Whether symptoms are exhibited
  - Duration of the concussion (5 minutes, > 24 hours)
- Symptoms
  - Headache, dizziness, vomiting, nausea
  - Lack of motor coordination, issues of balance
  - Light sensitivity, double vision, blurred vision
  - Convulsions, seizures

Concussions (3)

- Reported to be about 6 in 1,000 people
- Repeated incidents
  - Those who have had one concussion typically susceptible to another
  - Smaller impacts may trigger same severity
  - Increase risk for dementia, Parkinson’s disease, depression
- Recovery
  - Treatment involves physical and mental rest
  - Recovery typically within 3 weeks, but symptoms may persist

Diagnosis

- Lack of highly-noticeable symptoms makes diagnosis hard
- Concussion shares symptoms with so many other simpler injuries
- Athletes may minimize their injuries to remain in the competition
- 2005 study suggested that more than 88% of injuries go undiagnosed
- Diagnostics
    - Sports Concussion Assessment Tool (SCAT2) card
    - Brain-imaging scans
    - Check for unequal pupil-size
    - Neurophysiological tests
    - In sports, these are used to make the Return-to-Play (RTP) decision

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Sideline Evaluation

SCAT2 Cards

SCAT2 Cards

SCAT2 Cards

Graduated Return-to-Play (RTP) Protocol

Concussion Protection

- Rule changes in sports
  - Soccer studies show 50% of concussions due to limb-to-head contact
  - NHL: Introduced a Rule 48 “Illegal Check to the Head” in 2010-11
  - NFL: Play whistled dead as soon as player loses helmet, 2010
  - NFL: Players prohibited from using helmet to strike defenseless player
- Protective gear
  - Mouthgards
  - Helmets

Technology-Infused Gear

- Riddell's SpeedFlex smart helmet
- Reebok's Check Light
- Battle Sports' Impact Indicator
- Shockbox
- BiteTech's Smart Mouthgard

- None of these technologies diagnose concussions
- All of them aim to provide some kind of alert for hits/impact

Riddell's Smart Helmet

- Riddell's InSite System
  - Riddell's Head Impact Telemetry System (HITS)
  - Set of 5 sensors that can be embedded into a helmet
  - Wireless communication to coach's sideline devices
  - Player Management Software, to allow offline analysis

- SpeedFlex added polymer-film lining that develops a charge under impact
- Helmet contains a flexible panel that compresses on impact

Riddell's Smart Helmet

Reebok’s Checklight

- Reebok’s Checklight System
  - Black skullcap embedded with sensors, worn by players under helmet
  - LED light indicator that dangled under the helmet as a small “tail”
  - LED was normally green, would flash yellow/red for abnormal impact

- Checklight showed demonstrated value for a 13-year old player
- Uses pliable sensors embedded in fabric
- Combination of accelerometer + gyroscope
- Accelerometer measures initial impact
- Gyroscope detects/measures “aftershock” effect
- Visible indicator, no wireless communication to sidelines

Do These Actually Work?

Battle Sports Science's Impact Indicator

- Impact Indicator System
  - Accelerometers embedded in the chin-strap of the helmet
  - To determine the force, duration, direction of every hit on player
  - Blows with >50% chance of head injury activate the chin-strap light
- Patriots' BenJarvus Green-Ellis wore in the Super Bowl XLVI

BiteTech’s Smart Mouthguard

- BTX2 Impact Sensing Mouthguard
  - Accelerometers and gyroscopes embedded in mouthguards
  - To determine the force of head impacts on players
  - Data wirelessly transmitted to computers on the sidelines
  - Synchronized with the video of the play
  - Used for data collection with Stanford University football team

Mouth-guards for concussion detection

Shockbox

- Shockbox
  - Helmet g-force sensor, measures impact on player
  - Alerts of need for a medical assessment
  - Flexible strip with electronics with Bluetooth transmitter and battery
  - Can be embedded into the padding of any helmet (used for any sport)
  - Color-coded alerts sent to a mobile app (orange: >50g, red: >90g)
  - 128 Shockboxes can be tracked at once (useful for coaches)

xPatch

- Impact-sensing skin patches
  - Similar technology but miniaturized into a skin patch
  - Measures linear and rotational impacts

Breath Tests for Concussion

- Three chemicals that are released into the blood stream on a player's injury
    - Developed at the University of Birmingham
    - Molecules make their way into the lungs
    - Can be detected via a breath-test
    - Currently under test for rugby and soccer
    - Additional machine that uses magnetic pulses to detect brain damage

Our Class Project

Technology for Player Performance

Fitness Trackers

- Watches for runners
  - Garmin, Nike, Timex
  - + wearable sensor: Footpod sensor for more accuracy
  - + wearable sensor: Heartstrap for measuring heartrate
- Activity trackers for everyone
  - Fitbit, Jawbone Up24, Nike Fuelband, Basis wristband
  - Adidas miCoach smart wristband
- Pedometers
  - From a variety of organizations

MC10‘s BioStamp

- MC10 is the company that developed Reebok’s Checklight system
- Biostamp: Wearable stretchable electronics
    - Looks like a thin wearable band-aid that can be affixed to your body
    - Input from athletes on what to monitor for recovery, performance
    - Athletes (e.g., Grant Hill) serve on the Advisory Board
    - Players can simply stick on multiple Biostamps wherever they want
- What can it measure?
    - Heart-rate, hydration

Catapult's OptimEye

- Catapult Sports
    - Australian company making wearable devices used in sports
    - Rugby, soccer, Australian-rules football, rowing, now the NBA, NFL
- Matchbook-size GPS tracking device called OptimEye
    - Small wearable sensor fitted to player's jersey on their upper back
    - Tracks player's position in 3D space
    - Accelerometers, magnetometers, gyros track load, distance, direction
    - Uses filters to process data to determine athlete's direction for each step
    - For indoors, internal stadium antennas to pick up the signals

Catapult

Catapult's OptimEye

And, FIFA, too …

SportVU from STATS LLC

SportVU from STATS LLC

SportVU from STATS LLC

- Information stored in a database
  - Interactive Collaboration and Evaluation (ICE)
  - Data and statistics shared across NBA teams using the service
  - Scouting reports/analysis kept private to each team
- NBA scouts use this on a regular basis
  - Accessible via mobile/tablet worldwide
- NBA trainers starting to use this
  - For fitness monitoring

SportVU

SportVU

SportVU Challenges

- Expected challenges due to computer vision
  - Shadows on the court
  - Dark colors on the court
  - Detecting players’ jersey numbers
  - Accommodating uniform/jersey changes

Wilson Connected Basketball

- Contains a sensor to track shots
    - Tracks how many hoops
    - Tracks how many misses
    - Does not track passes or dribbles
    - Only tracks shots at least 7ft from the hoop
    - Only works with a regulation 10ft hoop (no additional technology)
    - Built-in battery to last more than 100,000 shots
    - Saves data for later
    - Connects via Bluetooth to a mobile app

Wilson Connected Basketball

Wilson Connected Basketball

Zepp: Improving your Golf Swing

- Wearable Zepp sensor + Zepp GolfSense app
  - Senses swing, speed, angle; creates virtual 360-degree replay of swing
- Three-axis MEMS gyroscope
  - Pitch (up/down tilt), yaw (left/right twist), roll (longitudinal spin)
- Two accelerometers
  - Measures the g-forces due to golf swing (two for improved accuracy)
- Combination of 1,000 data points per second
  - ARM processor helps to analyze, send data via Bluetooth to app
  - Helps visualize your game/play, and improve your swing
  - Gyroscope (if in pocket) measures hip rotation, provide tips to improve

Improving your Golf Swing

Bat Sensors for Baseball

Athos' Connected Apparel

- Clothing (workout pants, full-body suit) embedded with
  - Tiny sensors to measure muscle output, heart rate, respiration
  - Data is transmitted to a small wearable module, synchs with app
  - As user moves, activity measured on skin, converted to data
- User is provided with a "muscle-effort score"
  - Indication of how much you are pushing yourself
  - Provides data on whether stretching/lifting is being done correctly
- User is provided with a heart-rate activity indicator
  - Indication of if you are in the right heartrate zone to improve fitness
- Can also track reps and workout time

Athos' Connected Apparel

Zebra MotionWorks

- RFID tags affixable to any game asset
    - Quarter-sized RFID tags can be affixed to players' equipment
    - UWB (ultra-wideband, 500Mhz-1GHz) with range of 300 feet or so
    - Location granularity is claimed to be within 6 inches or so
    - 12-30 installed antennas/receivers placed around the stadium
    - Receivers pick up the data
    - Analyze player's location, speed, direction of movement
    - Analysis and visualization done by sideline equipment
- Used primarily for coaching and scouting right now

Zebra MotionWorks

Zebra MotionWorks

We got to use the data!

Biggest Debates

- Who owns the data?
  - Source of concern for athletes
- Questions
  - Line between fan engagement, performance and athlete privacy
  - Would the data be used in contract negotiations?
  - Would the data be used to decide who's in the starting line-up?
  - What if fans/coaches could "see" a field-goal kicker's stress?
  - What if it's too much information, and detracts from a player's instinct?
- Additional considerations
  - Quality of the data, quality of the device
  - Device non-invasiveness/comfort with respect to playing the game

Ways in Which Analytics Will Change Sports

- #1 Better officiating
    - Umpires rely on eyesight to call a strike or ball in baseball
    - Sportvision’s Pitchf/x has been installed in 30 MLB ballparks
    - Goal is to track pitches during a game
    - Two 60Hz tracking cameras
    - Each records pitch from leaving player’s hand to crossing the plate
    - Sends data to calculate speed, location and trajectory
    - Data is used for a variety of purposes, including broadcast
    - Attempts to classify curveball, fastball, etc.

Ways in Which Analytics Will Change Sports

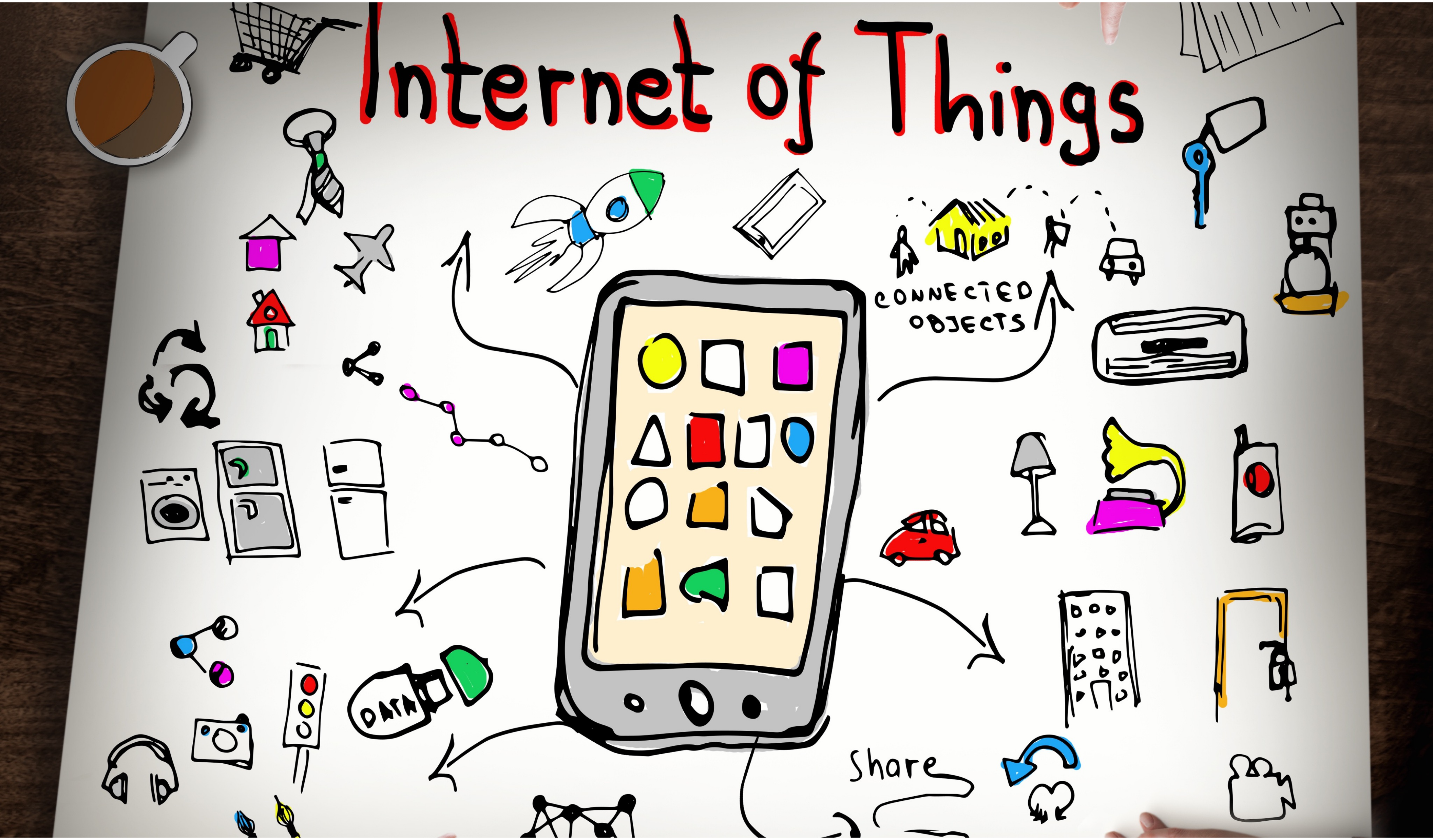
Ways in Which Analytics Will Change Sports

- #2 Incorporating data from wearable devices
  - Wearable data from players to track human activity/wellness
  - For scouting, fitness tracking, recovery, game-day readiness
  - For injury prevention, for injury detection/diagnostics
  - We’ve covered quite a bit of this in our lectures
- #3 Live on-field game-data collection
  - Game moves so fast it’s impossible for humans to keep up
  - Every asset on the field is becoming trackable
  - SportVU and Hawk-Eye, for example

Previous Course Projects

- Helping kids play soccer better
  - Outfitting cleats with sensors to provide audible/visual feedback
- Smart watch for visualizing your golf swing
  - Aim to reconstruct the 3D play and provide audible/visual feedback
- Visualizing plays
  - Quarterback to visualize the play on his armband
- Embedded slow-motion glasses
  - To be able to view the play in front of you, in slow motion

End of Class: A Sports Science Nugget



Safety and Performance

18-738 Sports Technology

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The Stadium of the Future

18-738 Sports Technology

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Wireless Technology

- Wireless inside stadiums
    - The need for having connectivity for fans has increased
    - Fairly recent (last 5 years) initiative

Wireless Technology

- Driven by what fans’ consumption patterns
- Let’s look at Super Bowl XLVIII in New Jersey, 2014
    - Peak usage: 13,500 (of 85,529 fans possible) connected over Wi-Fi
    - 3.2 terabytes of data was transferred over the Wi-Fi system
    - Facebook, Instagram and Twitter responsible for 10% of bandwidth
    - 60% of connected fans shared on Facebook, 18% Twitter, 17% Instagram
    - > 90,000 photos were uploaded to Instagram over Wi-Fi by devices
    - 18% of devices were running software updates
    - Peak usage of Wi-Fi was during the halftime show
- Increased move towards high-density Wi-Fi networks inside stadiums
- Increased discussion of multicast vs. unicast

Wireless Technology

DAS

- DAS = Distributed antenna system
  - Network of spatially-distributed antennas connected together
  - Think of a 4G cellular tower broken up into pieces, but distributed indoors
- Replace single antenna radiating at high power with
  - Collection of low-power antennas to cover the same area
- What are the advantages?
  - Less power wasted in overcoming shadowing losses
  - Line-of-sight channels easier to accomplish
  - Provide higher bandwidth, better coverage
- What are stadiums using?
  - DAS with Wi-Fi offload

Frequency Coordination in Stadiums

- Most stadiums have an appointed frequency coordinator
  - Challenge to “cram 500 MHz of users into 25 MHz of spectrum”
- Examples of too many people using the same channel/frequency
  - Airline pilots’ conversations (overhead flights)
  - Doppler radar from local weather stations
  - Concession worker requesting additional popcorn supplies
- What is done on game-day?
  - Root out unregistered devices with spectrum analyzer, direction-finders
  - Use time-division and (physical) space-division multiplexing
  - Prioritize the ones that matter (coaching system, under-the-hood review)
  - Provide backups for critical ones (100ft wire for coach-to-coach comms)

Instant Replay

- Concept invented by Tony Verna in 1963, to improve the telecast
  - Did not receive a patent/payment for his invention
- Army-Navy game, December 7, 1963
  - Verna had quietly brought with him a giant videotape machine
  - He had a roll of videotape in the machine (“I Love Lucy,” in fact)
  - He was hoping to capture a play and then play it back
  - He captured the touchdown play and it was aired
  - “This is not live! ... Army has not scored again,” the announcer shouted
  - By 1990s, instant replay for football, basketball, hockey
  - In 2014, baseball expanded to umpire challenges

Instant Replay (invented 40+ years ago)

What does in-stadium wireless enable?

Courtesy: YinzCam, Inc., Pro Bowl 2015

Mobile Replays at the Super Bowl

The Advent of Bluetooth LE

- BLE is a wireless personal area network technology
- Reduced power consumption without sacrificing communication range
- Called Wibree by Nokia in 2006, then named Bluetooth Smart, then BLE
- By 2018, 90% of Bluetooth smartphones expected to support BLE
- Can operate in an advertisement mode to notify nearby devices of presence
- Transmit a UUID
- Bluetooth profiles
  - Healthcare profiles: Blood Pressure Profile, Glucose Profile, ……
  - Fitness: Cycling Power Profile, Running Speed Profile, …..

