ENGR5720 – Mobile and Pervasive Computing

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Application and Requirements

Lecture notes based on Ubiquitous Computing: Smart Devices, Environments and Interactions (Chapter 2)

Disclaimer: The slides have been adapted from content developed by Dr. Ramiro Liscano

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Mobility and pervasive computing

- Mobility and pervasive computing are related but distinct concepts.
- Mobility focuses on the ability to use computing devices while on the move.
- While pervasive computing aims to embed computing power into everyday objects and environments, often without the user consciously interacting with a traditional computer.
- Examples of mobile computing include smartphones, tablets, and laptops used while traveling.
- Pervasive computing examples include smart homes, wearable health trackers, and automated transportation systems.

Learning Objectives

- To look at examples of everyday ubiquitous applications that facilitate people's routine activities.
- These can be grouped into
  - –human–computer interaction,
  - –human–physical world interaction,
  - –computer– physical world interaction,
  - –human–human interaction.

Human–Computer Interaction (HCI)

- Interaction where a human uses a computer or digital interface directly.
  - **Smartphone apps** (e.g., calendar, weather, maps)
  - **Voice assistants** (e.g., Siri, Alexa, Google Assistant)
  - **Web browsers** (searching for information, booking tickets)
  - **ATM machines** (banking interfaces)
  - **Self-service kiosks** (e.g., in airports or fast-food restaurants)

Human–Physical World Interaction

- Interaction where humans interact with the physical world, often mediated by sensors or augmented technologies.
  - **Augmented reality (AR) apps** (e.g., IKEA Place to visualize furniture in your room)
  - **Fitness trackers** (interpreting physical activity like steps or heart rate)
  - **Smart glasses** (e.g., Google Glass for overlaying digital data onto physical environments)
  - **Gesture-controlled devices** (e.g., gaming consoles like Nintendo Wii or VR systems)
  - **Contactless payment systems** (tapping a card or phone on a physical terminal)

4. Human–Human Interaction (mediated by technology)

- Technology facilitates communication between people.
  - **Messaging apps** (e.g., WhatsApp, Messenger)
  - **Social media platforms** (e.g., Facebook, Instagram)
  - **Video conferencing tools** (e.g., Zoom, Microsoft Teams)
  - **Collaborative workspaces** (e.g., Google Docs, Trello)
  - **Online multiplayer games** (cooperative or competitive interaction)

