General

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  – 4149 AVW

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  – Office Hours – M-W 3-4 PM

• Class Meets – Tu Th 8:00 – 9:30 CSIC 3117
Prerequisite

• Required Background
  – must have 351 and 330 (412 or 430 would be helpful)

• Expectations
  – Understand the basics of Computer Architecture
  – Experience in implementing non-trivial systems-type projects

  – Should know
    • Processor
    • Memory
    • Kernel vs. user process
  – Familiar with basic probability
Expectations – After the course

• Understand the fundamentals of networking protocols, including protocol layering, basic medium access including wireless protocols, routing, addressing, congestion control
• Understand the principles behind the Internet protocols and some application layer protocols such as http, ftp, and DNS, and a few peer-to-peer systems/protocols such as Gnutella and Chord.
• Understand some of the limitations of the current Internet and its service model
• Understand the causes behind network congestion, and explain the basic methods for alleviating congestion
• Design, implement, and test substantial parts of network protocols
Announcements

• Required Work
  – will require about the same amount of effort as 412
    • 412 a (slightly) harder project to debug
    • 417 project is (by design) more ambiguous

• Required Texts
Other Material

• Recommended Texts

• RFCs
Grading

• Final 30%
• In-Term Exam(s) 30%
• Programming Assignments 35%
• Class Participation 5%
  – Pop Quizzes
What is this course all about?

• Computer Networking
  – ???

![Diagram showing computer networking with User A, Computer A, User B, Computer B, and Internet]

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CMSC417 Set 1
Uses of Computer Networks

Computer networks are collections of autonomous computers, e.g., the Internet.

They have many uses:

- Business Applications »
- Home Applications »
- Mobile Users »

These uses raise:

- Social Issues »

This text covers networks for all of these uses.
Business Applications

- Companies use networks and computers for resource sharing with the client-server model:

- Other popular uses are communication, e.g., email, VoIP, and e-commerce
Business Applications of Networks (2)

• The client-server model involves requests and replies.

![Diagram showing client-server model with client and server machines connected by network, showing request and reply processes.]
Home Applications

- Homes contain many networked devices, e.g., computers, TVs, connected to the Internet by cable, DSL, wireless, etc.
- Home users communicate, e.g., social networks, consume content, e.g., video, and transact, e.g., auctions.
- Some applications use the peer-to-peer model in which there are no fixed clients and servers.
Home Network Applications (3)

- Some forms of e-commerce.

<table>
<thead>
<tr>
<th>Tag</th>
<th>Full name</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2C</td>
<td>Business-to-consumer</td>
<td>Ordering books on-line</td>
</tr>
<tr>
<td>B2B</td>
<td>Business-to-business</td>
<td>Car manufacturer ordering tires from supplier</td>
</tr>
<tr>
<td>G2C</td>
<td>Government-to-consumer</td>
<td>Government distributing tax forms electronically</td>
</tr>
<tr>
<td>C2C</td>
<td>Consumer-to-consumer</td>
<td>Auctioning second-hand products on-line</td>
</tr>
<tr>
<td>P2P</td>
<td>Peer-to-peer</td>
<td>File sharing</td>
</tr>
</tbody>
</table>
Mobile Users

• Tablets, laptops, and smart phones are popular devices; WiFi hotspots and 3G cellular provide wireless connectivity.

• Mobile users communicate, e.g., voice and texts, consume content, e.g., video and Web, and use sensors, e.g., GPS.