The Advent of Bluetooth LE

- Ideal for applications that require episodic transfer of small amounts of
- Client-server model
- The client wants data (client is typically a smartphone)
- The server has data (server is typically a sensor)
- Bluetooth Smart: Stand-alone BLE sensors (single-mode)
- Bluetooth Smart Ready: Both BLE and Bluetooth Classic (dual-mode)

Bluetooth vs. Bluetooth LE

- Just like Bluetooth, BLE operates in the 2.4 GHz ISM band
- Both do Adaptive Frequency Hopping
- Bluetooth hops across 79 channels at 1MHz each
- BLE hops across 40 channels at 2MHz each
- Unlike classic Bluetooth, BLE remains in sleep mode constantly except for when a connection is initiated
- Actual connection times are only a few milliseconds, unlike Bluetooth which would take ~100 milliseconds
- Bluetooth can handle a lot of data, but consumes battery life quickly
- BLE is used for applications that do not need to exchange large amounts of data, and can therefore run on battery power for years

Device Discovery

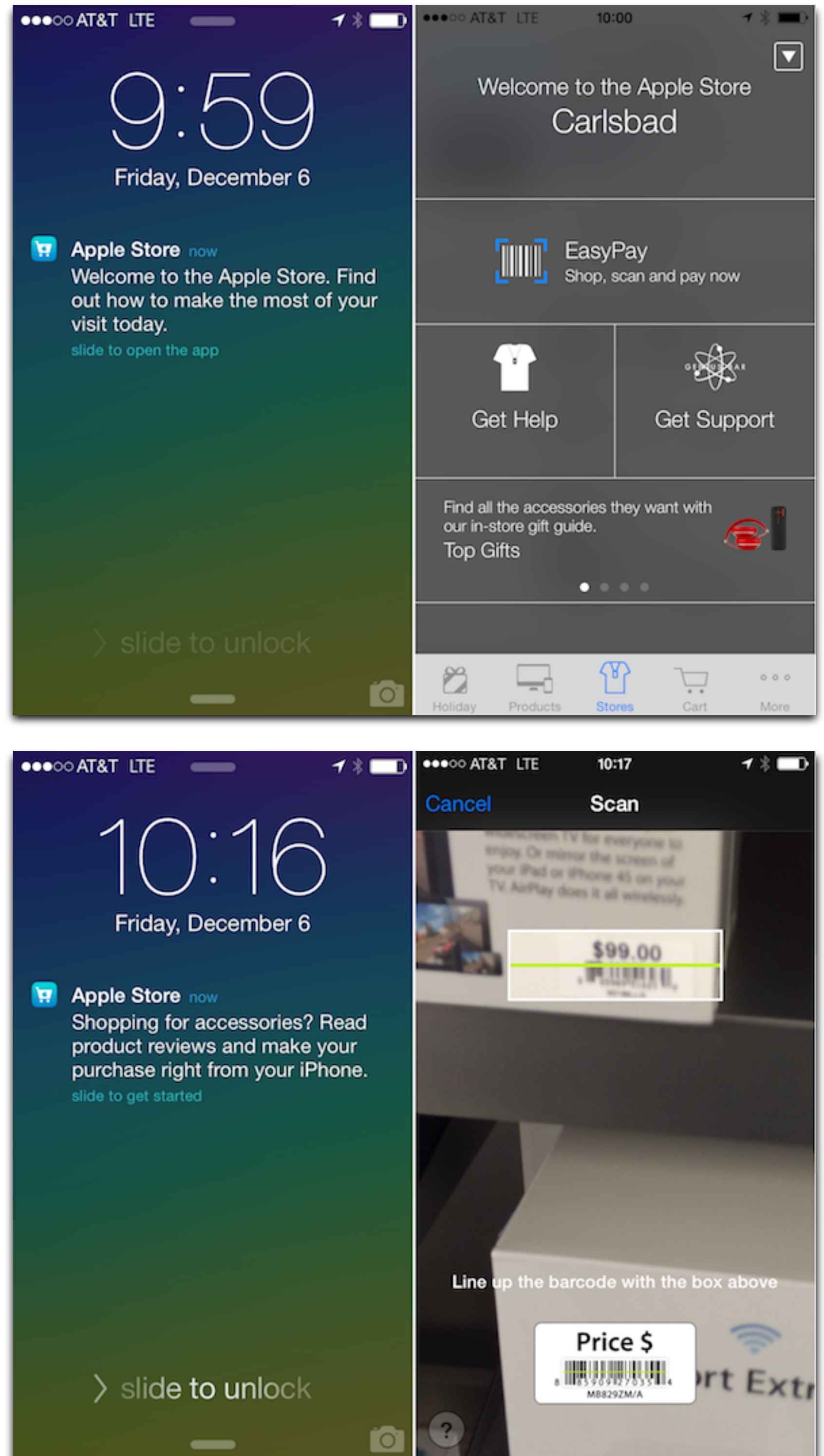
- Devices are in sleep mode until an advertisement is initiated

Device Connection

- When connected, then, the devices communicate by polling at intervals
- Application determines the polling interval

What is iBeacon?

- Announced by Apple in 2013, as a part of iOS7
- Fine-grained location services
- To increase foot traffic to stores
- To reduce showrooming
- Installed in 250+ Apple stores
- To create experiences around physical locations, such as ...



Let’s Go Behind the Scenes

Yet another location service? But why?

- Yes, our phones have maps
- Great for getting to a building, but stops short after that
- Accuracy via a combination of cellular, GPS, Wi-Fi
- Accuracy off, much worse in urban areas, in buildings
- No sense of proximity
- No micro-location

Location vs. Proximity

- **Location** is often represented by a point and a radius
- **Proximity** is the fact that you are close to a specific physical location
- "I'm waiting at the bar"
- "I just entered Gate 3 at the stadium"
- "I'm standing in front of a shelf of jeans and jackets"

More on Proximity

- Transmitter is a beacon, receiver is a phone app
- You can initiate actions based on signal strength
- You can initiate actions “next to,” “nearby,” and “far” from a beacon

Beacons vs. NFC

- Beacons are small wireless devices that transmit data to smartphones using Bluetooth LE (Low Energy)

- NFC uses short-range radio waves to allow two devices in proximity to exchange data

- Not all phones have NFC

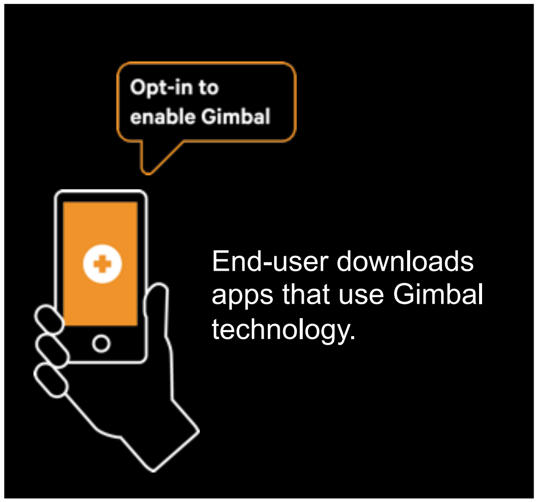
- Most phones have Bluetooth

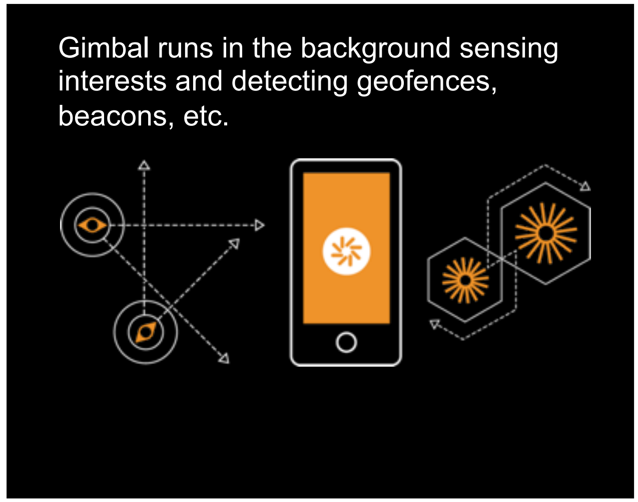
Beacons vs. NFC

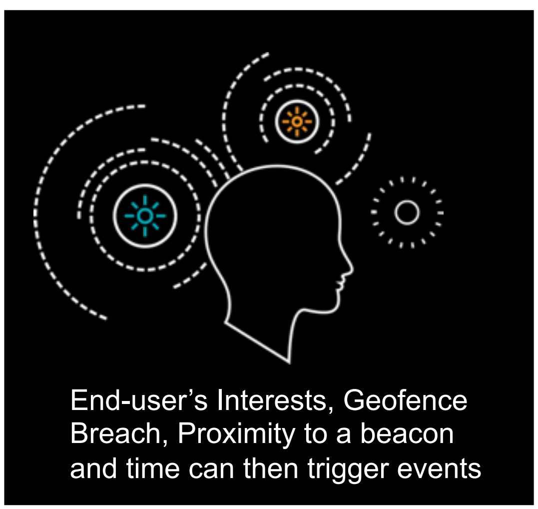
- BLE Beacons continually transmit a discovery signal received by BLE-enabled smartphones
- NFC tags only communicate when close to an NFC-enabled smartphone
- BLE beacons’ coverage radius can be multiple feet/meters
- NFC tags’ coverage radius is centimeters

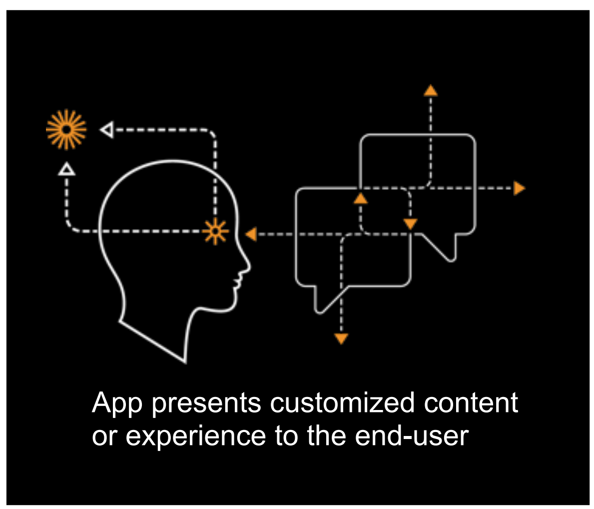
Here a Beacon, There a Beacon

How Beacons Work (from Qualcomm/Gimbal)









What about Privacy?

- Opt-in, always
- Opt-out with deletion of data
- Dictate which apps have access to which beacons
- Configure/register/unregister beacons
- Configure notifications
- Configure geofences

Connect Physical to Digital

Several industries are using beacons to change the game

Domains of Interest

Domains of Interest

How everything works together

Retail (65%)	Travel & Sports (30%)	Home Automation (5%)

400M beacons out there (as of May 2014)

Airline Industry

- Virgin Atlantic trials in Heathrow Airport club area
- Information about flights, delays
- Reminders for boarding
- Reminders of perks

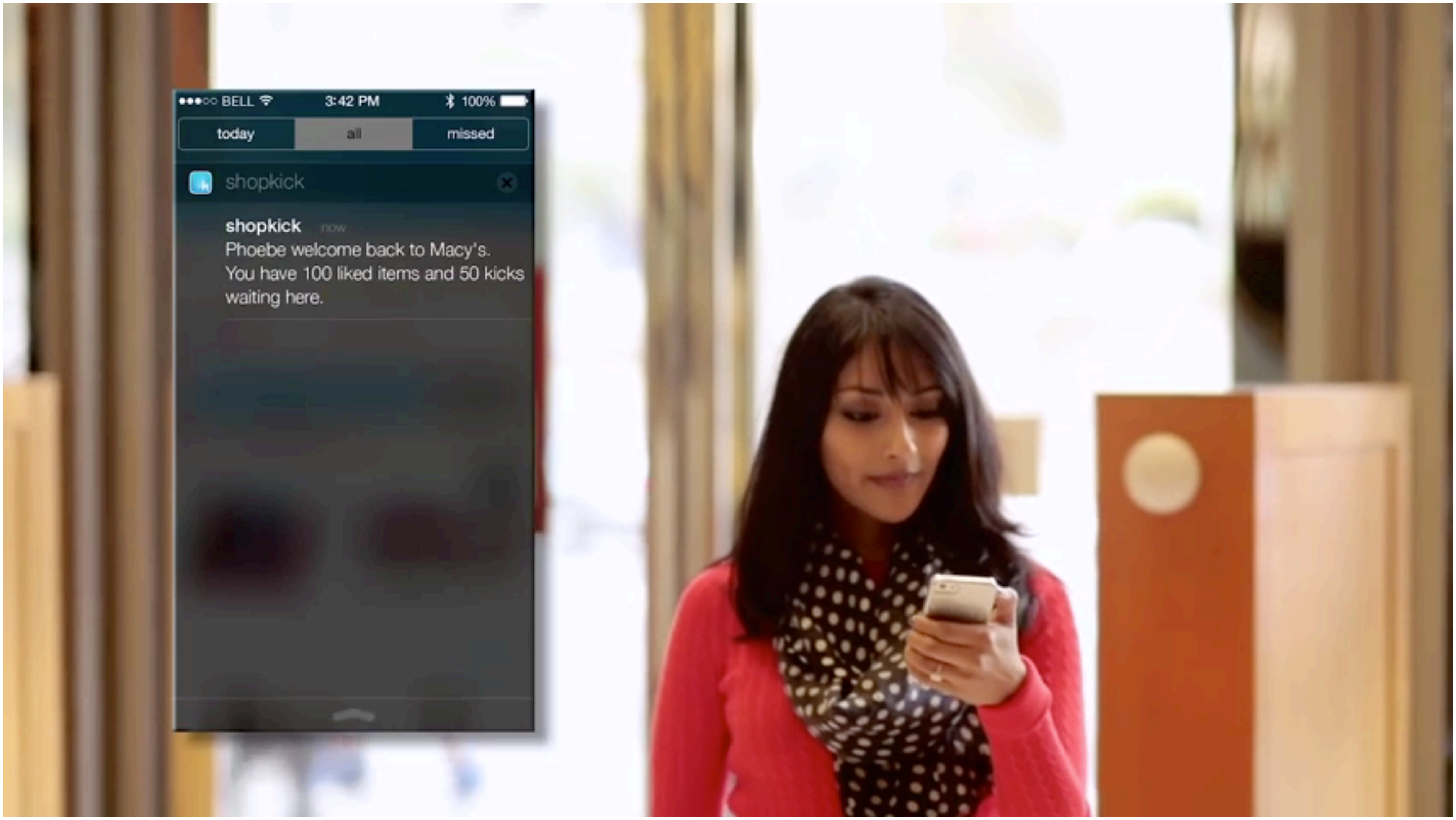
Mobile Payments

- Paypal beacons installed in stores, restaurants
- Works with the PayPal smartphone app
- Seamless, location-aware payments
- No card, no cash, no contact

Mobile Payments

Retail Industry

- Beacons installed in several stores and warehouses
- Works with the store app
- Offers, discounts, loyalty programs
- Incentivize spot purchases



In-Store Experiences

Smart Cities

- Beacons installed in cities, e.g., New York City
- Works with the city app, retailers' apps, transportation apps
- Information about attractions
- Transportation information

In-Store Experiences

Sports Industry

- Beacons installed in several stadiums and venues
- Works with the venue/team/league app
- Experiences associated with physical artifacts (hall of fame)
- Loyalty programs, season-ticket holder experiences

Interactive In-Stadium Experiences

In-stadium congestion

Wait-times

VIP areas

Interactive exhibits

Out-of-stadium
ingress, egress &
parking congestion

Beacon-Activated Fan Journey

Check-ins

- Enable fans to checkin on gameday

- “Construction on Route 39”
- “Tailgating starts at lot 4”
- “Don’t miss halftime show”
- “Kickoff in 5, head to your seats”
- “Welcome to the Ford Sideline Club”

- Selfies made easy

Offers

- Enable fans to know of merchandise

- “10% off team jersey”
- “Top selling jersey is #54”
- “Stop by for your free bobblehead”
- “Employee discount of 30% today”

Line-Busting

- Enable fans to know of wait-times
- Discounted offers for concessions
- Knowledge of new concession items

Experiences/Content

Competing Technologies (Visible Light)

Competing Technologies (Visible Light)

The Stadium of the Future

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IoT + The Fan Experience

18-738 Sports Technology

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The Hockey Puck

- Flat, solid, black disk-shaped objects made of vulcanized rubber
- Regulation National Hockey League (NHL) pucks:
  - Black in color
  - 3 in (7.6 cm) in diameter, 1 in (2.54 cm) thick
  - Weigh 5.5-6 oz (154-168 g)
  - Edge has a series of "diamonds," slightly raised bumps or grooves
  - Diamonds give a hockey stick something to grip when the puck is shot
- Each team has a freezer of pucks at all times (frozen to reduce bounce)
  - Team receives a supply of pucks at the beginning of each season
  - Rotated so that the older pucks are used first
  - Pucks are kept frozen in an icepacked cooler on the officials’ bench

The Hockey Puck

The FoxTrax Puck

Something Old, Something New

What did the viewer see?

Design #1: Finding the Puck

Design #1: Overlay on Broadcast Footage

Hockey Arenas and RF

Lessons Learned

Relevant Detour: Infrared (IR)

Design #2: How about going all IR?

Design #3: Modified radar approach

Final Solution: Free-running IR emitters

The Puck Truck

Sync Detection System (1)

Sync Detection System (2)

IR cameras

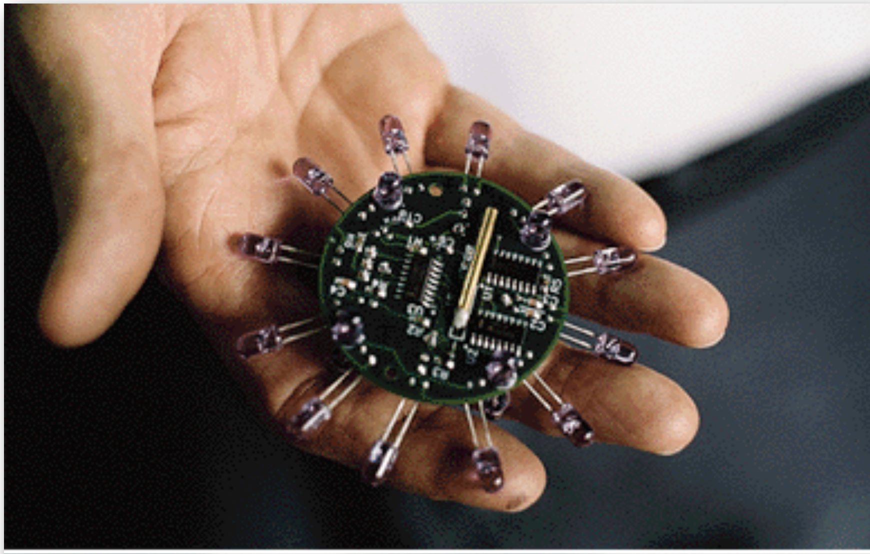
IT infrastructure

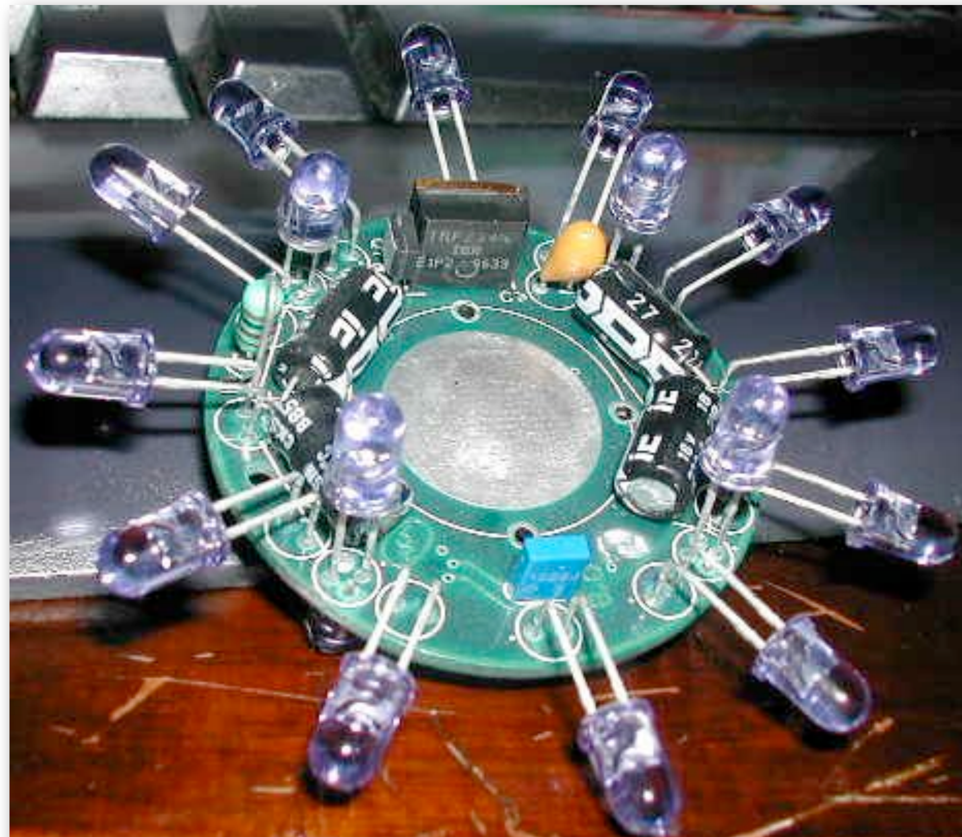
Final deployment

As for the puck itself

Electronic Puck

Final packaged product





The Puck Truck

- 40-foot "semi"
- Wired to the arena to collect all the necessary data
- Wired to Fox's production truck to receive the video signal and information about which broadcast camera or replay deck is on the air

Up-front calibration of the system

- Must know the location of each IR camera, the broadcast cameras, and the dasher boards that surround the ice
  - First established a 3D coordinate system in the arena
    - Origin of this system is placed on the center face-off circle with the X and Y axes on the ice and the Z axis pointing straight up
- Drill 9 small holes in the ice and filled them with freezing ice paint
  - Measured the distance between each of these marks and from several of these marks to the dasher boards with a laser range finder
  - Established the rink's dimensions and coordinate system relative to the rink
  - Placed an active puck on each mark at a time while taking note of its image in each of the IR cameras
  - Computed the position and orientation of each IR camera.
- Found and marked the optical axis of each broadcast camera (in 1X and 2X mode), point it at each ice mark, and solve for its location
- Calibrated the narrow-pass filters to eliminate spurious local IR interference
- Calibration took 3 hours, wiring the arena took 2 long days

Fear, adrenalin, no sleep

The system was finally "ready for prime time"—or so we thought. We had performed three demos for Fox Sports executives at various stages of development. Despite many long nights and a well-founded fear of failed demos while living in the rafters at the San Jose Arena, our final demo in San Jose was a genuine success.

