# Physical Infrastructure of Networks

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The Physical Network: Why Cables Still Matter

- Every like, text, and video depends on physical cables carrying electrical or light signals.
- Understanding the physical layer helps you troubleshoot problems and design reliable networks.
- We'll explore copper cables, fiber optics, and how to install them properly.
- By the end, you'll know how to choose the right cable for any networking situation.
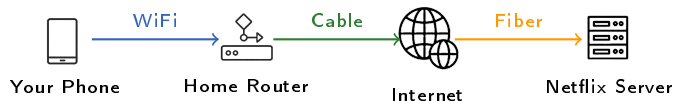
All transmitted as
electrical or light
signals through
physical cables!

How Networks Transmit Data

- Networks transmit data as **digital signals**, which are patterns of electrical voltages or light pulses representing 1s and 0s.
- Think of it like Morse code: just as dots and dashes can spell words, 1s and 0s can represent any information.
- A **bit** is a single binary digit (1 or 0), and 8 bits make a **byte** (enough to represent one letter).
- **Bandwidth** measures how many bits can be transmitted per second, like the width of a pipe determining water flow.

Key Insight

Your computer turns everything—text, images, videos—into billions of 1s and 0s, then cables carry these as electrical or light signals at incredible speeds.

Introduction to Ethernet

- **Ethernet** is the standard set of rules (protocols) that computers use to communicate over wired networks.
- Invented in the 1970s at Xerox, Ethernet has evolved from thick coaxial cables to today's twisted pair cables.
- Ethernet became the dominant standard because it's reliable, affordable, and continuously improves without requiring complete replacement.
- When you plug a cable into your computer or router, you're almost certainly using Ethernet technology.

Why It Matters

Over 90% of wired networks worldwide use Ethernet standards, making it essential knowledge for any network technician.

Copper Cables Overview

- **Copper cables** use copper wire to conduct electrical signals because copper is highly conductive, flexible, and cost-effective.
- The two main types are **twisted pair** (multiple wires twisted together) and **coaxial** (center wire surrounded by insulation and shield).
- Twisted pair cables connect most computers, phones, and network devices in homes, schools, and offices.
- Coaxial cables are commonly used for cable TV and internet connections from your Internet Service Provider.
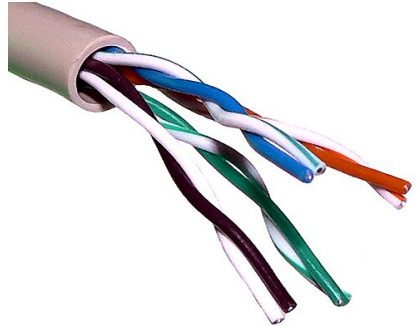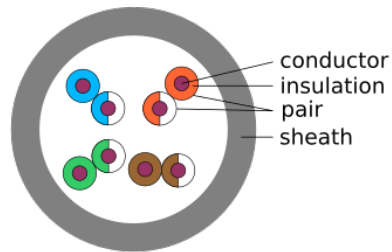

Twisted pair cable showing the twisted wire pairs inside

- **Unshielded Twisted Pair (UTP)** is the most common type of network cable, found in homes, schools, and most businesses.
- UTP contains 8 copper wires arranged in 4 color-coded pairs, with each pair twisted together at specific rates.
- The twisting reduces **electromagnetic interference (EMI)** by canceling out electrical noise that could corrupt the signal.
- UTP is "unshielded" because it has no metal foil or braiding protecting the wires—it relies entirely on twisting for protection.

UTP

conductor
insulation
pair
sheath

Cross-section showing 4 twisted pairs inside the cable jacket

Shielded and Screened Twisted Pair Cables

- **Shielded Twisted Pair (STP)** cables have metal foil or braided shielding around the wire pairs to provide extra protection from interference.

- These cables are necessary in environments with high electromagnetic interference, such as near motors, fluorescent lights, or heavy machinery.

- The trade-offs include higher cost (30-50% more expensive), reduced flexibility, and more difficult installation.

- **Screened Twisted Pair (ScTP)** uses an overall shield around all pairs, while STP may shield individual pairs as well.
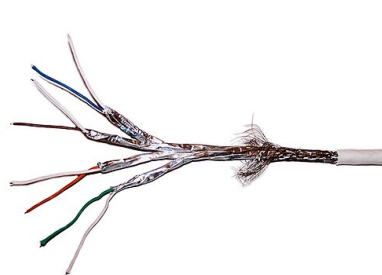
Shielded Cat 7 cable showing individual pair shielding and overall shield

Cable Categories (Cat Standards)

- The **Category (Cat)** rating system classifies twisted pair cables by their performance specifications—higher numbers mean better performance.
- Each category specifies maximum bandwidth, supported speeds, and maximum cable length (usually 100 meters).
- Choosing the right category depends on your current needs and future upgrade plans.