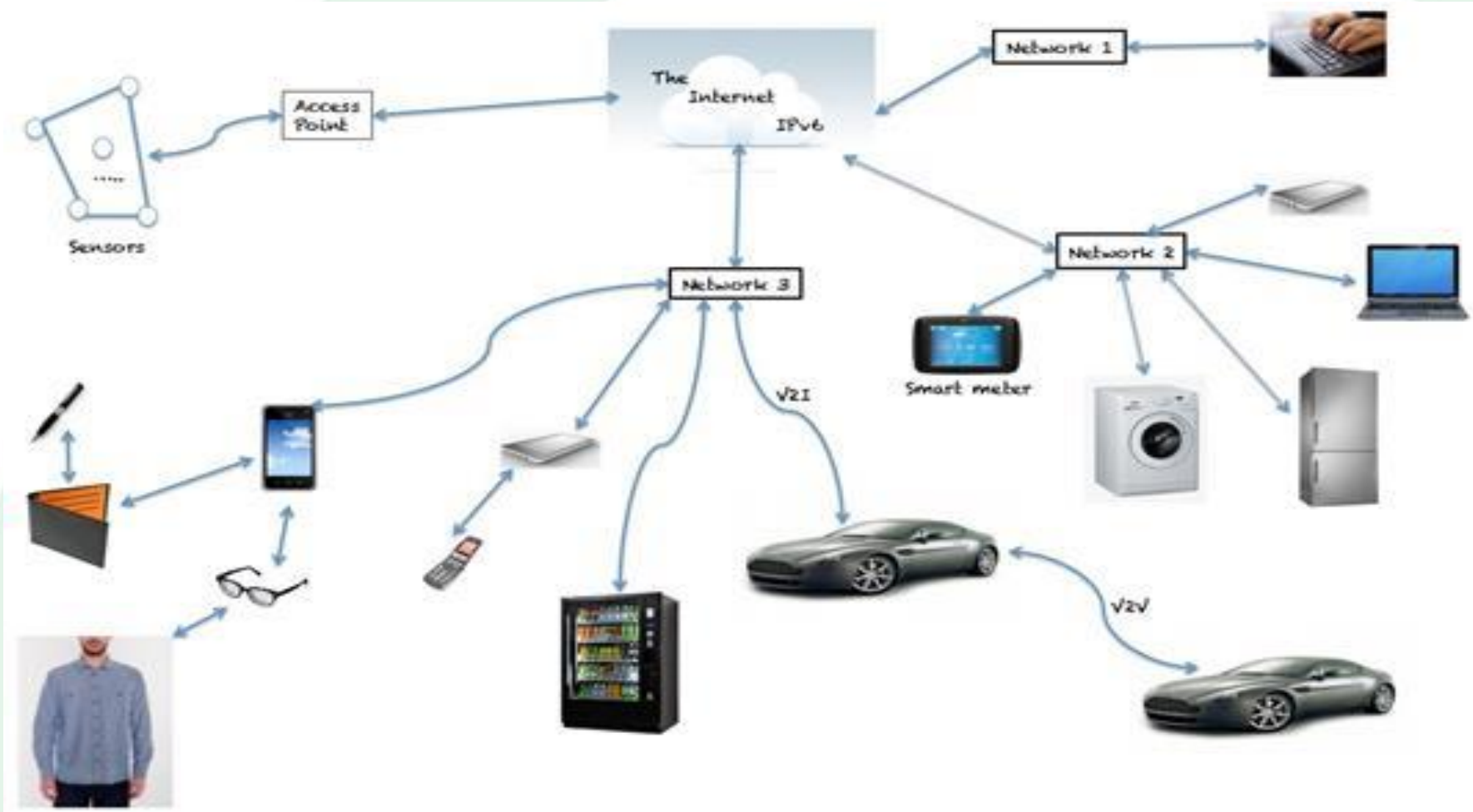
3. Computer–Physical World Interaction

- Computers or systems sense and/or act on the physical world without direct human input.
  - **Smart thermostats** (e.g., Nest auto-adjusts based on presence and temperature)
  - **Robotic vacuum cleaners** (e.g., Roomba navigating a home)
  - **Industrial automation systems** (robots in a factory line adjusting operations in real time)
  - **Smart irrigation systems** (adjust watering based on soil moisture and weather)
  - **Home security systems** (motion sensors triggering lights or alarms)

Ubiquitous Networks of Devices: CCI

- Three types of wide-area ICT networks are quite ubiquitous at this time:
  - GSM and other wireless telecoms networks;
  - TCP/IP-based wireless access networks attached to a wired Internet backbone;
  - satellite networks including Global Positioning System (GPS) networks.

Ubiquitous Networks of Devices: CCI



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Human–Computer Interaction

- Ubiquitous Audio-Video Content Access
  - Multi-media content should be available over every network and accessed by any suitable device.
  - Individual voice, video and audio services should be able to be dynamically arranged to offer more advanced services.
    - For example, when a voice call arrives, TV and radio are automatically paused or muted.
    - To support such dynamic service composition requires the use of a pervasive network infrastructure, standard multimedia data exchange formats, dynamic service discovery and the use of metadata.