Next we would experience fear and loathing in New Jersey: The electronic puck was scheduled for its first official NHL game (though the effect was not to be aired) when we learned that the real world is truly a cruel place. We had hoped to do arena surveys during development, but simply did not have the time. Now we found the east coast shut down by the biggest snowstorm in anyone's memory and could not get ourselves or the trucks to the Continental Arena in N.J.

When we finally arrived, we wished we hadn't. The entire development team put in a 24-hour shift culminating in a live demo that did not go well. Even during the game, we were modifying software and hardware to try and salvage the system. By the end of the event—when all we could track was a Zamboni—we realized that the IR environment at the Continental Arena (like some of the other older arenas) was truly hateful to our system.

We packed up and escaped like thieves in the night, headed for the much newer Boston Fleet Center, where the system was to debut in one week during the NHL All-Star game. While the environment was generally much better in Boston, we had not anticipated everything from laser lights to fireworks. Nevertheless, with some delicate conditioning we had the system up and running with two days of margin before the game. David Hill used this time to call a press conference where the system was demonstrated publicly for the first time. The resulting national coverage over the next three days was breathtaking. Two days after the system operated successfully at the press conference, it performed well at the All-Star game—and everyone exhaled.

[Rick Cavallaro, CTO, Sports Vision]

End-result

Public reaction

- New fans enjoyed it since they could follow the game more easily
- A Fox Sports survey found that 7 out of 10 respondents liked the new puck
- On the other hand, hockey purists hated it
  - Argued that the video graphics were a distraction and turned hockey into a video game
  - Claimed it really should not be that hard to see a black puck on white ice
- Pucks were too pricey and not available to players for practice
- Sportswriter Greg Wyshynski (Puck Daddy of Yahoo! Sports) called it the second-worst idea in North American sports history in his book *Glow Pucks and Ten-Cent Beer*
- Not used any more today

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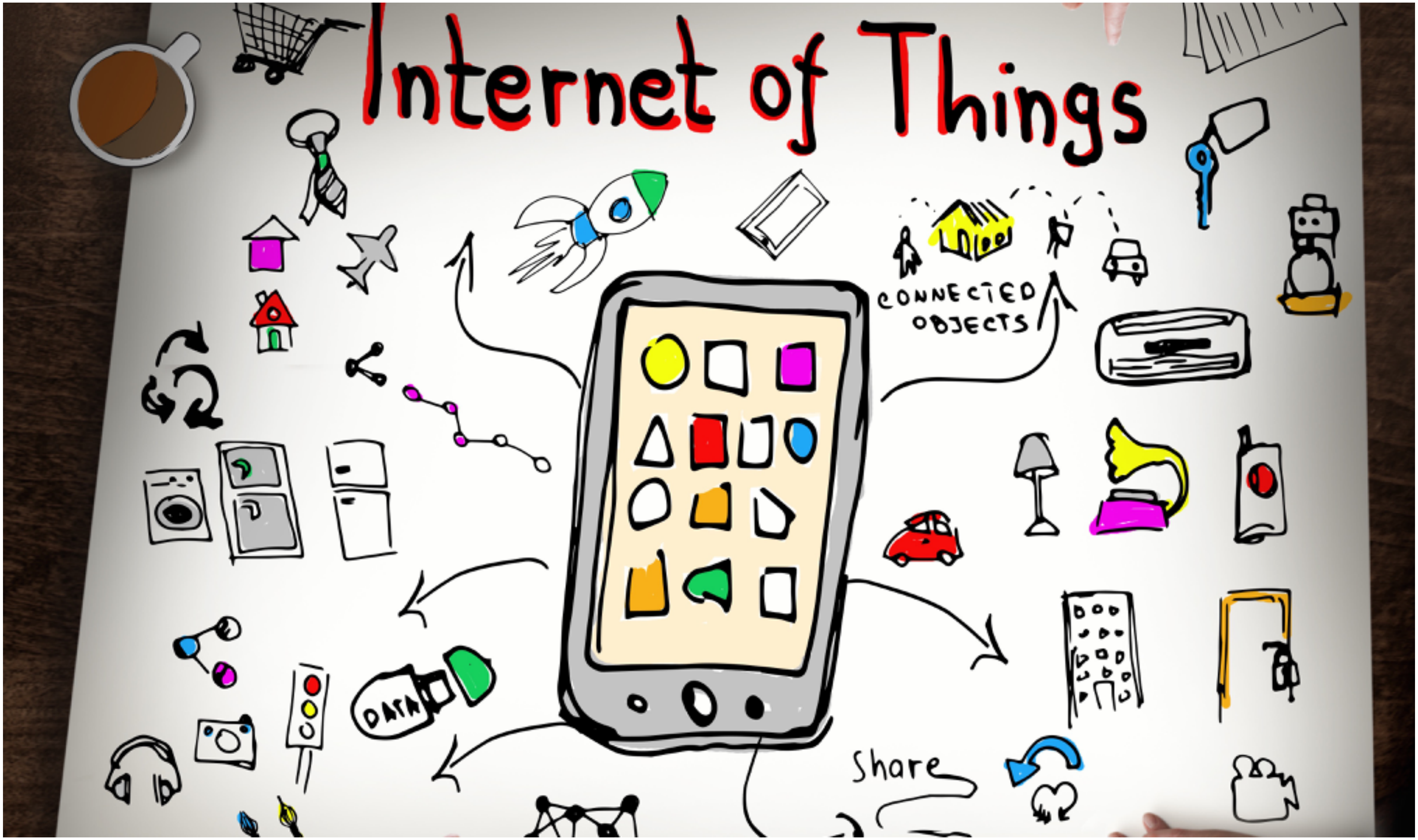

IoT Protocols

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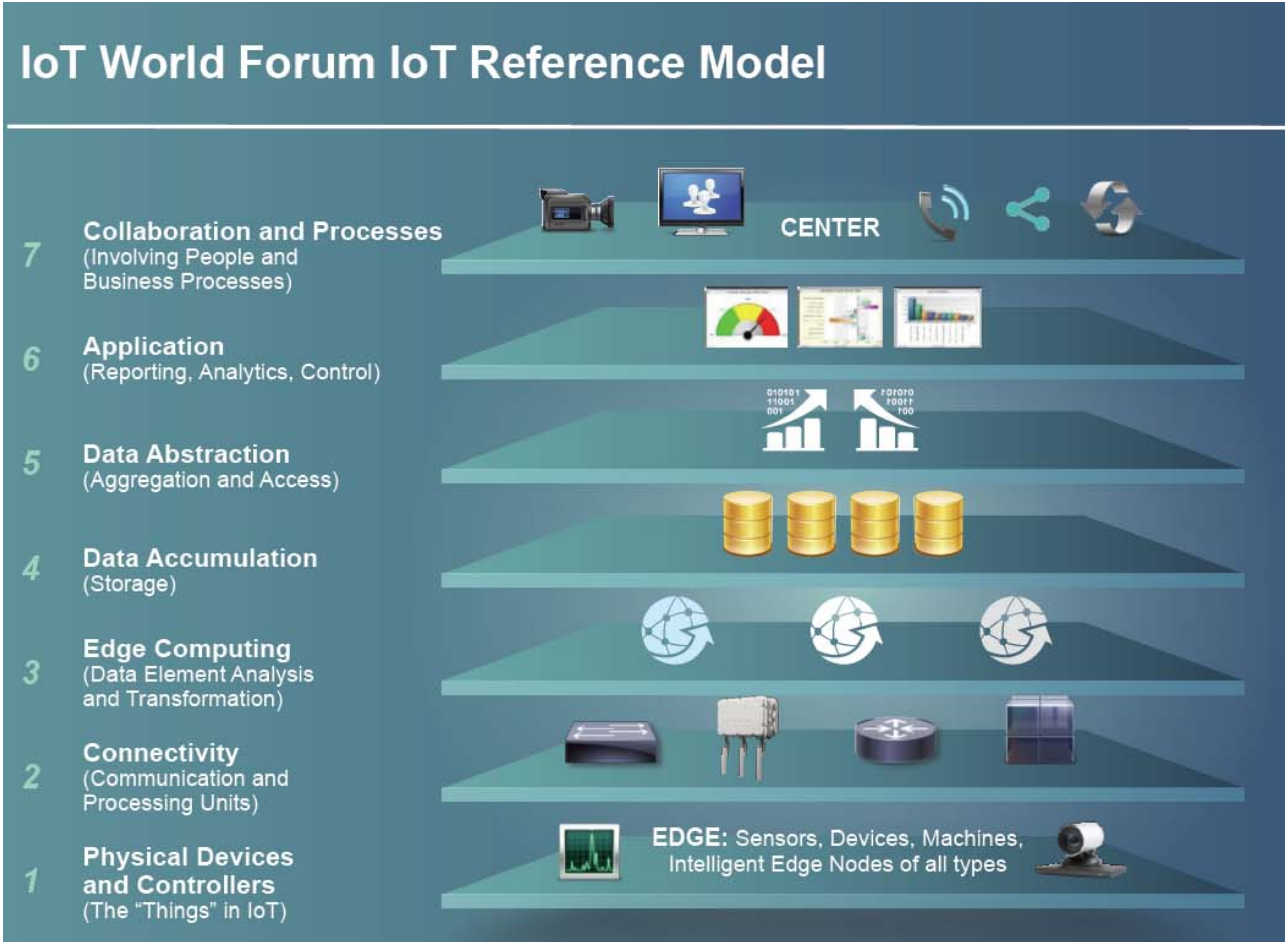
Overview of Lecture

- Bluetooth
- Protocol basics
- Architecture
- Piconets, scatternets
- Service discovery

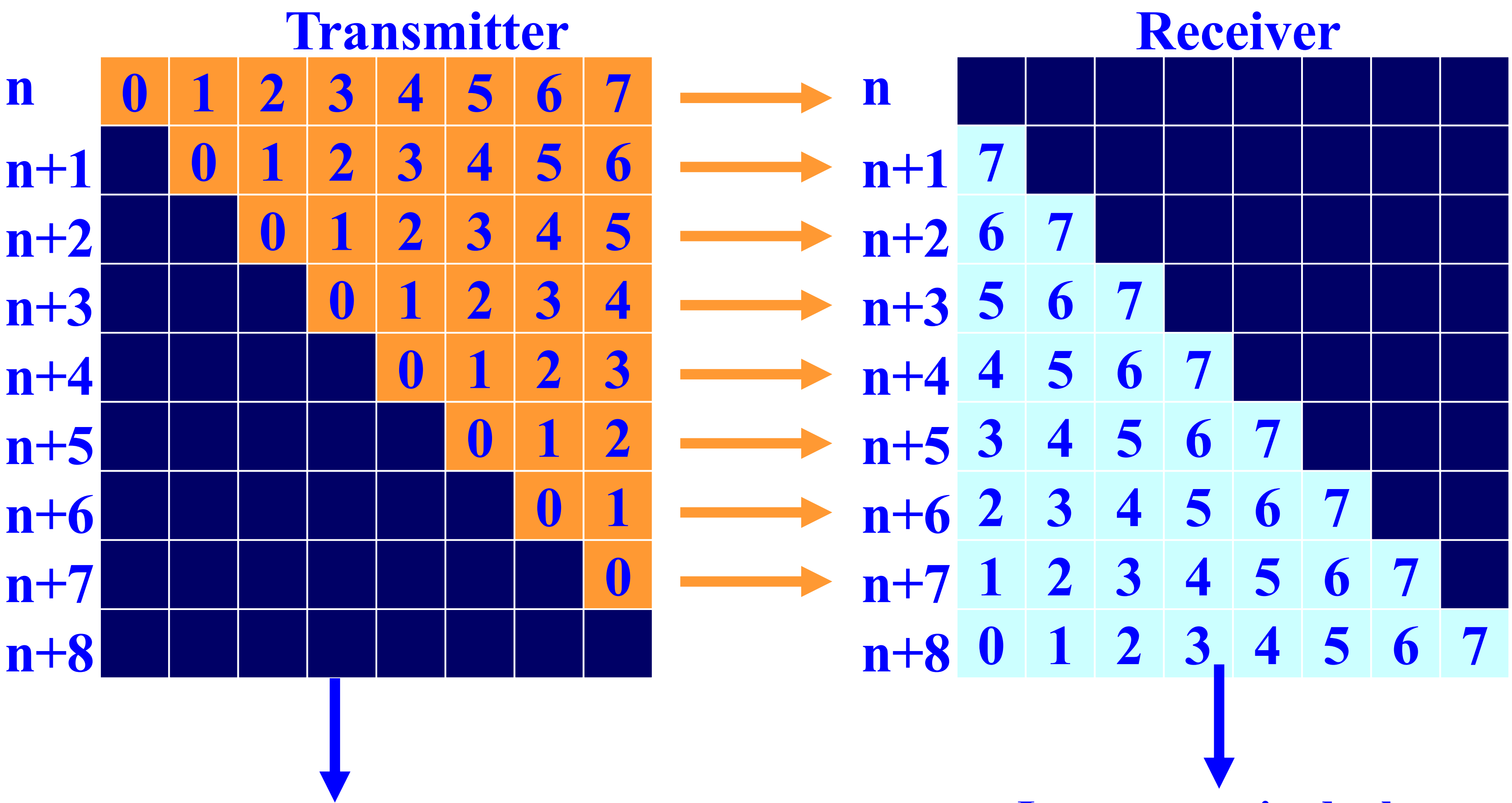

IoT World Forum IoT Reference Model
7
Collaboration and Processes
(Involving People and Business Processes)
6
Application
(Reporting, Analytics, Control)
5
Data Abstraction
(Aggregation and Access)
4
Data Accumulation
(Storage)
3
Edge Computing
(Data Element Analysis and Transformation)
2
Connectivity
(Communication and Processing Units)
1
Physical Devices and Controllers
(The "Things" in IoT)
CENTER
EDGE: Sensors, Devices, Machines, Intelligent Edge Nodes of all types

Why Serial Communication?

- Serial communication is a **pin-efficient** way of sending and receiving bits of data
  - Sends and receives data one bit at a time over one wire
  - While it takes eight times as long to transfer each byte of data this way, only a few wires are required
  - Typically one to send, one to receive, and a common signal ground wire

- **Simplistic** way to visualize serial port
  - Two 8-bit shift registers connected together
  - Output of one shift register (transmitter) connected to the input of the other shift register (receiver)
  - Common clock so that as a bit exits the transmitting shift register, the bit enters the receiving shift register
  - Data rate depends on clock frequency and number of bits transmitted

Simplistic View of Serial Port Operation



Interrupt raised when
Transmitter (Tx) is empty
⇨ Byte has been transmitted
and next byte ready for loading

Interrupt raised when
Receiver (Rx) is full
⇨ Byte has been received
and is ready for reading

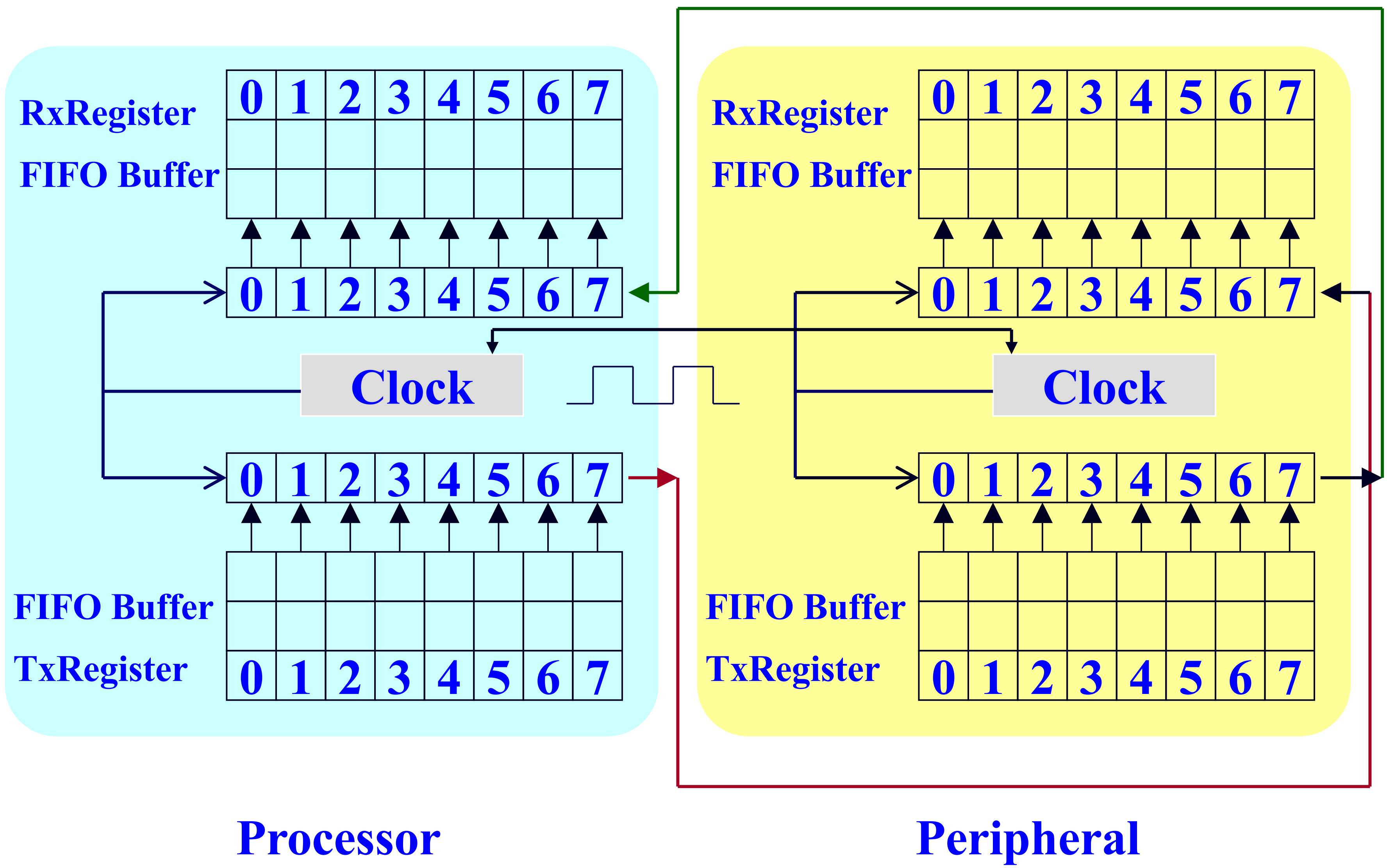
Protecting Against Data Loss

- How can data be lost?
  - If the transmitter starts to send the next byte before the receiver has had a chance to process/read the current byte
  - If the next byte is loaded at the transmitter end before the current byte has been completely transmitted

- Most serial ports use FIFO buffers so that data is not lost
  - Buffering of received bytes at receiver end for later processing
  - Buffering of loaded bytes at transmitter end for later transmission
  - Shift registers free to transmit and receive data without worrying about data loss

- Why does the size of the FIFO buffers matter?