Category	Max Speed	Bandwidth	Common Use
Cat 5e	1 Gbps	100 MHz	Standard for homes/offices
Cat 6	1-10 Gbps	250 MHz	Business networks
Cat 6a	10 Gbps	500 MHz	High-performance networks
Cat 7	10 Gbps	600 MHz	Data centers (shielded)
Cat 8	25-40 Gbps	2000 MHz	Server connections

Note: All support 100 meter maximum distance for full specifications

RJ-45 Connectors

- The **RJ-45 connector** is the standard plastic connector with 8 pins that plugs into network devices.
- Each of the 8 pins corresponds to one of the 8 wires inside the twisted pair cable.
- Connectors can be **crimped** directly onto cable ends (requires special tool) or cables can terminate at **keystone jacks** in wall plates.
- The clear plastic housing lets you visually inspect the wire connections to verify correct installation.
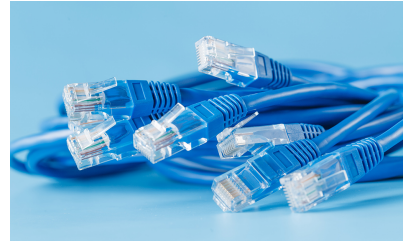
RJ-45 connectors showing the 8 pins and wire arrangement
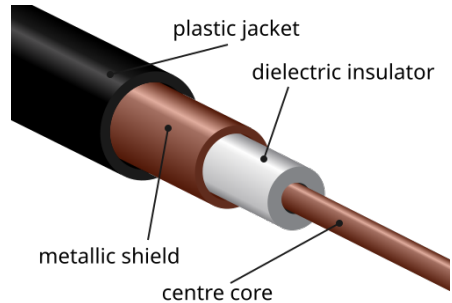

RJ45 Male

Ethernet Speed Standards

- Ethernet standards use a naming convention: **speed-transmission type-media type** (e.g., 1000BASE-T means 1000 Mbps, baseband, twisted pair).
- **10BASE-T** (10 Mbps) was the original standard, now obsolete but important historically.
- **100BASE-TX** (Fast Ethernet) runs at 100 Mbps and uses only 2 of the 4 wire pairs in Cat 5e or better cable.
- **1000BASE-T** (Gigabit Ethernet) runs at 1000 Mbps (1 Gbps), uses all 4 wire pairs, and requires Cat 5e minimum with Cat 6 recommended.

Standard	Speed	Wire Pairs	Min. Cable
100BASE-TX	100 Mbps	2 pairs	Cat 5e
1000BASE-T	1 Gbps	4 pairs	Cat 5e
10GBASE-T	10 Gbps	4 pairs	Cat 6a

Coaxial and Twinaxial Cable

- **Coaxial cable** has a completely different design: a single center conductor surrounded by insulation, a braided shield, and an outer jacket.

- The shield protects the center conductor from interference and prevents signal leakage, making coax more resistant to EMI than unshielded twisted pair.

- Common connectors include **F-type** (cable TV/internet) and **BNC** (older networks and video equipment).

- **Twinaxial cable** (twinax) uses two inner conductors and is used for short, high-speed data center connections.

plastic jacket

dielectric insulator

metallic shield

centre core

Coaxial cable construction and F-type

Case Study: The Addams Family Network

The Scenario

Wednesday Addams is rewiring the mansion's network. She needs to connect 4 computers in the torture chamber (basement) to the family router located in Gomez's office on the second floor—a distance of 150 feet through the mansion's walls.

The basement has significant electrical interference from Fester's experimental equipment, which frequently generates electromagnetic pulses. The family wants fast, reliable connections for streaming horror movies and conducting paranormal research.

Your Task:

- What type and category of cable should Wednesday use?
- Justify your choice considering distance, interference, speed, and cost.
- Are there any alternatives she should consider?