<table>
<thead>
<tr>
<th>Wireless</th>
<th>Mobile</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>No</td>
<td>Desktop computers in offices</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
<td>A notebook computer used in a hotel room</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Networks in unwired buildings</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Store inventory with a handheld computer</td>
</tr>
</tbody>
</table>
Social Issues

- Network neutrality – no network restrictions
- Content ownership, e.g., DMCA takedowns
- Anonymity and censorship
- Privacy, e.g., Web tracking and profiling
- Theft, e.g., botnets and phishing
Network Hardware

Networks can be classified by their scale:

<table>
<thead>
<tr>
<th>Scale</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vicinity</td>
<td>PAN (Personal Area Network) »</td>
</tr>
<tr>
<td>Building</td>
<td>LAN (Local Area Network) »</td>
</tr>
<tr>
<td>City</td>
<td>MAN (Metropolitan Area Network) »</td>
</tr>
<tr>
<td>Country</td>
<td>WAN (Wide Area Network) »</td>
</tr>
<tr>
<td>Planet</td>
<td>The Internet (network of all networks)</td>
</tr>
</tbody>
</table>
Personal Area Network

Connect devices over the range of a person

Example of a Bluetooth (wireless) PAN:
Local Area Networks

• Connect devices in a home or office building
• Called *enterprise network* in a company

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Wireless LAN with 802.11

Wired LAN with switched Ethernet
Local Area Networks

- Two broadcast networks
  - (a) Bus
  - (b) Ring
Metropolitan Area Networks

Connect devices over a metropolitan area
Example MAN based on cable TV:
Wide Area Networks

- Relation between hosts on LANs and the subnet.
Wide Area Networks (2)

- A stream of packets from sender to receiver.
Wide Area Networks (1)

• Connect devices over a country
• Example WAN connecting three branch offices:
Wide Area Networks (2)

- An ISP (Internet Service Provider) network is also a WAN.
- Customers buy connectivity from the ISP to use it.
Wide Area Networks (3)

- A VPN (Virtual Private Network) is a WAN built from virtual links that run on top of the Internet.
Broadcast Networks

• Types of transmission technology
• Broadcast links
• Point-to-point links
**Broadcast Networks (2)**

- Classification of interconnected processors by scale.

<table>
<thead>
<tr>
<th>Interprocessor distance</th>
<th>Processors located in same</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>Square meter</td>
<td>Personal area network</td>
</tr>
<tr>
<td>10 m</td>
<td>Room</td>
<td>Local area network</td>
</tr>
<tr>
<td>100 m</td>
<td>Building</td>
<td>Metropolitan area network</td>
</tr>
<tr>
<td>1 km</td>
<td>Campus</td>
<td>Wide area network</td>
</tr>
<tr>
<td>10 km</td>
<td>City</td>
<td>The Internet</td>
</tr>
<tr>
<td>100 km</td>
<td>Country</td>
<td></td>
</tr>
<tr>
<td>1000 km</td>
<td>Continent</td>
<td></td>
</tr>
<tr>
<td>10,000 km</td>
<td>Planet</td>
<td></td>
</tr>
</tbody>
</table>
Wireless Networks

• Categories of wireless networks:
  • System interconnection
  • Wireless LANs
  • Wireless WANs
Wireless Networks (2)

- (a) Bluetooth configuration
- (b) Wireless LAN
Wireless Networks (3)

- (a) Individual mobile computers
- (b) A flying LAN
Home Network Categories

- Computers (desktop PC, PDA, shared peripherals)
- Entertainment (TV, DVD, VCR, camera, stereo, MP3)
- Telecomm (telephone, cell phone, intercom, fax)
- Appliances (microwave, fridge, clock, furnace, airco)
- Telemetry (utility meter, burglar alarm, babycam).
Network Software

- Protocol layers »
- Design issues for the layers »
- Connection-oriented vs. connectionless service »
- Service primitives »
- Relationship of services to protocols »
Protocol Layers (1)

Protocol layering is the main structuring method used to divide up network functionality.

- Each protocol instance talks virtually to its peer
- Each layer communicates only by using the one below
- Lower layer services are accessed by an interface
- At bottom, messages are carried by the medium
Protocol Layers (2)

- Example: the philosopher-translator-secretary architect
- Each protocol at different layers serves a different purpose
Protocol Layers (3)

- Each lower layer adds its own header (with control information) to the message to transmit and removes it on receive.

- Layers may split and join messages, etc.