Serial Port



RxRegister
FIFO Buffer
0 1 2 3 4 5 6 7
Clock
FIFO Buffer
TxRegister
0 1 2 3 4 5 6 7
RxRegister
FIFO Buffer
0 1 2 3 4 5 6 7
Clock
FIFO Buffer
TxRegister
0 1 2 3 4 5 6 7
Processor
Peripheral

What is RS-232?

- So far, we've talked about clocks being synchronized and using the clock as a reference for data transmission
  - Fine for short distances (e.g., within chips on the same board)

- When data is transmitted over longer distances (off-chip), voltage levels can be affected by cable capacitance
  - A logic "1" might appear as an indeterminate voltage at the receiver
  - Wrong data might be accepted when clock edges become skewed

- Enter RS232: Recommended Standard number 232
  - Serial ports for longer distances, typically, between PC and peripheral
  - Data transmitted asynchronously, i.e., no reference clock
  - Data provides its own reference clock

Types of Serial Communications

- Synchronous communication
  - All transmitted bits are synchronized to a common clock signal
  - The two devices initially synchronize themselves to each other, and then continually send characters to stay synchronized
  - Even when actual data is not really being sent, a constant flow of bits allows each device to know where the other is at any given time
    - Each bit that is sent is either actual data or an idle character
  - Faster data transfer rates than asynchronous methods, because it does not require additional bits to mark the beginning and end of each data byte
- Asynchronous communication
  - Each device uses its own internal clock resulting in bytes that are transferred at arbitrary times
  - Instead of using time as a way to synchronize the bits, the data format is used
  - Data transmission is synchronized using the start bit of the word, while one or more stop bits indicate the end of the word
    - Asynchronous communications slightly slower than synchronous
    - However, processor does not have to deal with the additional idle character

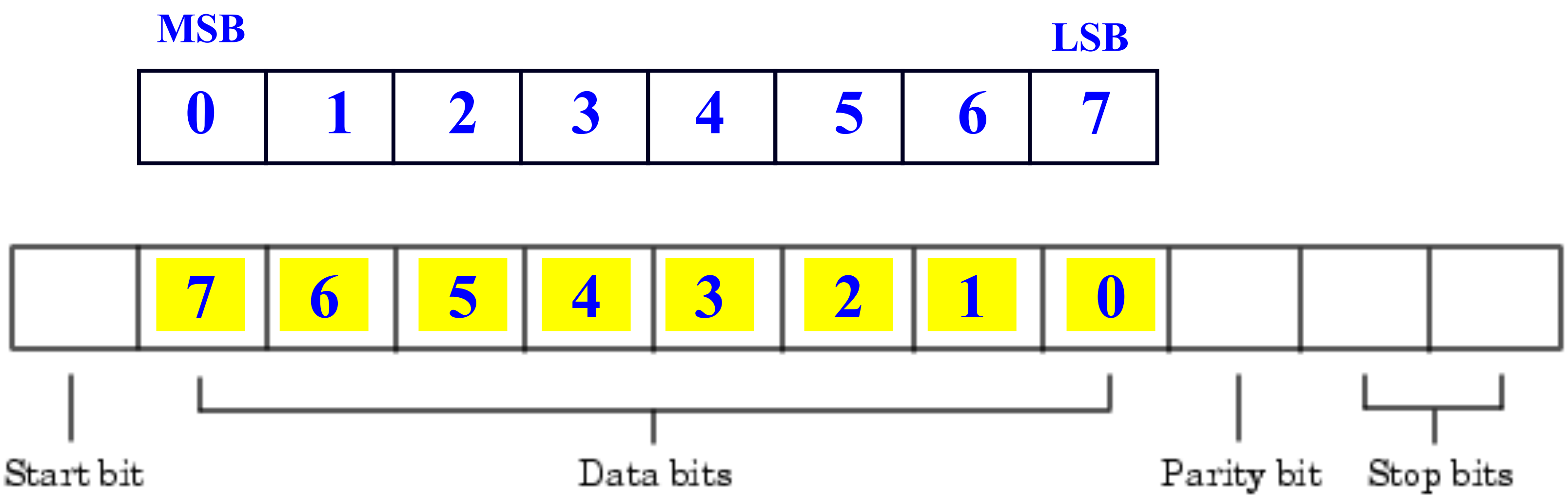
Here's an Analogy

- With asynchronous communication
  - You would need to stop after every word to make sure the listener understood your meaning, and knew that you were about to speak the next word.
- With synchronous communication
  - You would establish with your listener that you were speaking English, that you will be speaking words at measured intervals, and that you would utter a complete sentence/paragraph, before pausing to confirm
  - You would establish with your listener beforehand that any extraneous noises (coughing) should be ignored.

- Which is faster?
- Synchronous can be faster, even though initializing communication may take slightly longer

Bits and Serial Bytes

- Serial ports on IBM-style PCs support asynchronous communication only
- A "serial byte" usually consists of
  - *Characters:* 5-8 data bits
  - *Framing bits:* 1 start bit, 1 parity bit (optional), 1-2 stop bits
  - When serial data is stored on your computer, framing bits are removed, and this looks like a real 8-bit byte



- Specified as number of data bits - parity type - number of stop bits
  - 8-N-1 : eight data bits, no parity bit, and one stop bit
  - 7-E-2 : seven data bits, even parity, and two stop bits

Parity Bits

- Simple error checking for the transmitted data
- Even parity
  - The data bits plus the parity bit produce an even number of 1s
- Odd parity
  - The data bits plus the parity bit produce an odd number of 1s

- Parity checking process
  1. The transmitting device sets the parity bit to 0 or to 1 depending on the data bit values and the type of parity checking selected.
  2. The receiving device checks if the parity bit is consistent with the transmitted data; depending on the result, error/success is returned

- Disadvantage
  - Parity checking can detect only **an odd number of bit-flip errors**
  - Multiple-bit errors can appear as valid data

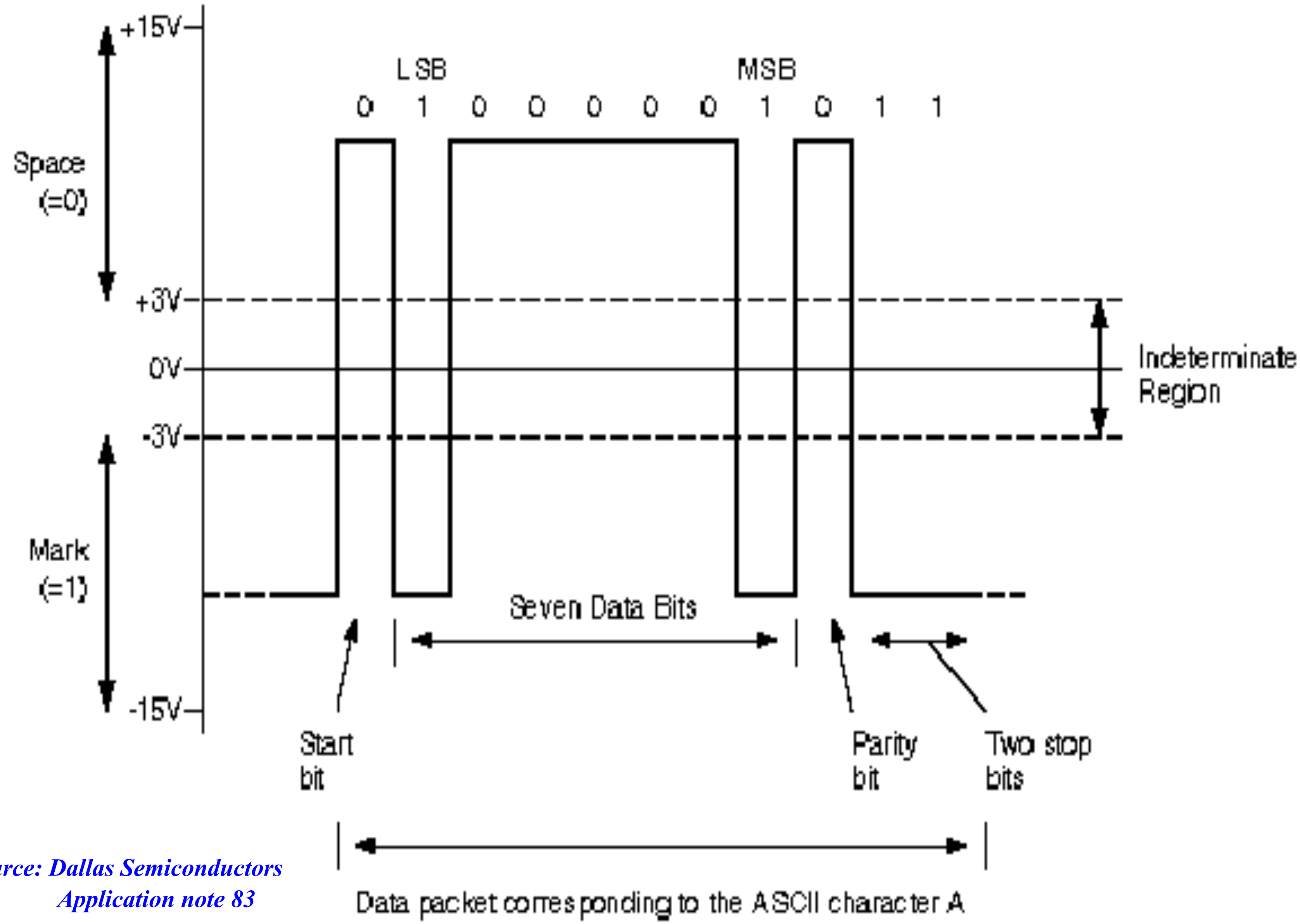
Data Modulation

- When sending data over serial lines, logic signals are converted into a form the physical media (wires) can support

- RS232C uses bipolar pulses
  - Any signal greater than +3 volts is considered a space (0)
  - Any signal less than 3 volts is considered a mark (1)

- Conventions
  - Idle line is assumed to be in high (1) state
  - Each character begins with a zero (0) bit, followed by 5-8 data bits and then 1, 11/2, or 2 closing stop bits
  - Bits are usually encoded using ASCII (**A**merican **S**tandard **C**ode for **I**nformation **I**nterchange)

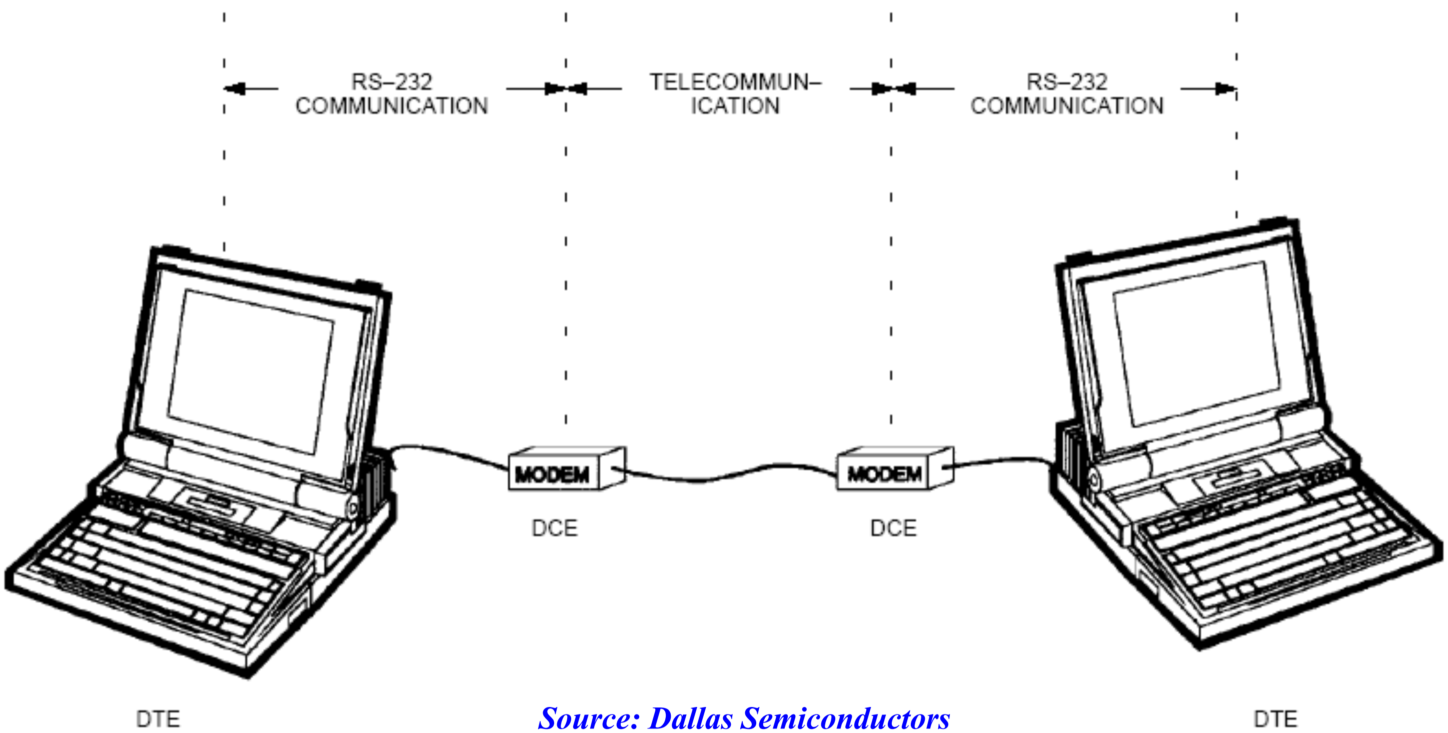
RS-232 Signal Levels



Source: Dallas Semiconductors
Application note 83

Terminology

- DTE: Data terminal equipment, e.g., PC
- DCE: Data communication equipment, e.g., modem, remote device
- Baud Rate
  - Maximum number of times per second that a line changes state
  - Not always the same as bits per second



Source: Dallas Semiconductors Application note 83

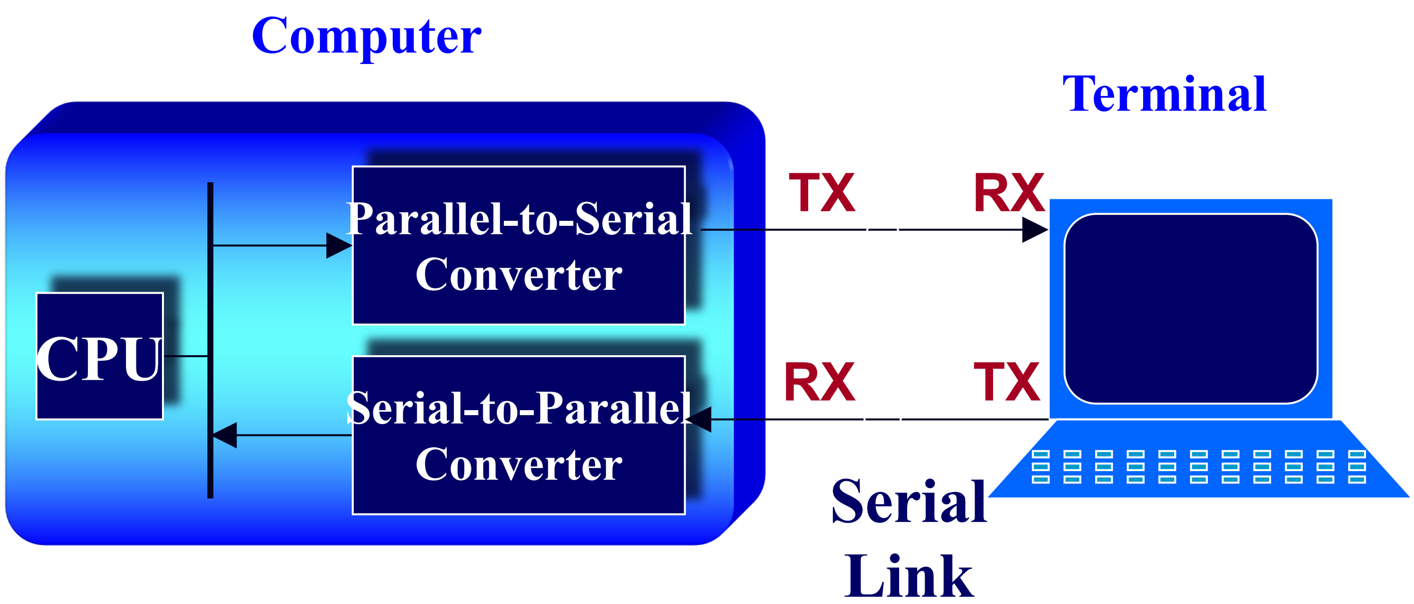
Serial Port Connector

- 9-pin (DB-9) or 25-pin (DB-25) connector

- Inside a 9-pin connector
  - **Carrier Detect** - Determines if the DCE is connected to a working phone line
  - **Receive Data** - Computer receives information sent from the DCE
  - **Transmit Data** - Computer sends information to the DCE
  - **Data Terminal Ready** - Computer tells the DCE that it is ready to talk
  - **Signal Ground** - Pin is grounded
  - **Data Set Ready** - DCE tells the computer that it is ready to talk
  - **Request To Send** - Computer asks the DCE if it can send information
  - **Clear To Send** - DCE tells the computer that it can send information
  - **Ring Indicator** – Asserted when a connected modem has detected an incoming call

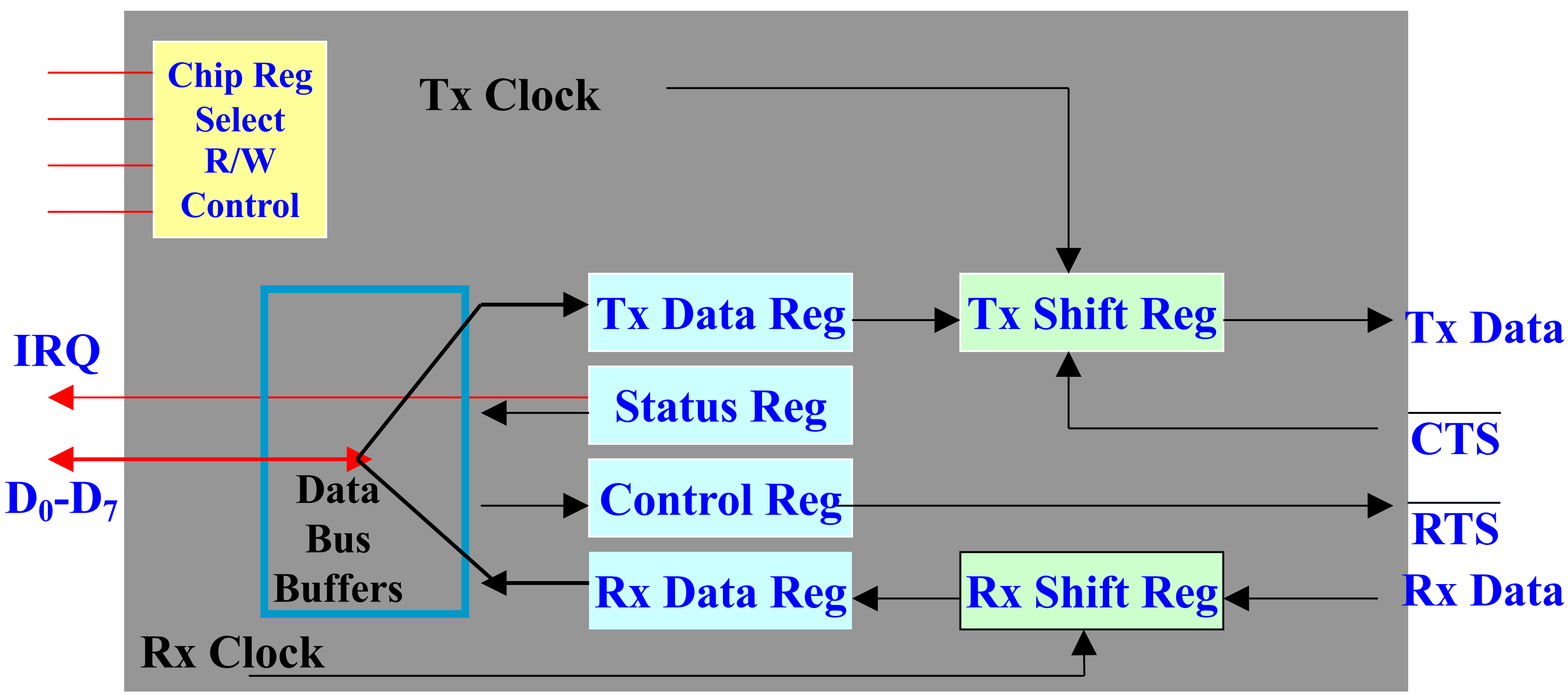
Data Communication

- Communications between computer and monitor over serial line
  - Data is converted from parallel (bytes) to serial (bits) in the bus interface
  - Bits are sent over wire (TX) to terminal (or back from terminal to computer)
  - Receiving end (RX) translates bit stream back into parallel data (bytes)