Case Study: Solution

Recommended Solution: Cat 6 or Cat 6a STP (Shielded Twisted Pair)

- **Distance Check:** 150 feet = 45.7 meters, well under the 100-meter (328 feet) limit for Ethernet ✓
- **Speed:** Cat 6 supports 1 Gbps (sufficient for streaming), Cat 6a supports 10 Gbps (future-proof) ✓
- **Interference:** Uncle Fester's equipment requires shielded cable; regular UTP would experience frequent dropouts ✓
- **Cost Analysis:** STP costs 30-50% more than UTP, but necessary for reliability in high-EMI environment

Alternative Option

If the interference proves too severe even for STP, Wednesday might consider fiber optic cable, which is completely immune to electromagnetic interference—though it's more expensive and harder to terminate.

MAC Addresses and Collision Domains

- Every network device has a unique **Media Access Control (MAC) address**, a 48-bit identifier burned into the network interface card at manufacturing.
- Think of a MAC address as your device's permanent physical "home address"—it never changes (e.g., 00:1A:2B:3C:4D:5E).
- A **collision domain** is a network segment where data packets can collide if two devices transmit simultaneously.
- Modern **switches** create separate collision domains for each port, preventing collisions and improving network performance dramatically compared to old hubs.

Why This Matters

Understanding collision domains explains why switches are superior to hubs—each device gets dedicated bandwidth instead of sharing and competing for access.

100BASE-TX Fast Ethernet

- **100BASE-TX** (Fast Ethernet) operates at 100 Megabits per second, which is 10 times faster than the original 10BASE-T standard.
- This standard only uses 2 of the 4 wire pairs in the cable: one pair for transmitting and one pair for receiving data.
- Fast Ethernet requires Cat 5e or better cable and can reach distances up to 100 meters (328 feet).
- While Gigabit Ethernet is now more common, you'll still find 100BASE-TX in older networks and devices like IP cameras or printers.

Legacy Technology

Many organizations still have 100BASE-TX equipment in use—knowing how to work with it is essential for technicians supporting existing infrastructure.

Gigabit Ethernet (1000BASE-T)

- **1000BASE-T** (Gigabit Ethernet) transmits data at 1000 Megabits per second (1 Gbps), providing 10 times the speed of Fast Ethernet.
- Unlike Fast Ethernet, Gigabit uses all 4 wire pairs simultaneously, with each pair both transmitting and receiving at the same time.
- This standard requires Cat 5e cable at minimum, though Cat 6 is strongly recommended for reliability and future-proofing.
- Gigabit Ethernet is currently the standard for most home and business networks, offering excellent performance at reasonable cost.

Design Choice

When installing new networks today, always use Cat 6 or better cable even if current devices only need Fast Ethernet—this prepares for inevitable upgrades.

Higher-Speed Ethernet Standards

- **10GBASE**-**T** (10 Gigabit Ethernet) operates at 10,000 Mbps and requires Cat 6a cable or better to reach the full 100-meter distance.
- **25GBASE**-**T** and **40GBASE**-**T** are emerging standards primarily used for server-to-switch connections in data centers.
- These ultra-high-speed standards use more sophisticated encoding and require higher-quality cables to combat signal degradation.
- Most homes and small businesses don't need speeds beyond 1 Gbps currently, but large organizations use 10+ Gbps for backbone connections and server farms.

Standard	Speed	Typical Use
1000BASE-T	1 Gbps	Workstations, most networks
10GBASE-T	10 Gbps	Servers, backbone links
25/40GBASE-T	25-40 Gbps	Data center core

Introduction to Structured Cabling Systems

- A **structured cabling system** is an organized, standardized approach to network cabling that provides a "blueprint" for how cables should be installed throughout a building.
- Without structure, cable installations become "spaghetti"—tangled, impossible to trace, and nearly impossible to troubleshoot or modify.
- The system divides the network into hierarchical subsystems: work areas (where users work), horizontal cabling (floor distribution), and backbone cabling (between floors/buildings).
- Following structured cabling standards ensures that any qualified technician can understand and work with your installation, even years later.
- Properly designed structured cabling can last 15-20 years, supporting multiple technology upgrades without rewiring.

Structured Cabling Components

- **Work Area Outlet**: Wall jack where users plug in devices (maximum 3 meters of patch cable to device).
- **Horizontal Cabling**: Permanent cable running from work area to telecommunications room (maximum 90 meters).
- **Telecommunications Room (TR)**: Central wiring closet on each floor with patch panels and switches.
- **Backbone Cabling**: Connects TRs across floors or between buildings.