Source machine

Destination machine

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Design Issues for the Layers

Each layer solves a particular problem but must include mechanisms to address a set of recurring design issues

<table>
<thead>
<tr>
<th>Issue</th>
<th>Example mechanisms at different layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability despite failures</td>
<td>Codes for error detection/correction (§3.2, 3.3)</td>
</tr>
<tr>
<td></td>
<td>Routing around failures (§5.2)</td>
</tr>
<tr>
<td>Network growth and evolution</td>
<td>Addressing (§5.6) and naming (§7.1)</td>
</tr>
<tr>
<td></td>
<td>Protocol layering (§1.3)</td>
</tr>
<tr>
<td>Allocation of resources like bandwidth</td>
<td>Multiple access (§4.2)</td>
</tr>
<tr>
<td></td>
<td>Congestion control (§5.3, 6.3)</td>
</tr>
<tr>
<td>Security against various threats</td>
<td>Confidentiality of messages (§8.2, 8.6)</td>
</tr>
<tr>
<td></td>
<td>Authentication of communicating parties (§8.7)</td>
</tr>
</tbody>
</table>
Connection-Oriented vs. Connectionless

• Service provided by a layer may be kinds of either:
  – Connection-oriented, must be set up for ongoing use (and torn down after use), e.g., phone call
  – Connectionless, messages are handled separately, e.g., postal delivery

<table>
<thead>
<tr>
<th>Service</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable message stream</td>
<td>Sequence of pages</td>
</tr>
<tr>
<td>Reliable byte stream</td>
<td>Movie download</td>
</tr>
<tr>
<td>Unreliable connection</td>
<td>Voice over IP</td>
</tr>
<tr>
<td>Unreliable datagram</td>
<td>Electronic junk mail</td>
</tr>
<tr>
<td>Acknowledged datagram</td>
<td>Text messaging</td>
</tr>
<tr>
<td>Request-reply</td>
<td>Database query</td>
</tr>
</tbody>
</table>
Service Primitives (1)

• A service is provided to the layer above as primitives
• Hypothetical example of service primitives that may provide a reliably byte stream (connection-oriented) service:

<table>
<thead>
<tr>
<th>Primitive</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISTEN</td>
<td>Block waiting for an incoming connection</td>
</tr>
<tr>
<td>CONNECT</td>
<td>Establish a connection with a waiting peer</td>
</tr>
<tr>
<td>ACCEPT</td>
<td>Accept an incoming connection from a peer</td>
</tr>
<tr>
<td>RECEIVE</td>
<td>Block waiting for an incoming message</td>
</tr>
<tr>
<td>SEND</td>
<td>Send a message to the peer</td>
</tr>
<tr>
<td>DISCONNECT</td>
<td>Terminate a connection</td>
</tr>
</tbody>
</table>
Service Primitives (2)

- Hypothetical example of how these primitives may be used for a client-server interaction

**Client**
- CONNECT (1): Connect request
- SEND (3): Accept response
- RECEIVE (3): Request for data
- DISCONNECT (5): Reply

**Server**
- LISTEN (0)
- ACCEPT (2)
- RECEIVE (2)
- SEND (4)
- DISCONNECT (6)

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Service Primitives (2)

- Packets sent in a simple client-server interaction on a connection-oriented network.
Relationship of Services to Protocols

Recap:
- A layer provides a **service** to the one above
- A layer talks to its peer using a **protocol**
Reference Models

Reference models describe the layers in a network architecture

- OSI reference model
- TCP/IP reference model
- Model used for this text
- Critique of OSI and TCP/IP
Reference Models

The OSI reference model.
OSI Reference Model

• A principled, international standard, seven layer model to connect different systems

<table>
<thead>
<tr>
<th>Layer</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Application</td>
</tr>
<tr>
<td>6</td>
<td>Presentation</td>
</tr>
<tr>
<td>5</td>
<td>Session</td>
</tr>
<tr>
<td>4</td>
<td>Transport</td>
</tr>
<tr>
<td>3</td>
<td>Network</td>
</tr>
<tr>
<td>2</td>
<td>Data link</td>
</tr>
<tr>
<td>1</td>
<td>Physical</td>
</tr>
</tbody>
</table>