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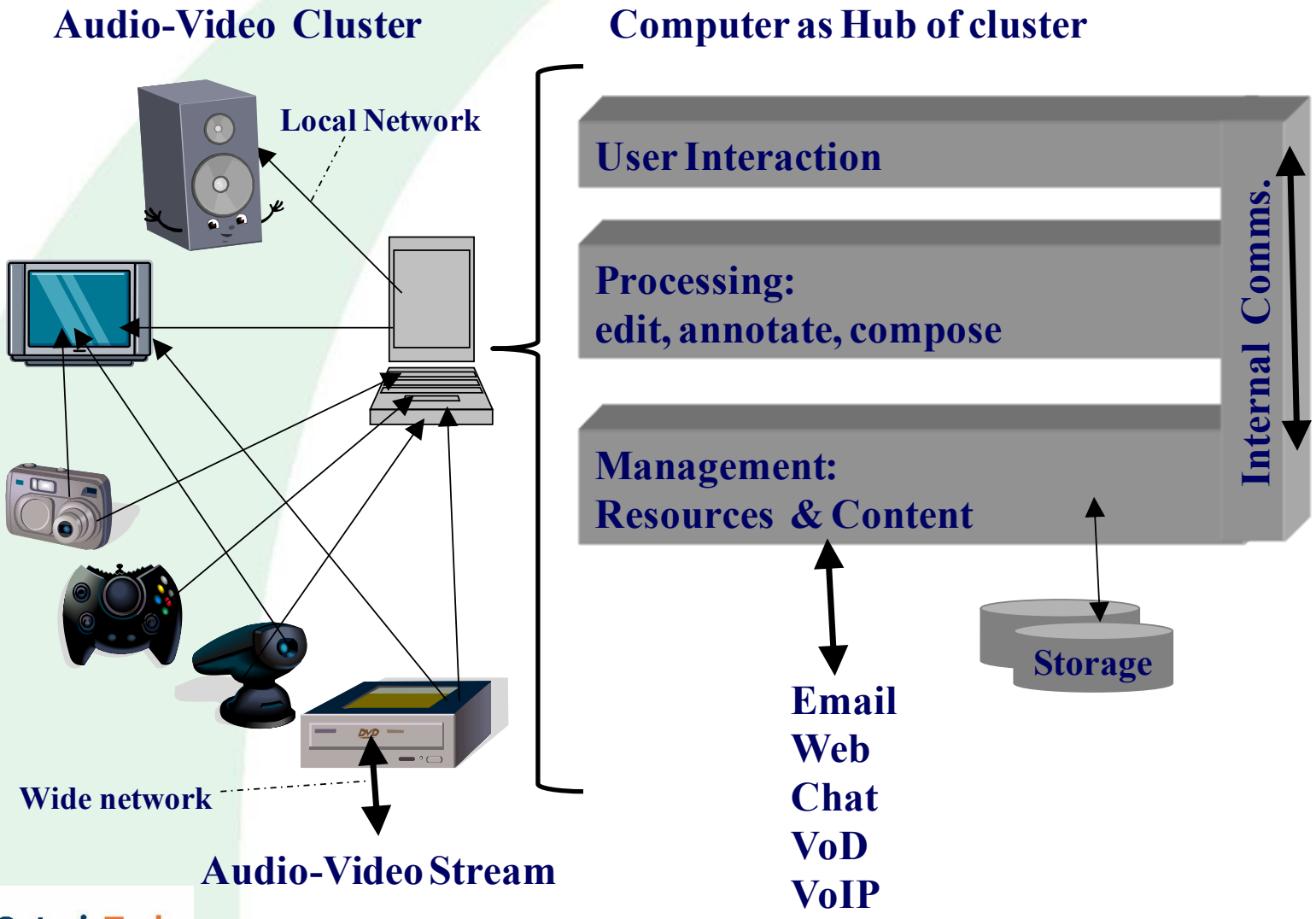
Ubiquitous Audio-Video Content Access



Human–Computer Interaction

- Universal Local Control of ICT Systems
  - Many appliances have device interfaces such as infrared ones allowing them to be controlled via short range local control devices, within a distance of a few metres.
  - Software-based universal device controllers contain both hardware buttons and a display for soft buttons
  - Key design issues are how a controller can discover which devices are situated locally, what features the device supports and how to describe them.
    - One way to do this is to enable the device to notify users of various Web URLs that specify the presentation, model and manufacturer URL.

Universal Local Control of ICT Systems

- Limitations
  - Many everyday situations, direct manipulation of the appliance is easier, faster, and more convenient than handheld-mediated interaction.

  - Some appliances may also require a user presence at the device for safety reasons.
  - Universal controllers also introduce concurrent control issues when multiple users try to control the same device using multiple controllers.

Universal Local Control of ICT Systems

Implications:

- Loss of user experience quality due to simultaneous, conflicting commands.
- Lack of coordination or user priority policy leads to device instability.
- Trust issues with smart systems due to unexpected behavior.

Possible Solutions:

- Implement user session ownership, where one user has control priority until released.
- Use context-aware conflict resolution, e.g., detecting room occupancy or active session.
- Notify other users when a device is in use and allow collaborative control negotiation.
- Introduce access control or scheduling, especially in multi-user environments.

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Human-to-Human Interaction (HHI) Applications

- Wide area electronically mediated HHI enables social links to persist by voice, video and text when people are not so co-located.
  - U-Commerce: contactless smart cards and context-aware service provisioning.
  - Enhancing the Productivity of Mobile Humans: Location-aware services.
  - Care in the Community: Elderly care. First, a normal activity profile of users is built up. Next, new data can be analysed automatically for anomalies.