Interfacing Serial Data to Microprocessor

- Processor has parallel buses for data need to convert serial data to parallel (and vice versa)
- Standard way is with UART
- UART Universal asynchronous receiver and transmitter



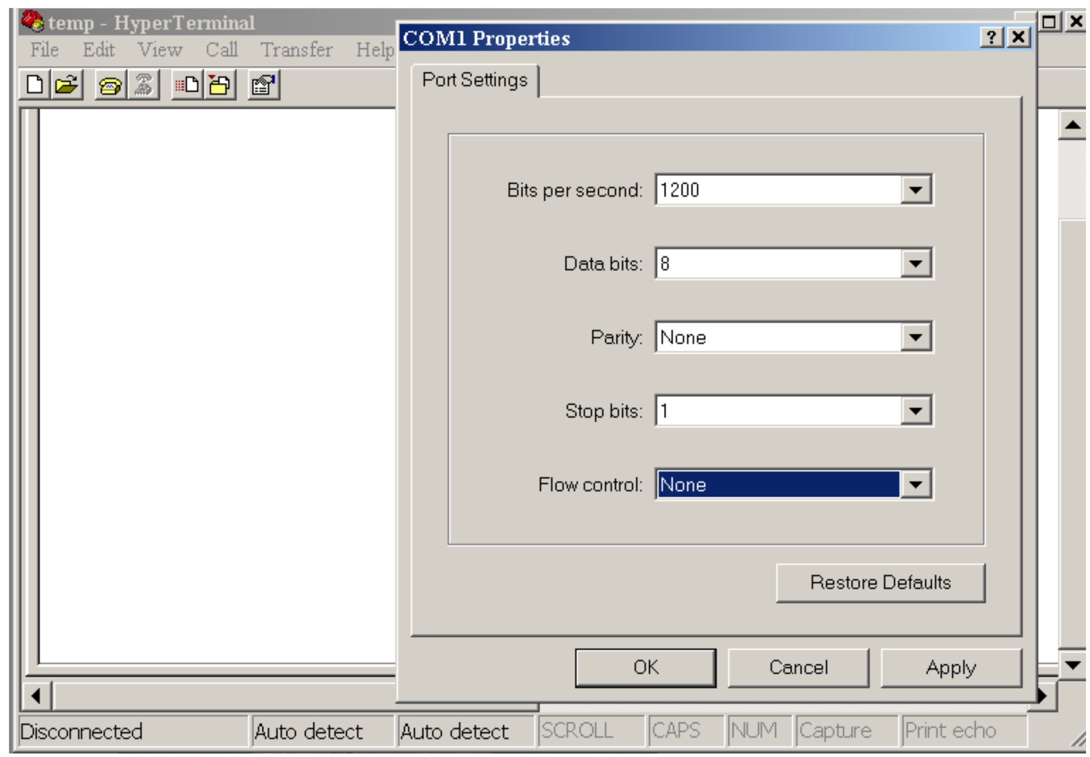
Flow Control

- Necessary to prevent terminal from sending more data than the peripheral can consume (and vice-versa)
  - Higher data rates can result in missing characters (data-overrun errors)
- Hardware handshaking
  - Hardware in UART detects a potential overrun and asserts a handshake line to prevent the other side from transmitting
  - When receiving side can take more data, it releases the handshake line
- Software flow-control
  - Special characters XON and XOFF
  - XOFF stops a data transfer (control-S or ASCII code 13)
  - XON restarts the data transfer (control-Q or ASCII code 11)
- Assumption is made that the flow-control becomes effective before data loss happens

HyperTerminal

- A (hyper) terminal program is an application that will enable a PC to communicate directly with a serial port
  - Can be used to display data received at the PC's serial port

- Can be used to configure the serial port
  - Baud rate
  - Number of Data bits
  - Number of parity bits
  - Number of stop bits
  - Flow control



Example: When You Press a Key

- Pressed key generates a specific ASCII code which represents the character being pressed
- Code converted to a bit pattern for transmission via the serial port
- Converted bit pattern encapsulates start bits, stop bits, parity, etc.
- Bit pattern is sent down the serial line by a UART at a specific baud rate

Serial vs. Parallel

- Serial ports
  - Universal Asynchronous Receiver/Transmitter (UART): controller
  - Takes the computer bus' parallel data and serializes it
  - Transfer rate of 115 Kbps
  - Example usage: Modems
- Parallel ports
  - Sends/receives the 8 bits in parallel over 8 different wires
  - 50-100 KBps (standard), upto 2 MBps (enhanced)
  - Example usage: Printers, Zip drives

Bluetooth: Why the Name?

- Harald Blaatand (910-986 AD) was a Danish Viking king in late 10th century
  - "Blaatand" = Bluetooth
- United Denmark and part of Norway into a single kingdom
- Introduced Christianity into Denmark
- Left behind a large monument, the Jelling rune stone, in memory of his parents
- Why the name "Bluetooth"?
  - Indicates how important this standard is to Nordic industries (companies in Denmark, Sweden, Norway and Finland) are to the communications industry)
  - Aimed at the unification of computing and telecom industries

Introduction

- Intended as a replacement for short-range cables
- Essentially, replacement for RS-232 cables
- 30,000 companies belong to the Bluetooth Special Interest Group (SIG)
- Developed a standard or a set of specifications
- Some implementation details left open to the developer—a manufacturer must meet Bluetooth SIG standards to market something as a Bluetooth device
- IEEE standardized it as IEEE 802.15.1 (but does not maintain it)

Bluetooth opens doors to a new generation of “connectionless” devices

On 6 December 2016, Bluetooth took a massive leap forward to deliver advanced beacon and location-based capabilities in home, enterprise and industrial environments. Bluetooth 5 quadruples the range, doubles the speed, and boosts broadcast messaging capacity by 800%—the key to enabling robust, reliable Internet of Things (IoT) connections that make full-home and building and outdoor use cases a reality.

Bluetooth Everywhere (Source: Bluetooth SIG)

As a trusted standard for wireless connectivity, *Bluetooth*® is integrated into more than 8.2 billion products produced by over 30,000 Bluetooth SIG members. Discover how Bluetooth is helping to transform the way people and devices connect across a variety of markets.

Automotive	Consumer Electronics
Home Automation	Medical & Health
Mobile Phones & Smart Phones	PC & Peripherals
Wearables	Sports & Fitness
Retail & Location-based Services	

Relevant Detour: Let’s talk Infrared (IR)

- Also a replacement for short-range cables
- Using light waves of a lower frequency than the human eye can interpret
- Inexpensive as well, but a couple of drawbacks
- Line-of-sight technology, e.g., point the remote-control at the TV to operate it
- One-to-one technology—only send data between two devices at a time
- However, interference between devices is rare
- Message only goes to the intended recipient (the one-to-one nature of the tech), even in a room full of IR receivers

- Bluetooth—also inexpensive, also replacement for short-range cables—but addresses the limitations of IR systems

Introduction

- [1994] Ericsson started to look at alternatives to connect their mobile phones to accessories
  - Cable replacement that could connect devices such as mobile phone handsets, headsets and portable computers
  - Looked at option of using radio – not directional, no line of sight, many-to-one
- [1998] Original Bluetooth SIG: Ericsson, Intel, IBM, Toshiba, Nokia
- [1999] Version 1.0 of an open, global specification that defines a complete protocol, from the underlying physical (radio) layer to the application level
  - Bluetooth 1.0 has a maximum transfer speed of 1 megabit/s (Mbps)
  - Bluetooth 2.0 can handle up to 3 Mbps (and is backward-compatible with 1.0 devices)

- Standardized wireless communications between electrical devices in proximity
  - Location independent – devices do not need to know each other's specific locations
  - Low-cost, low-power, short-range radio technology
- Notion of a Personal Area Network (PAN) – a close-range wireless network
- Protocol usually implemented partly in hardware and partly as software

Speeds

- Bluetooth 1.0 has a maximum transfer speed of 1 megabit/s (Mbps)
- Bluetooth 2.0 can handle up to 3 Mbps (and is backward-compatible with 1.0 devices)
- Bluetooth 3.0 can handle up to 25 Mbps
- Bluetooth 4.0 can handle up to 25 Mbps
- Bluetooth 5.0 can handle up to 50 Mbps

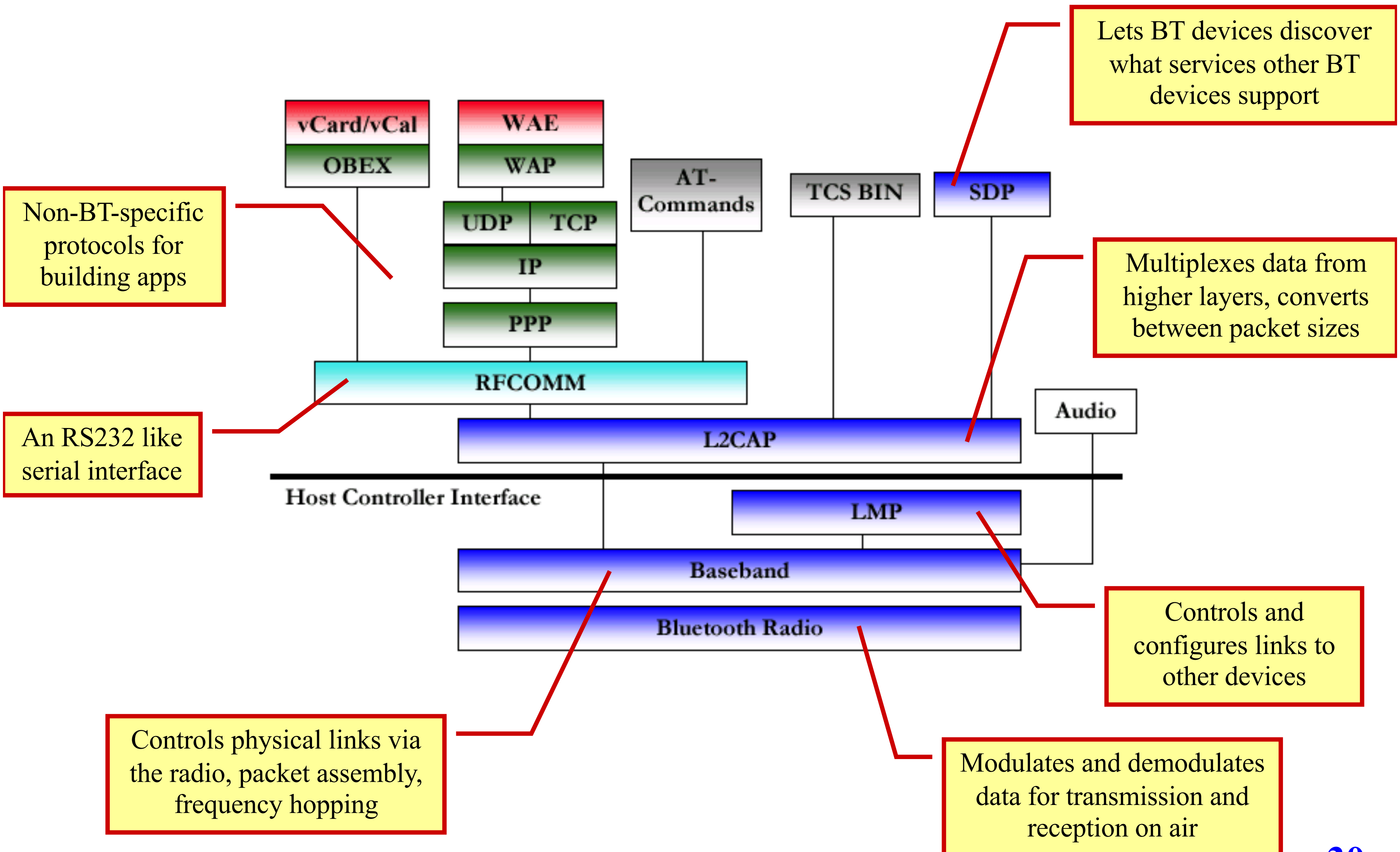
- The Bluetooth Core Specification specifies minimum range of 10m (33 ft), but there is no upper limit on actual range

Some Implicit Requirements

- Bluetooth envisioned as a cable-replacement technology – this imposes some requirements

- Cost
  - Can't be more expensive than a cable
- Battery-operated
  - Target market was mobile devices
  - Must be low power
  - Must be able to run on low voltages
  - Must be lightweight and compact enough not to intrude on the design of mobile devices
- Ease of use
  - Must be as simple as (if not simpler than) plugging in a cable
  - Must be as reliable as a cable, must cope with errors (resilience)
  - Must not be captive to a vendor

Bluetooth Protocol Stack



Physical Radio Layer

- Bluetooth devices operate in the globally available, unlicensed ISM band situated at 2.4 GHz
  - General use by Industrial, Scientific and Medical (ISM) applications
  - Has restrictions in some countries – Bluetooth SIG is lobbying to harmonize these regulations
- ISM band
  - Occupied by a variety of other RF emitters
  - Car security, cordless headphones, baby monitors, garage-door openers, random-noise generators (microwave ovens, sodium vapor street lamps)
- The 2.4 GHz is not a terribly stable or reliable medium
  - But its worldwide availability ensures widespread acceptance of Bluetooth
  - Coping with interference becomes a huge issue
- To cope with the hostile environment, Bluetooth employs special means
  - Frequency hopping, adaptive power control, short data packets
- Three different power ranges
  - Provide transmission ranges of 10m (lowest power), 20m or 100m

Hedy Lamarr and Frequency Hopping

- Lamarr worked on a jam-proof radio guidance for torpedoes during the World War
- Lamarr and Antheil worked on a frequency-hopping spread-spectrum technology
  - Continually change the radio signals sent to the torpedo
  - Underlies Wi-Fi, CDMA and Bluetooth
- Posthumously inducted into the National Inventors Hall of Fame

UNITED STATES PATENT OFFICE

2,292,387

SECRET COMMUNICATION SYSTEM

Hedy Kiesler Markey, Los Angeles, and George Antheil, Manhattan Beach, Calif.

Application June 10, 1941, Serial No. 397,412

6 Claims. (Cl. 250—2)

This invention relates broadly to secret communication systems involving the use of carrier waves of different frequencies, and is especially useful in the remote control of dirigible craft, such as torpedoes.

An object of the invention is to provide a method of secret communication which is relatively simple and reliable in operation, but at the same time is difficult to discover or decipher.

Briefly, our system as adapted for radio control of a remote craft, employs a pair of synchronous records, one at the transmitting station and one at the receiving station, which change the tuning of the transmitting and receiving apparatus from time to time, so that without knowledge of the records an enemy would be unable to determine at what frequency a controlling impulse would be sent. Furthermore, we contemplate employing records of the type used for many years in player pianos, and which consist of long rolls of paper having perforations variously positioned in a plurality of longitudinal rows along the records. In a conventional player piano record there may be 88 rows of perforations, and in our system such a record would permit the use of 88 different carrier frequencies, from one to another of which both the transmitting and receiving station would be changed at intervals. Furthermore, records of the type described can be made of substantial length and may be driven slow or fast.

sible for a pair of records,

ting station and one at the

run for a length of time a

control of a device such as

Fig. 2 is a schematic diagram of the apparatus at a receiving station;

Fig. 3 is a schematic diagram illustrating a starting circuit for starting the motors at the transmitting and receiving stations simultaneously;

Fig. 4 is a plan view of a section of a record strip that may be employed;

Fig. 5 is a detail cross section through a record-responsive switching mechanism employed in the invention;

Fig. 6 is a sectional view at right angles to the view of Fig. 5 and taken substantially in the plane VI—VI of Fig. 5, but showing the record strip in a different longitudinal position; and

Fig. 7 is a diagram in plan illustrating how the course of a torpedo may be changed in accordance with the invention.

Referring first to Fig. 7, there is disclosed a mother ship 10 which at the beginning of operations occupies the position 10a and at the end of the operations occupies the position 10b. This mother ship discharges a torpedo 11 that travels successively along different paths 12, 13, 14, 15 and 16 to strike an enemy ship 17, which initially occupies the position 17a but which has moved into the position 17b at the time it is struck by the torpedo 11. According to its original course, the enemy ship 17 would have reached the position 17c, but it changed its course following the firing of the torpedo, in an attempt to evade the

ce with the present invention, the

be steered from the mother ship

rse changed from time to time as

cause it to strike its target. In

Frequency Hopping

- The operating band, 2.4 GHz ISM, band is 2400 - 2483.5 MHz
- The 79 RF channels are ordered from channel number 0-78 and are spaced 1 MHz apart, starting at 2402 MHz
  - Each channel signals data at 1 Megasymbol per second
- GFSK (Gaussian Frequency Shift Keying) modulation
  - Binary 1 gives rise to a positive frequency deviation from the nominal carrier frequency
  - Binary 0 gives rise to a negative frequency deviation
  - Effective on-air data rate is 1Mb/s
- After each packet, both devices return their radio to a different frequency, effectively hopping from one radio channel to another
  - FHSS: frequency hopping spread spectrum
- Why?
  - Bluetooth devices will end up using the whole of the available ISM band
  - If a transmission is compromised by interference on one channel, the retransmission will occur on a different (hopefully clear) channel
- Each Bluetooth time-slot is 625 microseconds – devices hop once per packet (which can be 1, 3 or 5 time slots)

Master-Slave Organization

- If devices are to hop to new frequencies after each packet, they must all agree on the sequence of frequencies that they will use
- BT devices can operate in two modes: Master or Slave
- All devices share the Master's clock
- The Master sets the frequency-hopping sequence
- The Slave synchronizes to the Master in time and frequency by following the Master's hopping sequence
- Every BT device has a unique BT device address and a BT clock
- The devices can switch roles, by agreement, and the Slave device can become the Master device
  - For example, a headset initiating a connection to a phone necessarily begins as a Master device—as initiator of the connection—but may subsequently operate as a Slave device
- Being a Master of 7 Slaves is possible; being a Slave of more than one Master is possible

Master Controls Multiple Things

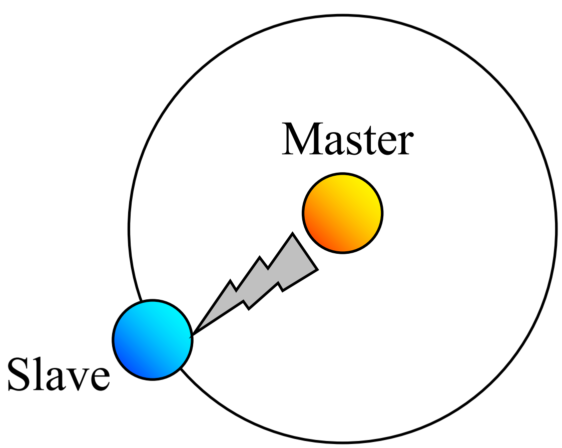
- Frequency-hopping: When Slaves connect to a Master, they are told the BT device address and clock of the Master
  - The frequency-hop sequence can be calculated from this BT device address and a BT clock
  - Because all Slaves use the Master's clock and address, they are all synchronized to the Master's frequency-hop sequence