- Provides functions needed by users
- Converts different representations
- Manages task dialogs
- Provides end-to-end delivery
- Sends packets over multiple links
- Sends frames of information
- Sends bits as signals
The TCP/IP Reference Model Layers

- Link layer
- Internet layer
- Transport layer
- Application layer
TCP/IP Reference Model

- A four layer model derived from experimentation; omits some OSI layers and uses the IP as the network

Protocols are shown in their respective layers
Reference Models (2)

**OSI**

<table>
<thead>
<tr>
<th>7</th>
<th>The 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Application</td>
</tr>
<tr>
<td>5</td>
<td>Presentation</td>
</tr>
<tr>
<td>4</td>
<td>Session</td>
</tr>
<tr>
<td>3</td>
<td>Transport</td>
</tr>
<tr>
<td>2</td>
<td>Network</td>
</tr>
<tr>
<td>1</td>
<td>Data link</td>
</tr>
</tbody>
</table>

**TCP/IP**

- Application
- Transport
- Internet
- Host-to-network

Not present in the model
Reference Models (3)

Layer (OSI names)

Application

Transport

Network

Physical + data link

Protocols

Networks

TELNET FTP SMTP DNS

TCP UDP

IP

ARPANET SATNET Packet radio LAN
Model Used in this Course

It is based on the TCP/IP model but we call out the physical layer and look beyond Internet protocols.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Application</td>
</tr>
<tr>
<td>4</td>
<td>Transport</td>
</tr>
<tr>
<td>3</td>
<td>Network</td>
</tr>
<tr>
<td>2</td>
<td>Link</td>
</tr>
<tr>
<td>1</td>
<td>Physical</td>
</tr>
</tbody>
</table>
Critique of OSI & TCP/IP

OSI:
+ Very influential model with clear concepts
  • Models, protocols and adoption all bogged down by politics and complexity

TCP/IP:
+ Very successful protocols that worked well and thrived
  • Weak model derived after the fact from protocols
Comparing OSI and TCP/IP Models

- Concepts central to the OSI model
- Services
- Interfaces
- Protocols
A Critique of the OSI Model and Protocols

• Why OSI did not take over the world
• Bad timing
• Bad technology
• Bad implementations
• Bad politics
Bad Timing

- The apocalypse of the two elephants.
A Critique of the TCP/IP Reference Model

• Problems:
• Service, interface, and protocol not distinguished
• Not a general model
• Host-to-network “layer” not really a layer
• No mention of physical and data link layers
• Minor protocols deeply entrenched, hard to replace
Example Networks

- The Internet »
- 3G mobile phone networks »
- Wireless LANs »
- RFID and sensor networks »
The ARPANET

- (a) Structure of the telephone system.
- (b) Baran’s proposed distributed switching system.
The ARPANET (2)

• The original ARPANET design.
The NSFNET backbone in 1988.
Internet (1)

Before the Internet was the ARPANET, a decentralized, packet-switched network based on Baran’s ideas.

ARPANET topology in Sept 1972.

Nodes are IMPs, or early routers, linked to hosts.

56 kbps links.
Internet (2)

The early Internet used NSFNET (1985-1995) as its backbone; universities connected to get on the Internet.