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Human-Physical World-Computer Interaction (HPI) and (CPI)

- Physical Environment Awareness: This is primarily the area of location-aware services such as tracking of objects and locating services based on location context.
- Environment Control: We already touched based on these types of interactions in the HCI section that describe the concept of universal remote access to devices.
- Smart Utilities: Considers the objective of energy savings by monitoring the environment and adapting to it.
- Smart Buildings and Home Automation: There is a significant amount of activity in this area with many home communication protocols like X10, ZigBee, and WiFI competing for the market.
- Smart Living Environments and Smart Furniture: The idea here is to augment normal day to day items with sensors to support the determination of a user's context. Smart cups, sofa, mats, etc.
- Smart Vehicles, Transport and Travel: The InternetCAR.

Summary

- Smart Devices
  - There are many sensory devices being embedded into our environment. In this area research is primarily in MEMS (Micro-Electro-Mechanical Systems).
- Context-Awareness and Service Discovery
  - Service discovery of local network resources is weak and the discovery of other local environment resources is still virtually non-existent, even though there have been much prior work on this (i.e. Cooltown).
- Wearable Smart Devices and Implants
  - Still in its infancy. There are many ethical questions with this technology.

Mobile and Pervasive Computing System Characteristics

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A Definition for Pervasive and Ubiquitous Computing

- The terms Pervasive and Ubiquitous are commonly used together. In actuality they mean different things.
  - Pervasive: means that the technology is “everywhere”. We expect to be able to use or access that form of technology anywhere we go.
    - For example, telephone communication is pervasive. This has come about from many years of standardisation and network formation.
    - It is possible to measure if a technology is pervasive by simply determining how accessible it is.
  - Ubiquitous: means that the technology is hidden and invisible to the user. The user is unaware that something is happening in the background.
    - This requires more user evaluation because it is ultimately the user that decides if they are aware of the technology or not.
    - What do you think are good examples of ubiquitous computing?

Ubiquitous Computing - History

- Mark Weiser at Xerox Parc has been given credit for the start of ubiquitous computing with his famous quote and paper:
  - "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."
  - M. Weiser, "The Computer for the 21st Century," Sci. Amer., Sept., 1991.
    - This is more than 20 years ago. In fact we find that we are currently living in the era of pervasive computing.

Pervasive Computing - History

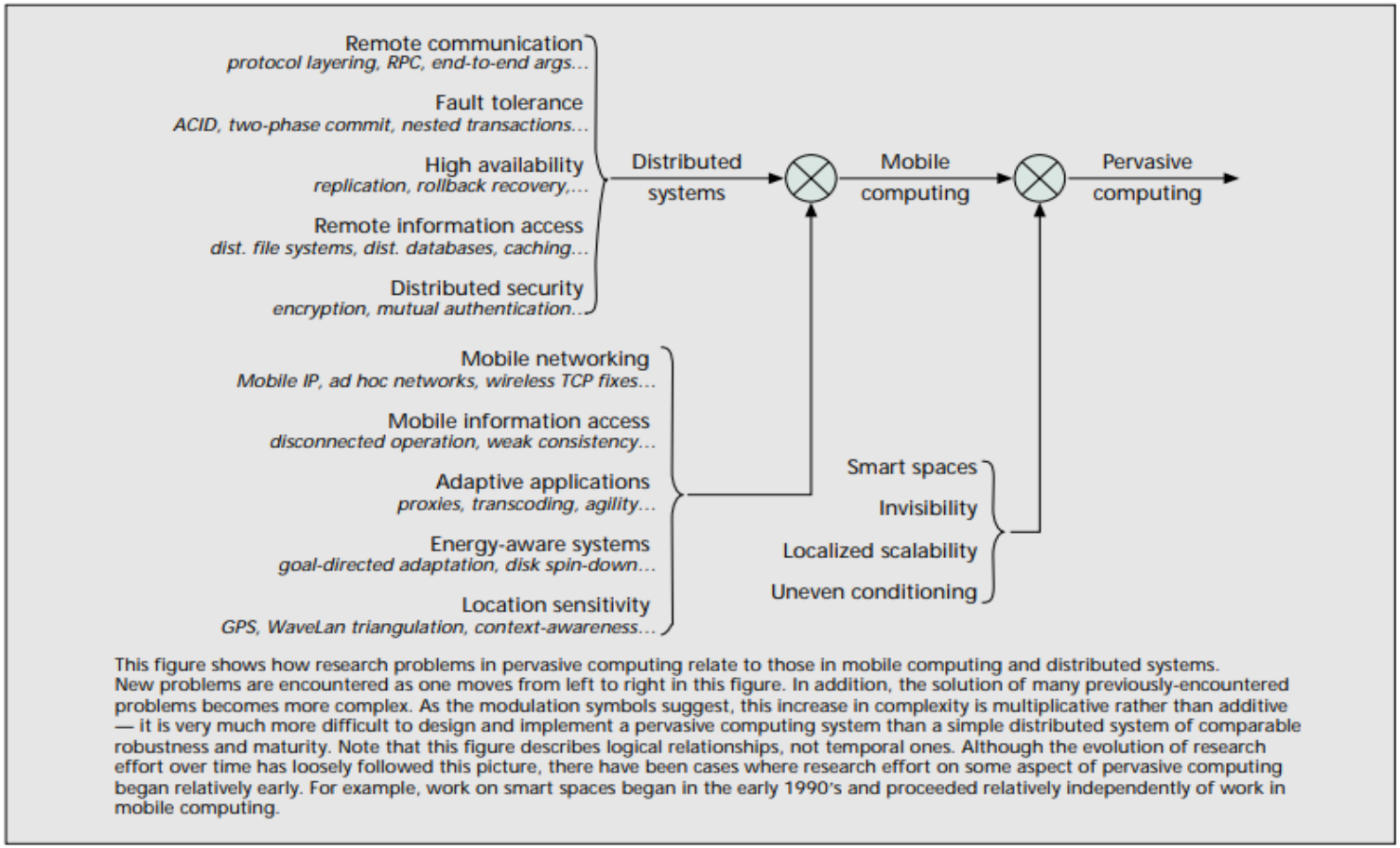
- On the other hand Pervasive Computing has been a goal since the early 70s with the advent of telecommunications.
- Two distinct earlier steps in this evolution are distributed systems and mobile computing.
- We now see the fruition of this research in what is termed as the “Internet of Things” or IoT.