Standard 6 work areas per TR
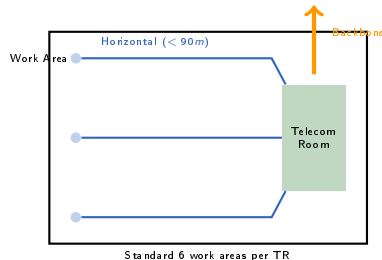
T568A and T568B Wiring Standards

- **T568A** and **T568B** are two different standards for arranging the 8 wires within an RJ-45 connector.

- The standards differ only in the positions of the orange and green pairs—all other wires are identical.

- A **straight-through cable** uses the same standard on both ends (most common), while a **crossover cable** uses different standards on each end.

- Consistency matters more than which standard you choose—pick one and use it throughout your entire installation.
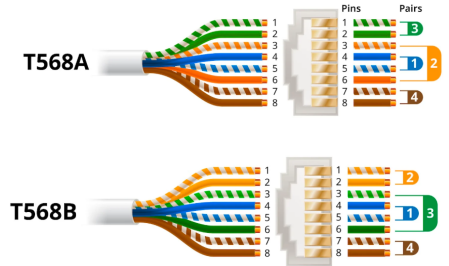
T568A (top) and T568B (bottom) pin assignments

Patch Panels: The Organized Network

- A **patch panel** serves as the central connection point in a telecommunications room where all horizontal cables terminate.

- The front of the panel has RJ-45 ports labeled for each cable run; the back has punch-down blocks where wires are terminated.

- Patch panels make troubleshooting easier by providing a single, organized location to test and reroute connections without touching permanent wiring.

- Short **patch cables** connect from the patch panel to switches, allowing flexible network configuration changes.

24-port patch panel with labeled ports

Pro Tip

Always label both ends of every cable and document which patch panel port goes to which room!

Cable Installation Best Practices

- **Plenum-rated cables** (CMP) must be used in air handling spaces because they produce less toxic smoke in fires; **riser-rated cables** (CMR) are for vertical shafts between floors.
- Never exceed the cable's **minimum bend radius** (typically 4 times the cable diameter)—sharp bends damage internal wires and degrade performance.
- Maintain proper cable management with no kinks, avoid running parallel to electrical cables (maintain 12+ inches separation), and never exceed maximum pulling tension (25 lbs for Cat 6).
- Label everything immediately during installation: both cable ends, patch panel ports, wall jacks, and create detailed documentation showing cable routes.

Critical Safety Rule

Building codes legally require specific cable ratings for different locations—using the wrong cable type can result in failed inspections, fines, and serious fire hazards.

Cable Installation Tools

- **Punch-down tools** (with 110 blade) are used to terminate wires onto patch panels and keystone jacks by forcing the wire into the connector and cutting off excess.

- **Cable strippers** remove the outer jacket without damaging internal wires, while **crimpers** attach RJ-45 connectors to cable ends.

- **Cable testers** verify that all 8 wires are correctly connected and detect opens, shorts, and miswires.

- **Tone generators** send a signal through a cable while a probe traces the cable to identify which physical cable corresponds to which connection.

Case Study: The Addams Family Crypt Network

The Scenario

Morticia wants to add network connectivity to the family crypt in the basement for livestreaming séances. The router is in Gomez's office on the second floor. The cable must run 65 meters through the mansion's ceiling plenum (the old ventilation system), then 20 meters down a vertical shaft behind the walls to reach the crypt.

Thing has found three boxes of cable in the attic:

- Cat 6 standard PVC jacket (CMG rated)
- Cat 6 Plenum rated (CMP)
- Cat 6 Riser rated (CMR)

Your Task:

- Which cable(s) should Morticia use for each part of the run?

- Will the total distance work for Gigabit Ethernet?

- What happens if she uses the wrong cable type?

Case Study: Solution

Best Solution: Cat 6 Plenum-rated (CMP) cable for the entire run
Alternative: CMP for plenum section (65m) + CMR for riser section (20m)

- **Distance Check:** 85 meters total is under the 90-meter horizontal limit (100m with patch cables) ✓
- **Plenum Section:** MUST use CMP-rated cable—CMR or CMG would violate fire codes ✗
- **Riser Section:** Could use CMR or CMP (CMP works everywhere, CMR only in vertical shafts)
- **Practical Choice:** Using CMP throughout is simpler and ensures compliance everywhere

What Goes Wrong?

Using CMG anywhere: Fails building inspection, expensive rewiring. Using CMR in the plenum: Fire hazard—toxic fumes could spread through ventilation. The mansion's insurance company would not be pleased!