NSFNET topology in 1988

T1 links (1.5 Mbps)
The modern Internet is more complex:

- ISP networks serve as the Internet backbone
- ISPs connect or peer to exchange traffic at IXPs
- Within each network routers switch packets
- Between networks, traffic exchange is set by business agreements
- Customers connect at the edge by many means
  - Cable, DSL, Fiber-to-the-Home, 3G/4G wireless, dialup
- Data centers concentrate many servers ("the cloud")
- Most traffic is content from data centers (esp. video)
- The architecture continues to evolve
Internet (4)

Architecture of the Internet
3G Mobile Phone Networks (1)

3G network is based on spatial cells; each cell provides wireless service to mobiles within it via a base station.
3G Mobile Phone Networks (2)

• Base stations connect to the core network to find other mobiles and send data to the phone network and Internet.
3G Mobile Phone Networks (3)

As mobiles move, base stations hand them off from one cell to the next, and the network tracks their location.
Fourth-Generation Mobile Phone Networks

• Technologies
  – WiMAX
    • MAXWell Lab at UMd
  – LTE
• TDM Based
• Higher user level bandwidth
Ethernet

- Architecture of the original Ethernet.
Wireless LANs

- (a) Wireless networking with a base station.
- (b) Ad hoc networking.
Wireless LANs (2)

Signals in the 2.4GHz ISM band vary in strength due to many effects, such as multipath fading due to reflections

- requires complex transmission schemes, e.g., OFDM
Wireless LANs (3)

Radio broadcasts interfere with each other, and radio ranges may incompletely overlap

- CSMA (Carrier Sense Multiple Access) designs are
Wireless LANs (4)

- A multicell 802.11 network.
Ad hoc Networks

• Similar to Sensor Networks
• All nodes are equal
  – Some distinguished nodes may have servers/external connections
• Information moves from node to node
RFID and Sensor Networks (1)

Passive UHF RFID networks everyday objects:

- Tags (stickers with not even a battery) are placed on objects
- Readers send signals that the tags reflect to communicate
RFID and Sensor Networks (2)

Sensor networks spread small devices over an area:

- Devices send sensed data to collector via wireless hops
Network Standardization

- Who’s Who in the Telecommunications World
- Who’s Who in the International Standards World
- Who’s Who in the Internet Standards World
Network Standardization

Standards define what is needed for interoperability

Some of the many standards bodies:

<table>
<thead>
<tr>
<th>Body</th>
<th>Area</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITU</td>
<td>Telecommunications</td>
<td>G.992, ADSL, H.264, MPEG4</td>
</tr>
<tr>
<td>IEEE</td>
<td>Communications</td>
<td>802.3, Ethernet, 802.11, WiFi</td>
</tr>
<tr>
<td>IETF</td>
<td>Internet</td>
<td>RFC 2616, HTTP/1.1, RFC 1034/1035, DNS</td>
</tr>
<tr>
<td>W3C</td>
<td>Web</td>
<td>HTML5 standard, CSS standard</td>
</tr>
</tbody>
</table>
ITU

• Main sectors
  • Radiocommunications
  • Telecommunications Standardization
  • Development

• Classes of Members
  • National governments
  • Sector members
  • Associate members
  • Regulatory agencies
## Who’s Who in International Standards (1)

<table>
<thead>
<tr>
<th>Number</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.1</td>
<td>Overview and architecture of LANs</td>
</tr>
<tr>
<td>802.2</td>
<td>Logical link control</td>
</tr>
<tr>
<td>802.3</td>
<td>* Ethernet</td>
</tr>
<tr>
<td>802.4</td>
<td>‡ Token bus (was briefly used in manufacturing plants)</td>
</tr>
<tr>
<td>802.5</td>
<td>‡ Token ring (IBM’s entry into the LAN world)</td>
</tr>
<tr>
<td>802.6</td>
<td>‡ Dual queue dual bus (early metropolitan area network)</td>
</tr>
<tr>
<td>802.7</td>
<td>‡ Technical advisory group on broadband technologies</td>
</tr>
<tr>
<td>802.8</td>
<td>† Technical advisory group on fiber optic technologies</td>
</tr>
<tr>
<td>802.9</td>
<td>‡ Isochronous LANs (for real-time applications)</td>
</tr>
<tr>
<td>802.10</td>
<td>‡ Virtual LANs and security</td>
</tr>
<tr>
<td>802.11</td>
<td>* Wireless LANs (WiFi)</td>
</tr>
<tr>
<td>802.12</td>
<td>‡ Demand priority (Hewlett-Packard’s AnyLAN)</td>
</tr>
</tbody>
</table>