Pervasive Computing - Enabling Technologies

- What technologies have enabled Pervasive Computing?
  - Wired communication networks.
    - The SS7 PSTN network. The current Virtual Home Environment (VHE) project.
  - Wireless communication networks.
    - mostly cellular, currently 3G/4G/5G, and UMTS.
  - The Internet
- "Wireless Internet is the catalyst for the convergence of digital communications, computing, and rich media."
  - Hansmann et al.
- This is one meaning for "Pervasive Computing" and can be achieved by simply conforming to one communication standard and a set of universal and common services.

Trend: smaller, higher resource devices

Technology Relationships for Pervasive Computing



This figure shows how research problems in pervasive computing relate to those in mobile computing and distributed systems. New problems are encountered as one moves from left to right in this figure. In addition, the solution of many previously-encountered problems becomes more complex. As the modulation symbols suggest, this increase in complexity is multiplicative rather than additive — it is very much more difficult to design and implement a pervasive computing system than a simple distributed system of comparable robustness and maturity. Note that this figure describes logical relationships, not temporal ones. Although the evolution of research effort over time has loosely followed this picture, there have been cases where research effort on some aspect of pervasive computing began relatively early. For example, work on smart spaces began in the early 1990's and proceeded relatively independently of work in mobile computing.

Figure 1. *Taxonomy of computer systems research problems in pervasive computing.*

M. Satyanarayanan. Pervasive computing: Vision and challenges. *IEEE Personal Communications*, 8(4):10–17, Aug. 2001.

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Pervasive and Mobile Computing