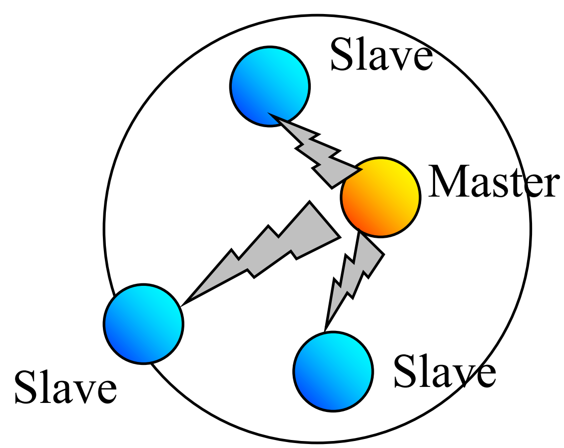
- Transmission: The Master also controls when devices are allowed to transmit
  - Master allows Slaves to transmit by allocating slots for voice/data traffic
  - In data-traffic slots, Slaves can transmit only when responding to a transmission sent to them by the Master
  - In voice-traffic slots, Slaves are required to transmit regularly in reserved slots whether or not they are responding to the Master

- Bandwidth: Master controls how total bandwidth is divided up amongst the Slaves
  - By deciding when and how often to communicate with each Slave
  - Time Division Multiplexing (TDM)
  - How many slots each Slave gets depends on its data-transfer needs

Piconet

- Another term for a Bluetooth Personal Area Network (PAN)
- A collection of Slave devices operating together with one common Master
- All devices on a piconet follow the Master’s frequency hopping & timing
- Slaves in a piconet only have links to the Master
- There are no direct links between the Slaves in a piconet
- Specification mandates a maximum of 7 Slaves in a piconet – why 7?
- Typical range of a piconet is 10m, but can be more with higher power
- Larger coverage can be hand by linking piconets into a scatternet



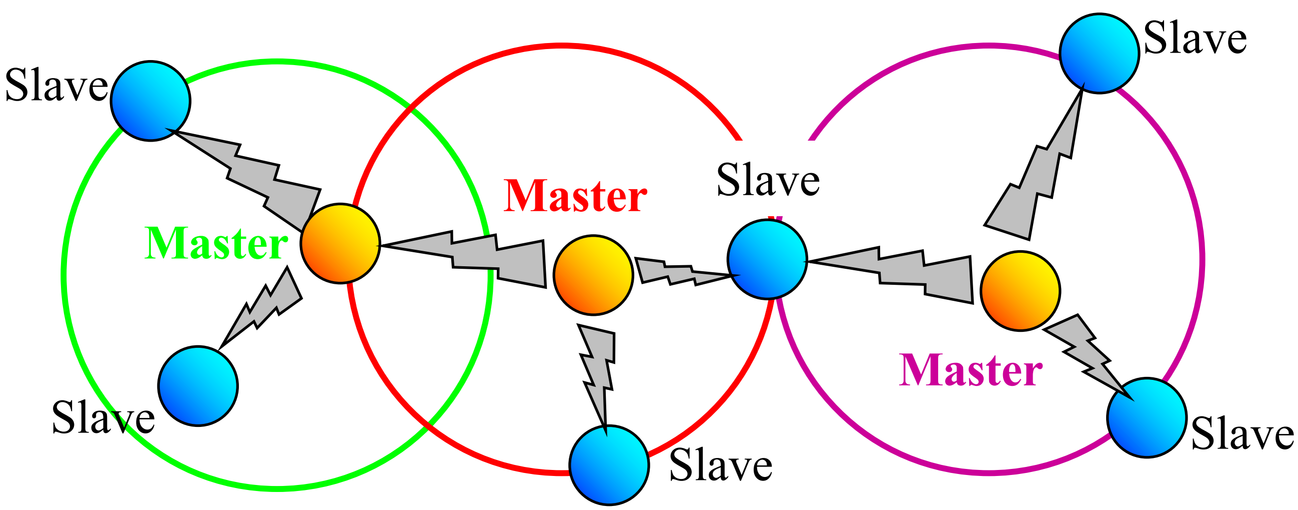


Side-Story

- The BlueSniper rifle from Flexilis can scan and attack Bluetooth devices (called BlueSnarfing) from more than a mile away
- The first version of the gun showed up at Defcon 2004
- John Hering, from Flexilis: *"The parts are easily available for a few hundred dollars and you can make this gun in a long afternoon."*

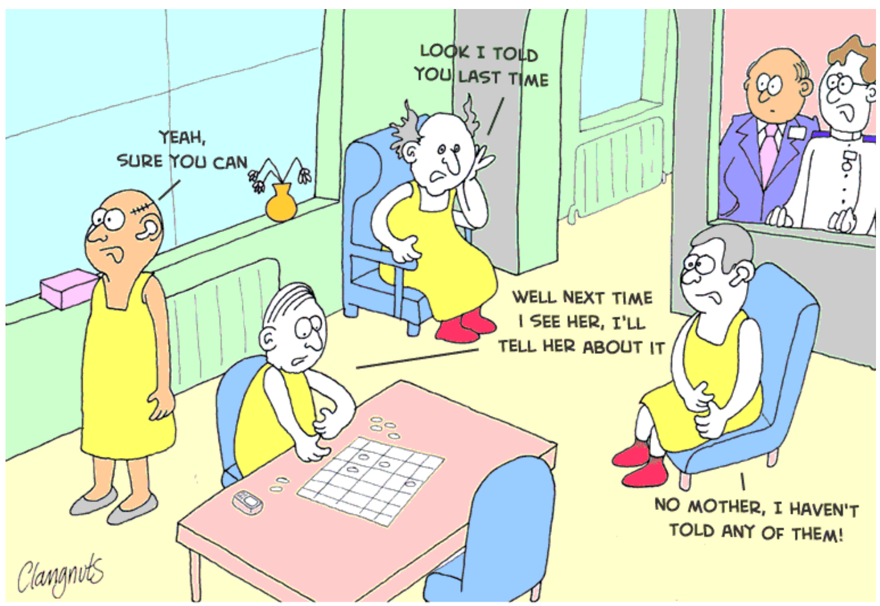
Scatternet

- Some devices are members of more than one piconet
- When a device belongs to more than one piconet, it must time share
  - Spends few slots on one piconet, and then a few other slots on the other piconet
- Slave in one piconet can be a Master in the other
- Slave in one piconet can be a Slave in the other as well (Slave has two Masters, one in each piconet)
- What is not possible?
  - To have a device that is a Master of two different piconets since all Slaves in a piconet are synchronized to the Master



Piconet

- Slaves in a piconet are synchronized to avoid interference with each other
  - But, other unsynchronized piconets in the area might randomly collide on the same frequency
  - If there is a collision on a particular channel, those packets will be lost and will need to be retransmitted
  - The more piconets in an area, the more retranmissions that will occur, causing data rates to fall (can also happen in a scatternet)



"SINCE THEY ALL GOT BLUETOOTH, IT'S HARD TO TELL WHO'S HEARING VOICES!"

Radio Power Classes

- Three types of radio power classes
  - Class 1: 100mW (range 100m)
  - Class 2: 2.5mW (range 20m)
  - Class 3: 1mW (range 10m)
- Most manufacturers produce Class 3 devices
  - Ideal range is 10m
  - Because human bodies, furniture, etc. absorb waves, practical range is ~5m
- Also a minimum range for Bluetooth devices
  - If radios are too close together, the receiver saturates
  - Minimum range for a BT radio link is 10cm
- Possible to create piconets with a mixture of high and low power devices at different operating ranges (e.g., Class 1 Master can have a Class 3 Slave, but the range is now dictated by the lower-class device)

Communication

- Supports data and voice traffic
- Asynchronous Connectionless (ACL) links
  - Data communication
  - Packet: 72-bit access code, 54-bit packet header, 16-bit CRC + payload
  - Largest packet size (DH5 packet) can carry 339 bytes (2712 bits) of payload and needs 142 bytes of overhead (72+54+16 bits)
  - DH5 packet takes 5 time-slots to send and a minimum of 1 time-slot for reply
  - **Effective** max data rate in one direction = (2712 bits)/ (6 time-slots * 625 μs/slot) = 723.2 kb/s
  - Using more packets for reply reduces this effective data rate
  - Higher layers can add more protocol overhead, so max data rate might drop
- Synchronous Connection Oriented (SCO) links
  - Voice communication
  - Work at 64 kb/s
  - Possible to have three full-duplex links at once (to mix voice and data)
  - Audio quality not really sufficient for delivery of music, for good enough for modern cellular phone system
  - Perhaps use ACL for audio delivery using compression

Error Correction

- Cyclic Redundancy Check (CRC)
  - Performed on all packet headers and on payload data
  - CRC will flag any errors in the data
  - 16-bit CRC over the payload header + payload data

- ARQ (Automatic Repeat Request)
  - For data or voice packets
  - Error detection through CRC at receiver
  - Receiver discards packets in error
  - Receiver returns a positive ACK for received error-free packets
  - Receiver returns a NACK to packets in error; sender retransmits such packets
  - Retransmission occurs after a time-out

- Whitening or Bit Randomisation
  - Mixing a pseudo random bit sequence with the data bitstream to randomize the data
  - Greatly reduces the possibility of long sequences of 0s or 1s (basically, DC bias)
  - Avoids offsets that might build up
  - Avoids problems that might cause certain radio architectures to drift off channel

Forward Error Correction (FEC)

- By adding extra parity bits created from the input data
- Can detect (and sometimes correct) bit errors

- Three FEC options decided based on packet type: non, 1/3 and 2/3

- **1/3 FEC** – strongest
  - For high quality voice packets
  - Transmits 3 copies of each bit
  - Decoded at the receiver through a majority function
- **2/3 FEC**
  - For data or voice packets
  - Packet header uses 1/3 FEC since it is the most critical part
  - Uses Hamming code
    - For every 10 bits, 15 bits are generated to allow detection of 2 bit errors in the 10-bit input and correct 1 bit error in the 10-bit input
    - Input needs to be padded to ensure multiple of 10

Bluetooth Profiles

- Bluetooth specification includes a profiles document
- Describes how a particular application can be implemented using BT
- Specifies which parts of the core BT protocol should be used for these applications

- Version 1.0 provides profiles for connecting
  - Mobile cellphone to public switched telephone network (PSTN) through an access point
  - Mobile cellphone to a notebook PC
  - Mobile cellphone to a headset
  - LAN access points for laptops or palmtops
  - Notebook, palmtop or other Internet access device to the Internet via a PSTN access point or access modeul
  - Laptops and palmtops

Example Bluetooth Profiles

- Bluetooth profiles save time in communicating parameters when the profiles are interpreted
- A2DP (Advanced Audio Distribution Profile)
  - Streaming music
- HID (Human Interface Device Profile)
  - Bluetooth-enabled mice and keyboards
- BIP (Basic Imaging Profile)
  - Send photos and images to Bluetooth-enabled printers, picture frames, etc.
- GATT (Generic Attribute Profile)
  - Build your own Bluetooth-enabled thing!

Device Discovery

- Suppose I have two Bluetooth devices
  - Cellphone capable of acting as a modem using a BT dialup networking profile
  - Laptop running an application that needs a BT dialup networking connection
- Cellphone will periodically scan to see if anyone needs to use it
- Laptop will perform an inquiry to look for any BT devices nearby
  - Through a series of inquiry packets
- Cellphone responds (eventually) with a Frequency Hop Synchronization (FHS) packet
  - Contains all the info that the laptop needs to connect to the cellphone
  - Plus, the device class – the fact that this is a phone and specifically, a cellphone
- Every other Bluetooth-enabled device nearby will also respond with an FHS packet – laptop accumulates a list of all nearby devices
- Laptop can now
  - Present the user with this list, allowing the user to decide what to do next
    - User will only know about the devices, but not their services
  - Take the next step of discovering which of these devices support the dialup networking profile that is needed

Service Discovery – I

- To find out whether a device supports a specific service, the Service Discovery Protocol (SDP) needs to be used
- Laptop pages the cellphone, using the information gathered during inquiry
- If the cellphone is scanning for pages, it responds
  - An ACL baseband connection can be set up to transfer data between the two devices
- Once ACL connection is set up, an L2CAP connection can be established
  - Used whenever data has to be transferred between Bluetooth devices
  - Allows many protocols and services to piggyback onto one ACL link
    - Protocol and Service Multiplexor (PSM) embedded in every L2CAP packet to distinguish the specific protocol/service using the ACL link
    - Different PSMs for different protocols or services
  - PSM=0x0001 ⇨ service discovery protocol is using the ACL link

Service Discovery – II

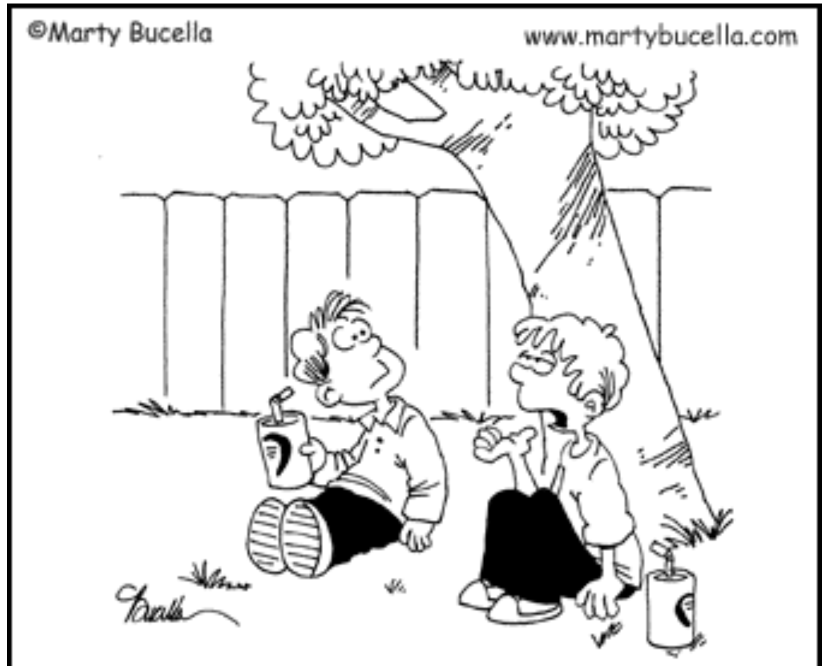
- Laptop uses L2CAP channel to connect to the service discovery *server* on the cellphone
  - Laptop runs a service discovery *client*
  - Client asks the server to send any and all information related to a dialup networking profile
  - Server looks through its database and returns attributes related to dialup networking
- Laptop receives this information
  - Can decide to tear down connection to the cell phone
  - Particularly the case if there are many devices in the area – no sense in waiting with open connections while collecting service information
- At the end of this service discovery phase
  - It's up to the application what to do – can let the application decide for itself or can involve the user in deciding which device to select

Connecting to a Service

- Same initial process as establishing an ACL connection
- Except the connection might have specific quality-of-service requirements this time
  - Basically, a link configuration phase
- Now, an L2CAP connection on top of the ACL connection
  - Dialup networking uses RFCOMM, an RS-232 emulation layer
  - PSM=0x0003 ⇨ RFCOMM is using the ACL link
- RFCOMM can also multiplex several protocols or services, each with its own channel number
  - Knows which channel number to use from the service discovery information
- Finally, the Dialup Networking (DUN) connection is set up over the RFCOMM connection and the laptop can use the dialup networking services of the cellphone
- If cellphone goes out of the laptop's range, the laptop will need to repeat the entire process and find another device
- Important
  - Both ends of the connection have to be willing to connect
  - Some devices might be set up not to scan for inquiries
  - Others might be set up to not be discoverable – effectively, these are invisible

Bluetooth Limitations

- Does not address routing, most network functions are pushed into the link layer
- Does not support multi-hop multicasting
- Does not necessarily cope with mobility
- The Master node is often the bottleneck
- The number of nodes in a piconet is limited to 8
- Does not incorporate or exploit power-saving methods done at upper layers, above the link-layer



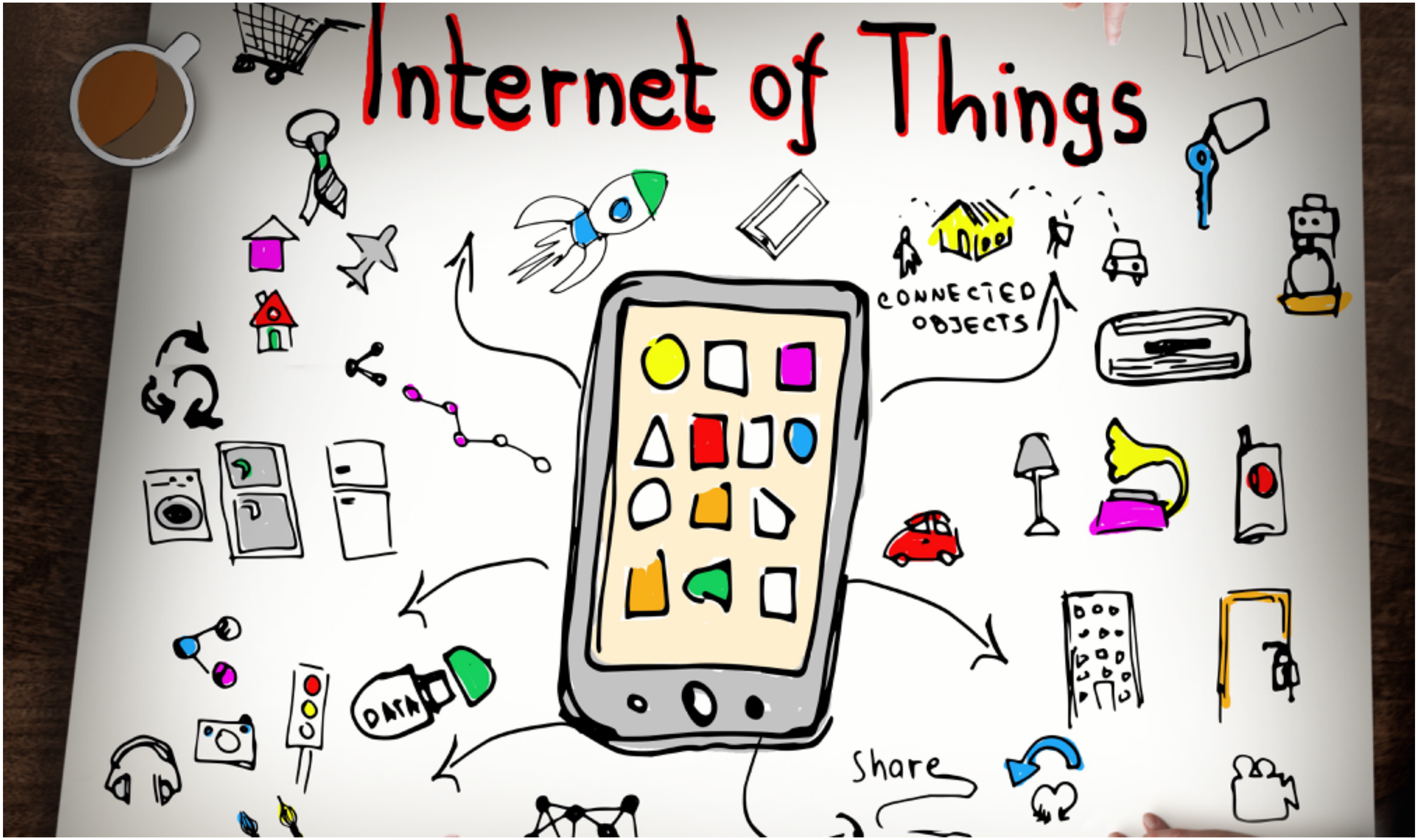
"I gave up trying to explain Bluetooth to my parents, and just told them it's a character on Sesame Street."