The 802 working groups. The important ones are marked with *. The ones marked with ‡ are hibernating. The one marked with † gave up and disbanded itself.
### Who’s Who in International Standards (2)

<table>
<thead>
<tr>
<th>802.13</th>
<th>Unlucky number; nobody wanted it</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.14 †</td>
<td>Cable modems (defunct: an industry consortium got there first)</td>
</tr>
<tr>
<td>802.15 *</td>
<td>Personal area networks (Bluetooth, Zigbee)</td>
</tr>
<tr>
<td>802.16 *</td>
<td>Broadband wireless (WiMAX)</td>
</tr>
<tr>
<td>802.17</td>
<td>Resilient packet ring</td>
</tr>
<tr>
<td>802.18</td>
<td>Technical advisory group on radio regulatory issues</td>
</tr>
<tr>
<td>802.19</td>
<td>Technical advisory group on coexistence of all these standards</td>
</tr>
<tr>
<td>802.20</td>
<td>Mobile broadband wireless (similar to 802.16e)</td>
</tr>
<tr>
<td>802.21</td>
<td>Media independent handoff (for roaming over technologies)</td>
</tr>
<tr>
<td>802.22</td>
<td>Wireless regional area network</td>
</tr>
</tbody>
</table>

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Metric Units

The main prefixes we use:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Exp.</th>
<th>prefix</th>
<th>exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>K(ilol)</td>
<td>$10^3$</td>
<td>m(illi)</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>M(ega)</td>
<td>$10^6$</td>
<td>μ(micro)</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>G(iga)</td>
<td>$10^9$</td>
<td>n(ano)</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

- Use powers of 10 for rates, powers of 2 for storage
  - E.g., 1 Mbps = 1,000,000 bps, 1 KB = 1024 bytes
- “B” is for bytes, “b” is for bits
# Metric Units

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Explicit</th>
<th>Prefix</th>
<th>Exp.</th>
<th>Explicit</th>
<th>Prefix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>0.001</td>
<td>milli</td>
<td>$10^{3}$</td>
<td>1,000</td>
<td>Kilo</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>0.000001</td>
<td>micro</td>
<td>$10^{6}$</td>
<td>1,000,000</td>
<td>Mega</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>0.00000001</td>
<td>nano</td>
<td>$10^{9}$</td>
<td>1,000,000,000</td>
<td>Giga</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>0.0000000001</td>
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<td>$10^{12}$</td>
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<td>Peta</td>
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<tr>
<td>$10^{-18}$</td>
<td>0.00000000000000001</td>
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<td>$10^{18}$</td>
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<tr>
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<td>Yotta</td>
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</tbody>
</table>

- The principal metric prefixes.
# Metric Units (1)

<table>
<thead>
<tr>
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<th>Prefix</th>
</tr>
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<tbody>
<tr>
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<td>milli</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>0.000001</td>
<td>micro</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>0.000000001</td>
<td>nano</td>
</tr>
<tr>
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</tr>
<tr>
<td>$10^{-18}$</td>
<td>0.00000000000000001</td>
<td>atto</td>
</tr>
<tr>
<td>$10^{-21}$</td>
<td>0.000000000000000001</td>
<td>zepto</td>
</tr>
<tr>
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</tbody>
</table>

The principal metric prefixes
## Metric Units (2)

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<tr>
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<td>Giga</td>
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<tr>
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</tr>
<tr>
<td>$10^{15}$</td>
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<td>Peta</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>1,000,000,000,000,000,000</td>
<td>Exa</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>1,000,000,000,000,000,000,000</td>
<td>Zetta</td>
</tr>
<tr>
<td>$10^{24}$</td>
<td>1,000,000,000,000,000,000,000,000</td>
<td>Yotta</td>
</tr>
</tbody>
</table>

The principal metric prefixes