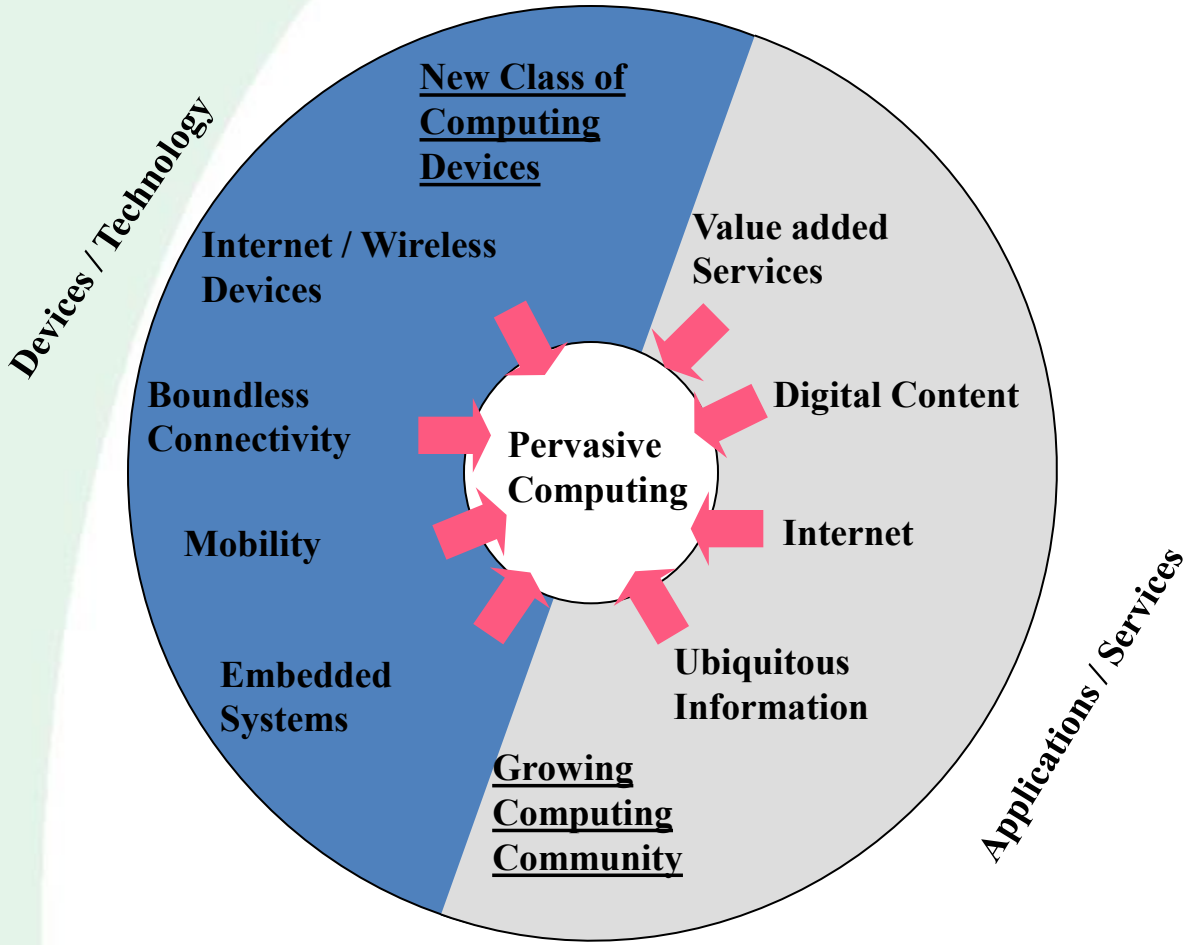
- An article by Professor M. Satyanarayanan "Pervasive Computing: Vision and Challenges" identifies the relationship between mobile and pervasive computing.
  - Pervasive and Ubiquitous computing are concerned as well with issues like "smart spaces" and "invisible technology"
  - These traits are mostly from the ubiquitous computing domain but have drifted into the area of pervasive computing.

M. Satyanarayanan. Pervasive computing: Vision and challenges. *IEEE Personal Communications*, 8(4):10–17, Aug. 2001.

Pervasive and Ubiquitous Computing

- In the Computer Science Domain, the trend has been to research in the topic of Ubiquitous Computing.
  - Context aware computing, software agents, and policy languages.
  - The chapters of the textbook “Fundamentals of Mobile and Pervasive Computing” Adelstein et al. related to Context-aware Computing and Service Discovery.

Factors driving Pervasive Computing



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Pervasive & Ubiquitous Computing Principles

- Pervasive Computing postulates the following paradigms:
  - Decentralization
  - Diversification
  - Connectivity
  - Simplicity
- Ubiquitous Computing postulates the following paradigms:
  - Invisibility
  - Context Aware or Smart Spaces
  - Personalization

Decentralization

- We have moved from the Mainframe -> Personal -> Pervasive Computing Era
  - Lightweight PC companions are handheld computers.
  - Smart cards are ultra-thin security tokens.
  - Cellular phones achieve wireless mobile access.
  - Set-top-boxes offer interactive TV and game consoles for home entertainment.
  - Intelligent appliances in a networked home allow access the access to a variety of controls from the Internet.
  - Industrial controllers or network switches will decentralize manufacturing.
  - Embedded systems for cars provide range of diagnostics, communications, navigation, and security features.

Results of Decentralization

- Heterogeneous Networks and Devices
  - Without heterogeneous devices, some of the issues we are trying to investigate simply go away.
    - In particular, content adaptation, network interoperability.
    - We could follow the telecom approach and have pervasive computing capabilities using homogeneous networks.
      - What has changed? Why can't we do this?
- End-point application deployment
  - There are more "smart-devices" now than before and end point applications.
    - The model for service or application deployment is now distributed both geographically and enterprise wide.
      - This leads to Diversification which is the next paradigm shift of Pervasive Computing.