Zigbee vs. Bluetooth

- Two different technologies with very different areas of application and different means of designing for those applications
  - ZigBee (IEEE 802.15.4) is focused on control and automation
  - Bluetooth is focused on connectivity between laptops, PDA's, and the like, as well as more general cable replacement
- ZigBee uses low data rate, low power consumption, and works with small-packet devices
- Bluetooth uses a higher data rate, higher power consumption, and works with large-packet devices
- ZigBee networks can support a larger number of devices and a longer range between devices than Bluetooth
- Bluetooth must rely on fairly frequent battery recharging, while the whole goal of ZigBee is for a user to be able to put a small number of batteries in the devices and forget about recharging for months to years
- In timing-critical applications, ZigBee is designed to respond quickly, while Bluetooth takes much longer and could be detrimental to the application

Zigbee vs. Bluetooth

Characteristic	ZigBee	Bluetooth
Range		
As designed	10-100 metres	10 metres
Special kit or outdoors	up to 400 metres	100+ metres dep. on radio
Data rate	20-250 Kbps	1 Mbps
Network Latency (typical)		
New slave enumeration	30ms	20s
Sleeping slave changing to active	15ms	3s
Active slave channel access	15ms	2ms
Power profile	Years Optimizes slave power requirements	Days Maximises adhoc functionality
Security	128 bit AES and application layer user definable	64 bit, 128 bit
Operating Frequency	868 Mhz, 902-928 MHz, 2.4 GHz ISM	2.4 GHz ISM
Complexity	Simple	Complex
Network Topology	Adhoc, star, mesh hybrid	Adhoc piconets
Number of devices per network	2 to 65,000	8
Scalability/Extendability	Very High/Yes	Low/No
Flexibility	Very High	Medium, profile dependent
Resilience and reliability	Very High	Medium



IoT Protocols

18-738 Sports Technology

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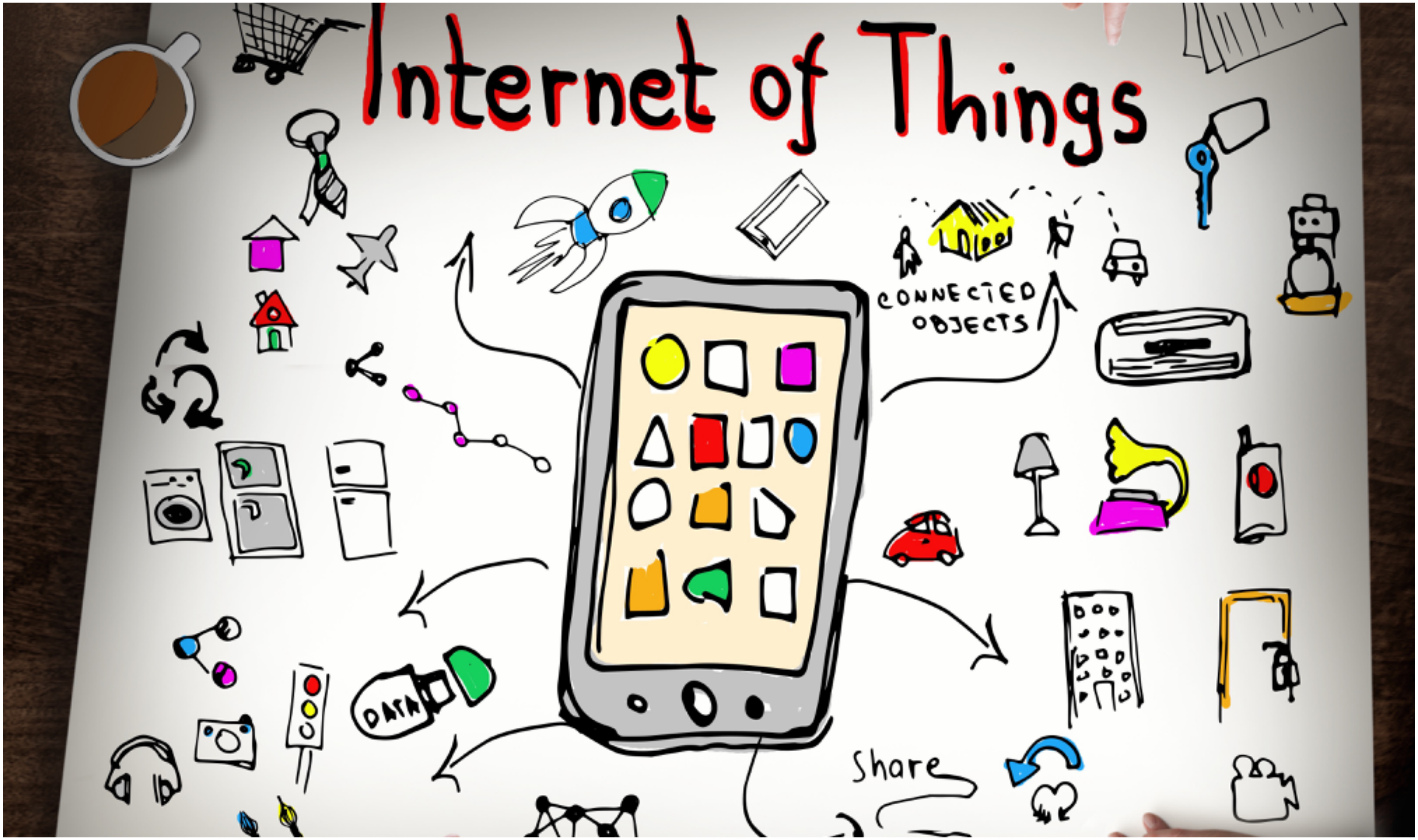

IoT Protocols: I2C, SPI

18-738 Sports Technology

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Outline of This Lecture

- I2C bus
- Master-slave protocol
  - Sending data
  - Acknowledgment
- Multi-master protocol
  - Arbitration
- Serial Peripheral Interconnect (SPI)

Background

- I2C is also written as I^{2}C (pronounced "eye-squared-see" or "eye-two-see")
  - Stands for Inter-Integrated Circuit (IIC)
- Two-wire party-line bus for "inside the box" communication
- Intended for short-range communication between ICs on a circuit board or across boards in an embedded system
- I2C devices commonly used in industrial applications
  - EEPROMs, thermal sensors, real-time clocks, RF tuners, video decoders/encoders
- Philips Semiconductors is the primary champion of I2C
  - Specification publicly available at http://www.nxp.com/acrobat_download/literature/9398/39340011.pdf
  - Originally developed for communication between devices inside a TV set in the mid-1980s

Purpose

- Designed by Philips ~20 years ago
- Original purpose was to allow easy communication between components which resided on the same circuit board
- Combines hardware and software protocols to provide a bus interface that can connect many peripheral devices
- I2C is now not only used on single boards, but also to connect components which are linked via cable
- All I2C-compatible devices have an on-chip interface that allows them to communicate directly with each other via the I2C-bus
- Supports easy, ready-to-use interfacing of various boards and digital circuits (even if they are independently designed)
- Allows for "plug-and-play" and evolution of ICs into a larger system

Characteristics of I2C

- Only two bus lines are required
- Each device connected to the bus is software-addressable by a unique address and
  - Simple master/slave relationships
- True multi-master bus including collision detection and arbitration to prevent data corruption if two or more masters simultaneously initiate data transfer
- Serial, 8-bit oriented, bidirectional data transfers
  - Slow: Up to 100 kbit/s in the standard mode
  - Fast: Up to 400 kbit/s in the fast mode
  - High-speed (3.4 Mbps), I2C version2.0
- On-chip filtering rejects spikes on the bus data line to preserve data integrity
- Limited to about 10 feet for moderate speeds

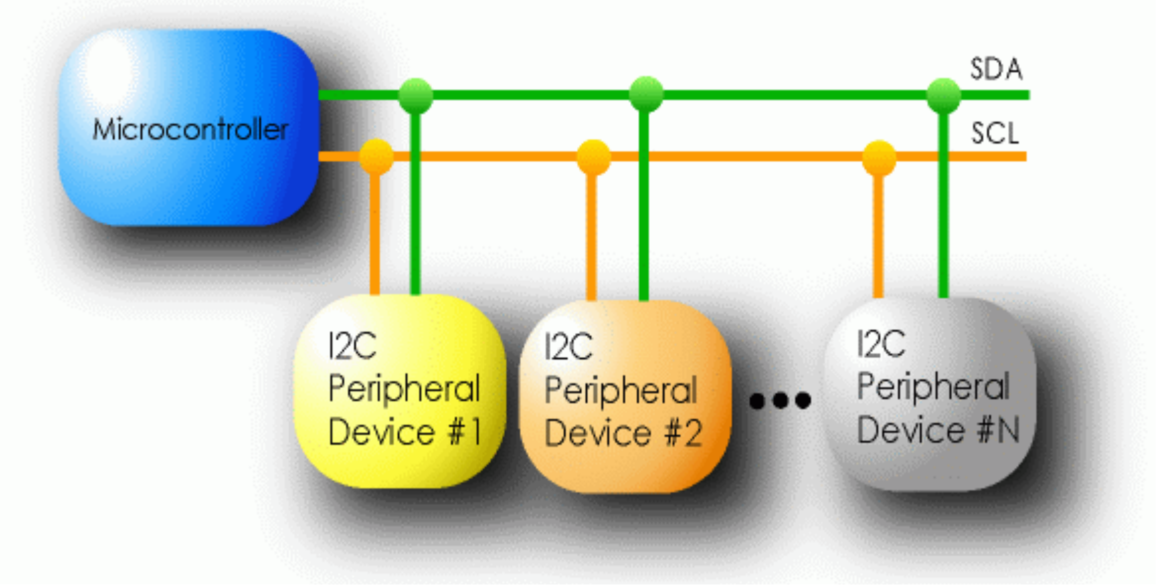
Design Criteria for I2C

- First of all, this is a serial bus
  - Targeting 8-bit microcontroller applications
  - Serial vs. parallel – anyone remember pros and cons?

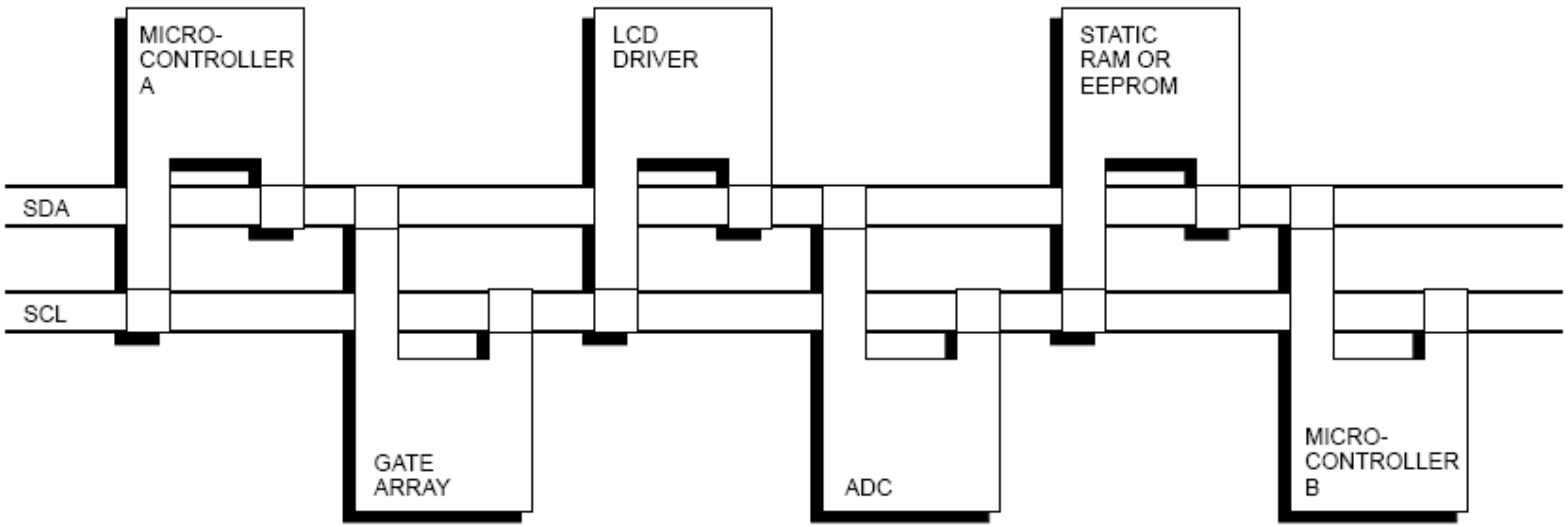
- Criteria for design of I2C
  - Need to avoid confusion between connected devices
  - Fast devices must be able to communicate with slow ones
  - Protocol must not be dependent on the devices that it connects
  - Need to have a mechanism to decide who controls the bus and when
  - If different devices with different clock speeds are connected, the bus clock speed must be defined

Details

- Two lines: Serial data line (SDA) & serial clock line (SCL)
- Each I2C device recognized by a unique address
- Each I2C device can be either a transmitter or receiver
- I2C devices can be masters or slaves for a data transfer
  - Master (usually a microcontroller): Initiates a data transfer on the bus, generates the clock signals to permit that transfer, and terminates the transfer
  - Slave: Any device addressed by the master at that time
  - Roles/relationships are not permanent



Example I2C-Connected System



Example I2C-connected system with two microcontrollers

(Source: I2C Specification, Philips)

Master-Slave Relationships

- Masters can operate as master-transmitters or master-receivers

- Suppose microcontroller A wants to send information to microcontroller B
  - A (master) addresses B (slave)
  - A (master-transmitter), sends data to B (slave-receiver)
  - A terminates the transfer.
- If microcontroller A wants to receive information from microcontroller B
  - A (master) addresses microcontroller B (slave)
  - A (master-receiver) receives data from B (slave-transmitter)
  - A terminates the transfer

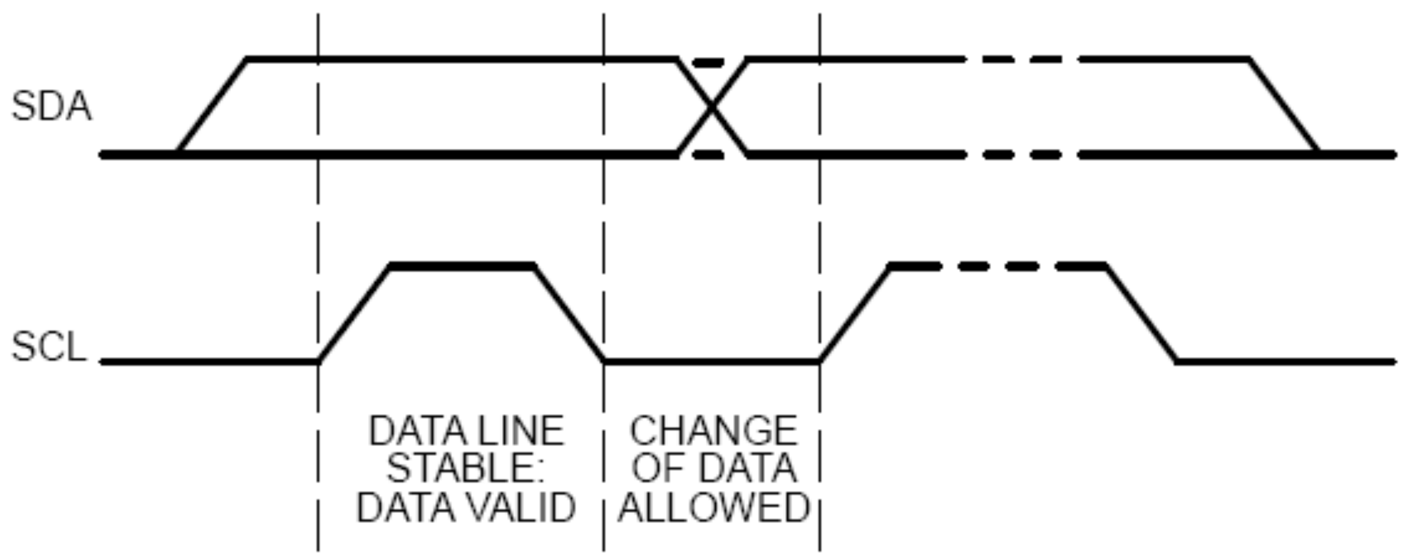
- In both cases, the master (microcontroller A) generates the timing and terminates the transfer

Multi-Master Capability

- Clearly, more than one microcontroller can be connected to the bus
  - What if both microcontrollers want to control the bus at the same time?
- Multi-master I2C capability supports this without corrupting the message
- Wired-AND connection of all I2C interfaces to the bus for arbitration
- If two or more masters try to put information onto the bus, the first to produce a ‘one’ when the other produces a ‘zero’ loses
- Clock signals during arbitration are a synchronized combination of the clocks generated by the masters using the wired-AND connection to the SCL line
- Generation of clock signals on the bus
  - Each master generates its own clock signals when transferring data on the bus
  - A master’s bus clock signals can be altered when stretched by a slow-slave device holding down the clock line, or by another master during arbitration

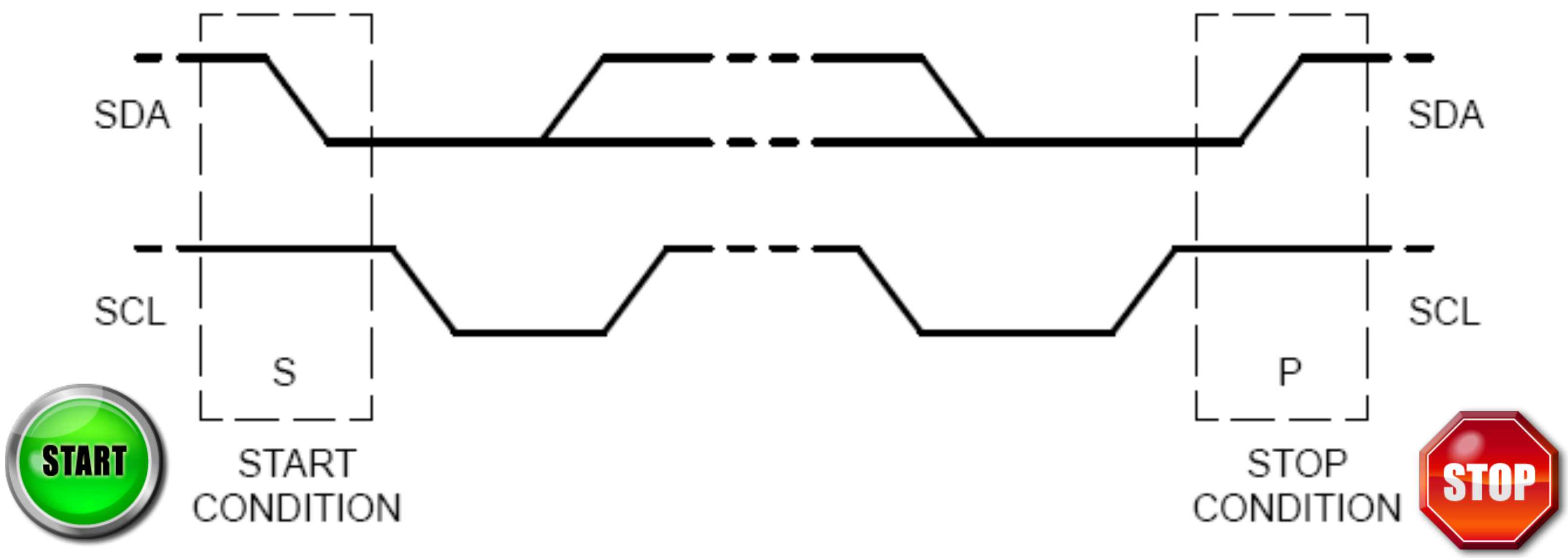
Transferring a Single Bit

- Absolute levels of logical ‘0’ (LOW) and ‘1’ (HIGH) depend on the associated level of VDD
- One clock pulse is generated for each data bit transferred
- Data on SDA line must be stable during *the HIGH period of the clock*
- HIGH/LOW state of the data line can only change when the clock signal on the SCL line is LOW