Device Diversification

- There is a clear shift from universal computers to diversified devices that meet the requirements of a group of users in particular situations.
- This diversification has led to the study of content adaptability to manage the plethora of different devices on the market.
  - Now in 2025 we see that our devices are becoming more powerful and in fact they can in principle computationally manage mush of what the Internet can produce, though human interfacing has become quite a challenge.
  - The challenge is how to manage the difference interfaces that these devices offer without having to develop many different applications.
  - One solution is to develop an interface based on XML and execute it on a general browser. Another solution is to use mobile code and a sandbox to run in, like Java. All of these approaches are used now.

Network Diversification

- Network Diversification has also occurred.
  - A quintessential characteristic of pervasive computing is the ability to adapt to dynamic changes in computing and communication environments.
  - This adaptation should be as transparent as possible to the user (i.e. without much effort). This a ubiquitous computing trait.
- Although we have made great strides in network connectivity, not all devices and not all locations support continuous network connectivity.
  - Thus, applications should support disconnected and weakly connected operation.

Mobile Computing Challenges

- Four key constraints of mobility have forced the development of specialized techniques for mobile computing to compensate for:
  1. Unpredictable variation in network quality,
  2. Lowered trust and robustness of mobile elements,
  3. Limitations on local resources imposed by weight and size constraints,
  4. and concern for battery power consumption.
- These all make good topics for investigation.

Core Properties of Pervasive and Ubiquitous Systems

- Distributed systems
  - Computers need to be networked, distributed, and transparently accessible.
- Implicit Human-Device Interaction (iHCI)
  - Human-computer interaction needs to be hidden.
- Context-aware
  - Computers need to be context-aware.
- Autonomous Systems
  - Computers need to operate autonomously **(No human supervision)**
- Intelligent Systems
  - Eventually, computers need to have intelligent organizational interaction.

Distributed Systems Properties

Property	Definition
Universal, seamless, heterogeneous	Able to operate across different heterogeneous environments
Networked	Often connected wirelessly
Synchronized, coordinated	Support synchronous or asynchronous coordination over time and space.
Open	Components can be dynamically and discovered.
Transparent, virtual	Acts as a single virtual system even though it is distributed
Mobile, nomadic	Users, services, data, code, and devices may be mobile.

S. Poslad. Ubiquitous Computing: Smart devices, Environments, and Interactions, John Wiley & Sons, 2009.

iHCI System Properties

Property	Definition
Non-intrusive	Integrated into the ecology of the home or workplace.
Tangible, natural	Natural user interfaces.
Anticipatory, proactive	Improves user experience through anticipated actions (related to context-awareness).
Affective, emotive	Computing that relates to human emotions.
User-aware	Aware of user characteristics and desires (related to context-aware).
Post-human	Extends person's normal experience across space and time.
Sense of presence	A person is in a real-time interactive environment.

S. Poslad. Ubiquitous Computing: Smart devices, Environments, and Interactions, John Wiley & Sons, 2009.

Context-aware Properties

Property	Definition
Sentient	Systems can discover and take advantage of the situation.
Adaptive	Systems actively adapt to context changes.
User-aware	Tailored to individual user or type of user.
Environment aware	General context awareness including spatial and temporal awareness.
ICT awareness	Awareness of ICT infrastructure and QoS of ICT.

S. Poslad. Ubiquitous Computing: Smart devices, Environments, and Interactions, John Wiley & Sons, 2009.

Autonomous Systems Properties

Property	Definition
Automatic	Operates without human prevention.
Embedded	I/O and computation are contained in the device it controls.
Resource constraint	Systems are designed to be constrained in size.
Untethered, amorphous	Able to work independently and proactively.
Autonomic, self-*	Self-configurable, self-healing, self-optimising, self-protecting behaviour.
Emergent, self-organizing	More complex behaviour can arise out of multiple simple behaviours.

S. Poslad. Ubiquitous Computing: Smart devices, Environments, and Interactions, John Wiley & Sons, 2009.

Intelligent System Properties

- Individual (these properties are very much the same as those used for agent systems)

Property	Definition
Reactive, reflex	Environment events are sensed, then a trigger action is selected.
Model-base rule, policy-based logic	Uses a logic based reasoning component.
Goal-oriented planning	User goals are driven by goals.
Utility-based, game theoretic	User goals can be used to plan actions.
Learning, adaptive	Systems can improve their own performance.