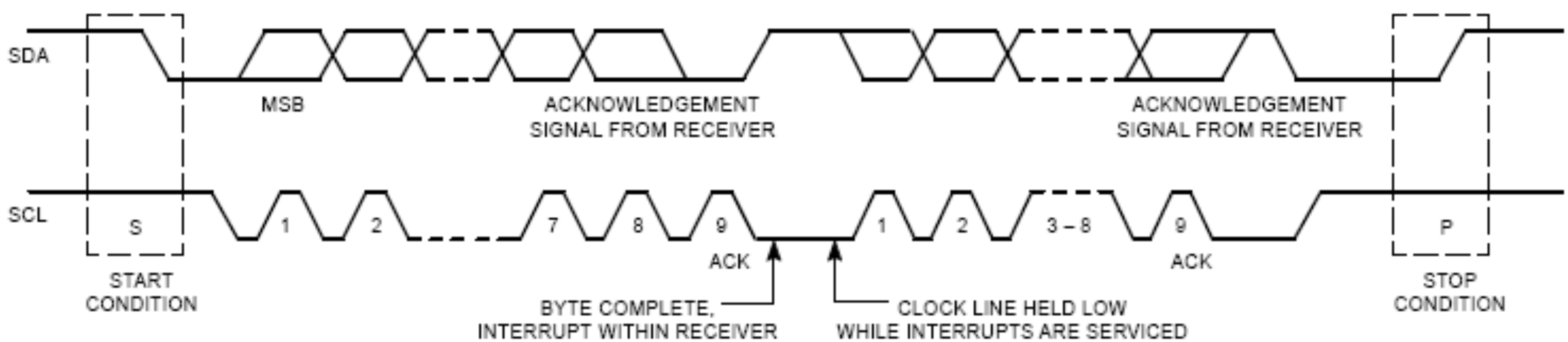
START and STOP Conditions

- START condition
  - HIGH to LOW transition on the SDA line *while SCL is HIGH*
- STOP condition
  - LOW to HIGH transition on the SDA line *while SCL is HIGH*
- START and STOP conditions are always generated by the master
- Bus considered to be busy after the START condition
  - Considered to be free again a certain time after the STOP condition



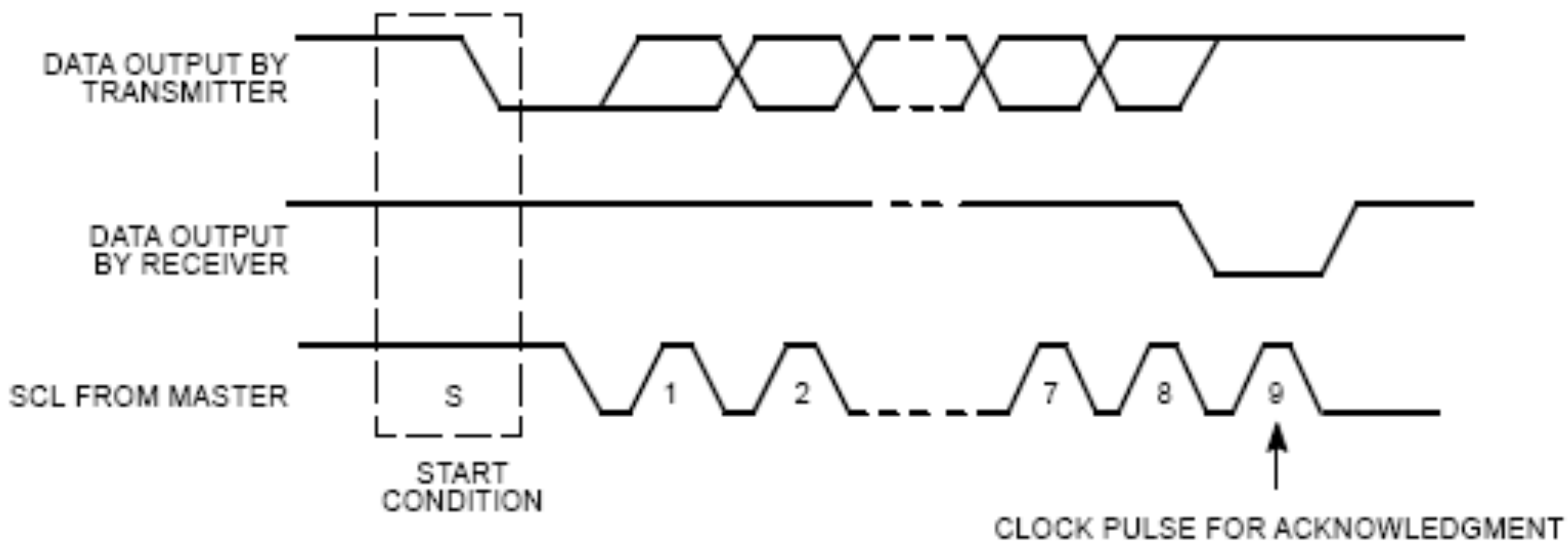
Transferring Data

- Every byte placed on the SDA line must be 8-bits long
  - Each byte has to be followed by an acknowledge (ack) bit
  - Data is transferred with the most significant bit (MSB) first
- Number of bytes that can be transmitted per transfer is unrestricted
- If a receiver can't receive another complete byte of data temporarily (e.g., busy servicing an internal interrupt)
  - Receiver can hold SCL LOW to force the transmitter into a wait state
  - Data transfer resumes when receiver is ready for another byte and releases SCL



Acknowledgment

- Data transfer with ack is obligatory
- Ack-related clock pulse is generated by the master
- Transmitter releases the SDA line (HIGH) during the ack clock pulse
- Receiver pulls down the SDA line during the ack clock pulse so that it remains LOW during the HIGH period of this clock pulse



Addressing

- First byte of transfer contains the slave address and the data direction
  - Address is 7 bits long, followed by the direction bit
  - Like all data bytes, address is transferred with the most significant bit first
- 7-bit address space allows for 128 unique I2C device addresses
  - 16 addresses are reserved for special purposes
  - Leaves only 112 addresses with this 7-bit address scheme
- New 10-bit address scheme has been introduced
- "General call" broadcast – to address every device on the bus
- What is the maximum number of devices in I2C limited by?

Clock Stretching

- Form of flow control
- An addressed slave device may hold the clock line low after receiving (or sending) a bit, indicating that it is not yet ready to process more data
- Master that is communicating with the slave will attempt to raise the clock to transfer the next bit, but
  - If the slave is clock stretching, the clock line will still be low
- Mechanism allows receivers that cannot keep up with a transmitter to control the flow of incoming data

SMBus & PMBus

- SMBus is a derivative of I2C
- Standard developed by Intel and now maintained by the SBS Forum
- Used to monitor critical parameters on PC motherboards and in embedded systems
  - Examples: Supply voltage monitor, temperature monitor, and fan monitor/control ICs with SMBus interfaces
- SMBus differs from I2C in that it incorporates
  - Packet Error Checking (PEC)
  - Timeout for transfers and clock stretching
  - ALERT line
  - SUSPEND line
  - Data-transfer formats
  - Maximum bitrate of 100 kHz/s
- PMBus standard is a new protocol on top of the SMBus
  - Defines commands and data structures for power control and management

Summary of Advantages

- Two-wire protocol
  - Minimizes interconnections and pins
  - Cost and power savings
- Multi-master capability
  - Allows for rapid testing
- Easy path for upgrades to embedded systems
  - Just clip on more I2C-compatible devices
  - I2C-compatible peripherals can also be added/removed while the system is running, which makes hot swapping possible

- The beauty is that a microcontroller can control a network of device chips with just two general-purpose I/O pins and software

Limitations

- Seven bits is not enough to prevent address collisions between the many thousands of available devices
  - Vendors rarely dedicate pins to configure the full address used on a given board
  - Vendors often provide pins to configure a few low order bits of the address and arbitrarily set the higher order bits to some value based on the model
    - Limits the number of devices of that model that can be present on the same bus
  - Ten-bit I2C addresses have not really caught on yet
- Supports a limited range of speeds
  - Bus capacitance also places a limit on the transfer speed
- The dark side of clock stretching
  - Can starve bandwidth needed by faster devices and increase latencies when talking to other devices
- So, typical practice is to have a number of I2C bus *segments*, each with a dozen devices and for a dedicated purpose
  - Example: One segment for high-speed devices, another for power management

Serial Peripheral Interconnect (SPI)

- Another kind of serial protocol in embedded systems (proposed by Motorola)
- Shorthand for “Serial Peripheral Interface”
- Generally faster than I^2C, capable of several Mbps

Applications:

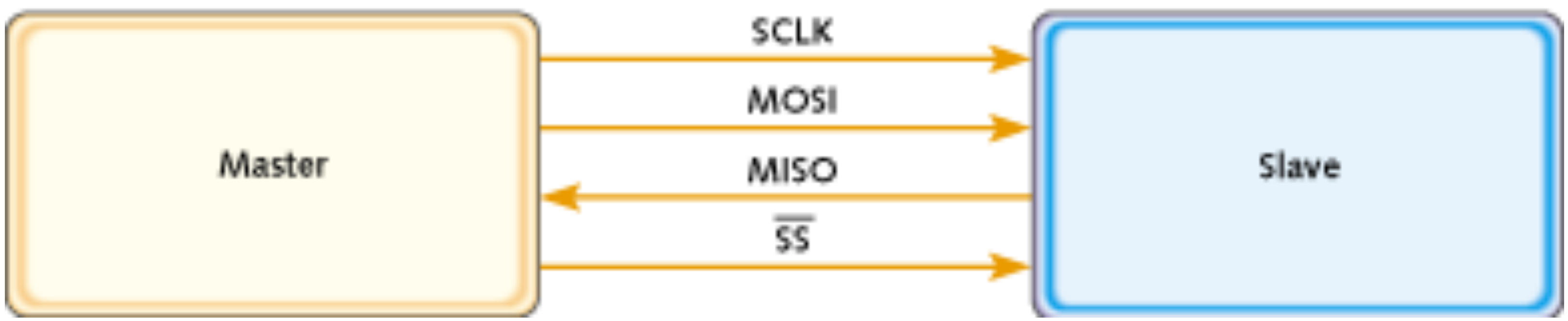
- Like I^2C, used in EEPROM, Flash, and real time clocks
- Better suited for “data streams”, i.e., analog-to-digital converters
- Full duplex capability: Communication between a codec and digital signal processor

Serial Peripheral Interconnect (SPI)

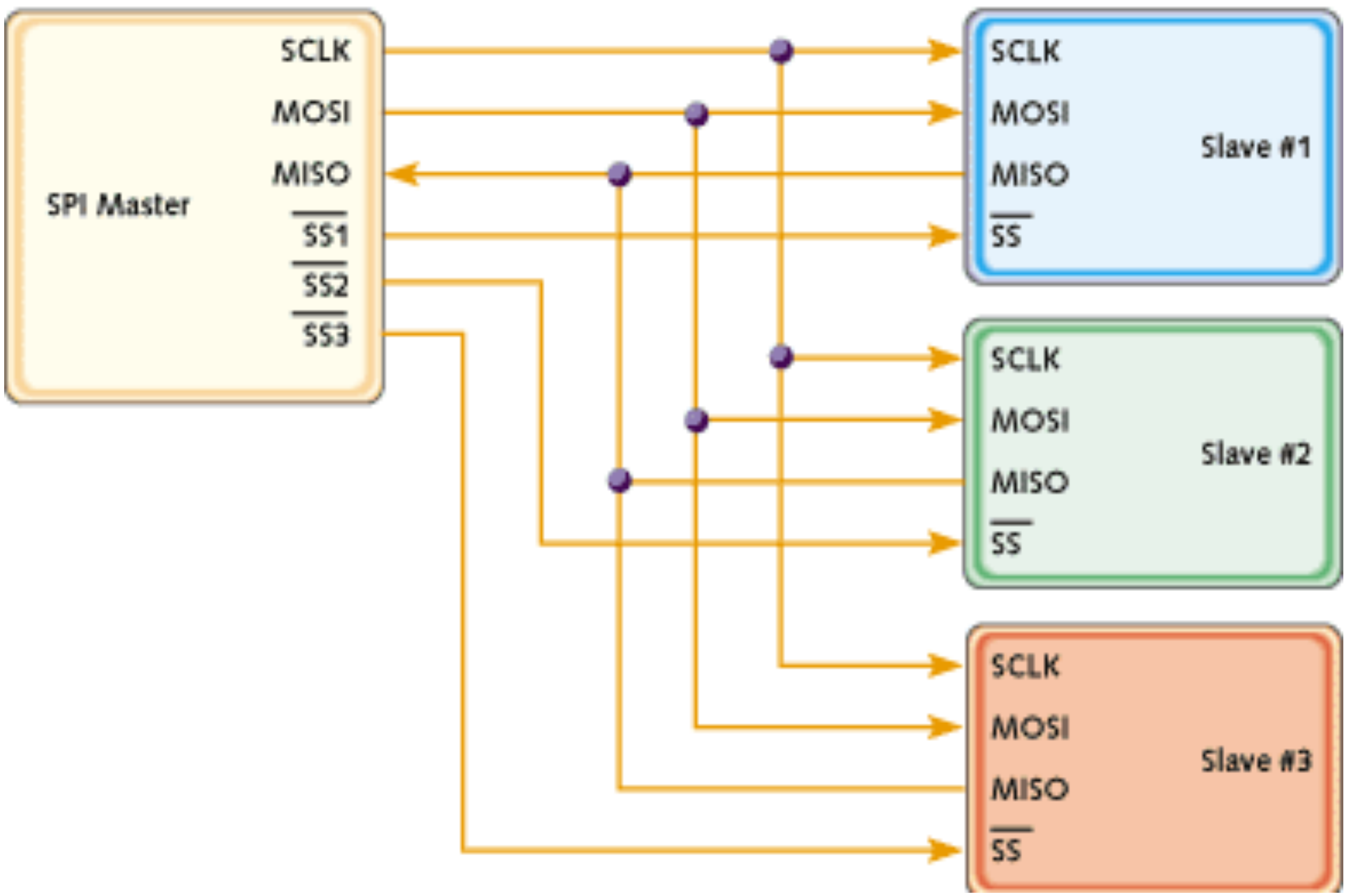
- Another kind of serial protocol in embedded systems (proposed by Motorola)
- Four-wire protocol
  - SCLK — Serial Clock
  - MOSI/SIMO — Master Output, Slave Input
  - MISO/SOMI — Master Input, Slave Output
  - SS — Slave Select
- Single master device and with one or more slave devices
- Higher throughput than I2C and can do “stream transfers”
- No arbitration required
- But
  - Requires more pins
  - Has no hardware flow control
  - No slave acknowledgment (master could be talking to thin air and not even know it)

Serial Peripheral Interconnect (SPI)

- Synchronous serial data link operating at full duplex
- For point-to-point, SPI is simple and efficient
  - Less overhead than I^2C due to lack of addressing, plus SPI is full duplex
- For multiple slaves, each slave needs separate slave select signal
  - More effort and more hardware than I^2C



Serial Peripheral Interconnect (SPI)

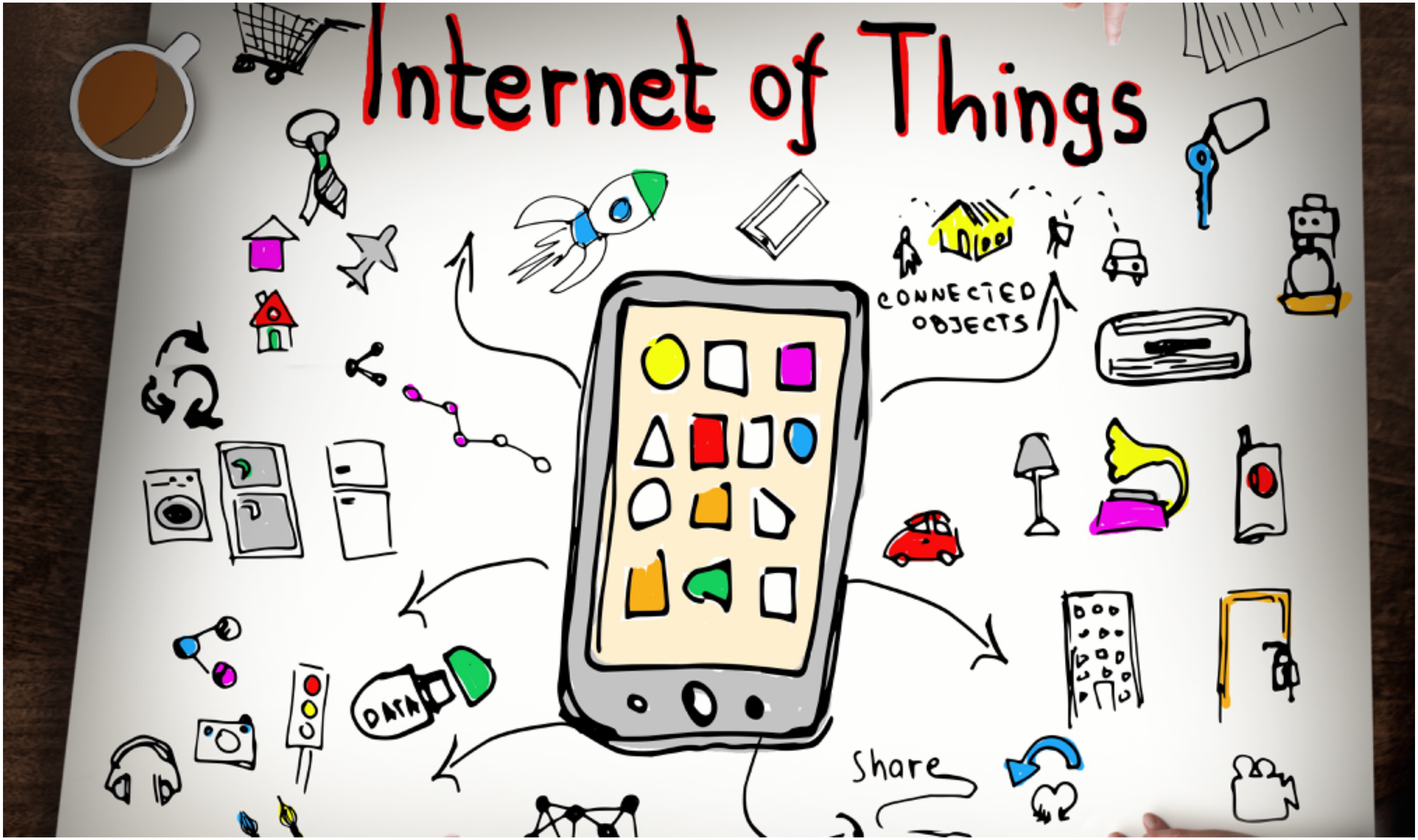


Serial Peripheral Interconnect (SPI)

- SPI interface defines only the communication lines and the clock edge
- There is no specified flow control
- No acknowledgement mechanism to confirm receipt of data
- For multiple slaves, must employ “bit-banging”

I2C and SPI

- I^2C and SPI provide good support for communication with slow peripheral devices that are accessed intermittently
- Serial communication protocols
- Meant for short distances "inside the box"
- Low complexity
- Low cost
- Low speed (a few Mbps at the fastest)
- Mainly EEPROMs and real-time clocks
- I^2C easily accommodates multiple devices on a single bus
- SPI is faster, but gets complicated when there is more than one slave involved.



IoT Protocols: I2C, SPI

18-738 Sports Technology

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