S. Poslad. Ubiquitous Computing: Smart devices, Environments, and Interactions, John Wiley & Sons, 2009.

Ubiquitous Computing Models

- Everything uses the term “Smart”
- ‘Smart’ means systems are:
  - active, digital, networked, autonomous, reconfigurable, local control of its own resources, e.g., energy, data storage etc.
- Smart Devices
  - Devices are now more complex, multi-functional, personalized & private.
- Smart Environments
  - Sense and react to events such as people, entering and leaving controlled environments.
- Smart Interactions
  - Use more service enabled devices with simpler functions and allow them to interoperate.

Smart Devices

- The most popular smart devices are mobile devices.
  - Accompanied
    - Carried in clothes like RFID
  - Portable
    - Laptops, highest resource capability.
  - Hand-held
    - Operated with one hand. Typical smart phones.
  - Wearable
    - Jewellery, operate autonomously, low resource devices.
  - Implanted
    - Specially treated to be placed into the body.

Smart Environments

- Tagging, Sensing, and Controlling
  - Tagging and annotating the physical env. RFID
- Sensing
  - Sensor networks or simple sensors
- Filtering
  - Abstract view of the physical world
- Adapting
  - System behaviour can adapt to the sensed data.
- Controlling
  - Physical devices can be controlled based on sensed data.
- Assembling
  - Robots can be controlled to assemble items
- Regulating
  - Work in a fixed location to regulate the enviroment.

Smart Interactions

- Coordinated interactions
  - Different components act together to achieve a common goal.
- Policy and convention-based interaction
  - Coordination is achieved based upon a set of agreed rules of contracts.
- Dynamic organisational interactions
  - Created based on arrangements between individuals. Auctions, brokers, contract-nets, subscriptions, etc.
- Semantic and linguistic interactions
  - Shared definitions about the use of the communication.

Conferences Related to Pervasive Computing

- Because the term Pervasive is very broad there can be quite a few conferences that discuss the topic. In particular several Wireless Conferences have tracks in Pervasive Computing.
  - Recently WiMob 2005-08, Montreal.
- Well Known Conferences
  - IEEE International Conference on Pervasive Computing and Communications (PERCOM)
  - International Conference on Ubiquitous Computing (UbiComp)
  - International Conference on Mobile and Ubiquitous Systems: Networking and Services (Mobiquitous)
  - International Conference on Pervasive Computing
  - NIST's Pervasive Computing Conferences
    - 2000 – 2003 (http://www.nist.gov/pc200x/ where x=0,1, 2, or 3

Journals related to Pervasive and Ubiquitous Computing

- IEEE Personal Communications
- IEEE Pervasive Computing: Mobile and Ubiquitous systems
- IEEE Distributed Systems Online: Mobile & Pervasive section
- Springer Verlag Personal and Ubiquitous Computing
- Elsevier Journal on Pervasive and Mobile Computing
- IBM Systems Journal - Pervasive computing
- UBICC – Ubiquitous Computing and Communications Journal

Internet of Things (IoT)

IoT Background

- The Internet of Things (IoT) is actually a marketing term that was coined by Kevin Ashton in 1999
  - Back in 1999, a technologist called Kevin Ashton pointed out that almost all the information available on the internet–a mere 50 petabytes at that time–had been captured or created by humans in the form of text, photos, videos etc.
  - Ashton suggested that this was likely to change in the not too distant future as computers became capable of generating and collecting data by themselves, without human oversight.

You can read a biography on Kevin Ashton in the Wikipedia, http://en.wikipedia.org/wiki/Kevin_Ashton

IoT Background

- It is primarily based on the use of RFID tags but active RFID tags with sensing capability have all the similarities of pervasive systems.
- There is recent IEEE conference on the subject as well and a lot of activity in the standard boards. (iot-conference.org/iot2025)

Challenges based on IEEE IoT

- "The IoT connects a vast number of **heterogeneous smart objects** that cooperate to support manifold applications. This requires **efficient use of scarce resources** in order to adapt to a dynamically changing environment. …"
- Most of the papers in the conference are similar to those that are found in pervasive and ubiquitous conferences
  - Localization
  - Embedded devices
  - Architectures
  - …
- What is interesting tough is the movement for a standard in device service interoperability.

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IoT Elements

- IoT Applications typically will consist of the following 6 hardware and software elements.

A. Al-Fuqaha et al., Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications, IEEE Comm. Surveys & Tutorials, Vol. 17, No. 4, pp 2347-2376, 2015.

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