Why Fiber Optic Cables?

- Copper cables have fundamental limitations: maximum distance of 100 meters, susceptibility to electromagnetic interference, and speed limits around 10 Gbps for twisted pair.
- **Fiber optic cables** use pulses of light instead of electrical signals, completely eliminating electromagnetic interference problems.
- Fiber provides dramatically longer distances (up to 40+ kilometers for single-mode), much higher speeds (100+ Gbps), and improved security (difficult to tap).
- The trade-offs include higher initial cost, more fragile physical properties, and requirement for specialized tools and training for installation.

When to Choose Fiber

Use fiber for: connections between buildings, long runs within buildings (>100m), environments with heavy EMI, high-security applications, and backbone connections requiring 10+ Gbps speeds.

- Light pulses represent digital data: light on = 1, light off = 0, transmitted billions of times per second.
- The light travels through a glass or plastic core using **total internal reflection**—light bounces off the walls at specific angles, staying contained within the fiber.
- Think of it like a slide at a water park: the walls keep water from spilling out as it travels down, just as the cladding keeps light inside the core.
- Light sources can be LEDs (cheaper, shorter distance) or lasers (expensive, longer distance, more precise).

Light bounces down the fiber

Cladding

Core

Buffer
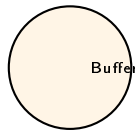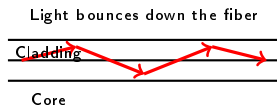
Fiber Cable Construction

- The **core** is the ultra-thin glass center where light actually travels—only 9 to 62.5 micrometers (μm) in diameter (thinner than a human hair).
- The **cladding** surrounds the core with a different glass that has a lower refractive index, causing light to reflect back into the core.
- A **buffer coating** protects the fragile glass from moisture and physical damage.
- **Strengthening fibers** (often Kevlar) provide tensile strength, and the **outer jacket** protects everything.
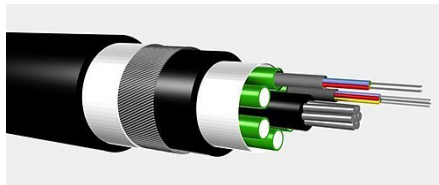
Multi-fiber cable showing individual fibers, strengthening materials, and jacket

Handle with Care!
Fiber is glass—it can break if bent too sharply or pulled too hard!

Single-Mode vs. Multimode Fiber

- **Single-mode fiber (SMF)** has a tiny 9-micrometer (μm) core that allows only one light path, using laser light sources for precise transmission.
- **Multimode fiber (MMF)** has a larger 50 or 62.5-micrometer (μm) core allowing multiple light paths, using cheaper LED light sources.
- Single-mode supports much longer distances (40+ km) but costs more for equipment; multimode is cheaper but limited to shorter distances (typically 550 meters or less).

Feature	Single-Mode (SMF)	Multimode (MMF)
Core Diameter	9 μm	50 or 62.5 μm
Light Source	Laser	LED
Max Distance	40+ km	550 m typical
Cost	Higher	Lower
Use Case	Long distance, WAN	Building/campus

Fiber Optic Connector Types

- **SC (Subscriber Connector)** has a square shape with a push-pull mechanism, making it easy to connect and disconnect without twisting.

- **LC (Lucent Connector)** is a small form-factor connector with a latch mechanism, commonly used in high-density installations.

- **ST (Straight Tip)** features a round bayonet-style connector that twists to lock, common in older installations and multimode networks.

- **MTRJ (Mechanical Transfer Registered Jack)** combines two fibers in a single small connector body, similar in size to RJ-45.

Fiber Ethernet Standards

- Fiber Ethernet standards use naming similar to copper: speed-BASE-distance/type (e.g., 1000BASE-SX means 1000 Mbps, baseband, short wavelength).
- **1000BASE**-**SX** uses short wavelength (850nm) lasers on multimode fiber for distances up to 550 meters.
- **1000BASE**-**LX** uses long wavelength (1310nm) lasers and works on both single-mode (up to 5 km) and multimode (up to 550 m) fiber.
- **10GBASE**-**SR/LR** provides 10 Gigabit speeds: SR (Short Reach) on multimode up to 400m, LR (Long Reach) on single-mode up to 10 km.

Understanding the Letters

S = Short wavelength, L = Long wavelength, R = Reach/Range. The letter tells you about distance capabilities and the type of fiber required.

Fiber Installation Considerations

- Never exceed the **minimum bend radius** (typically 10 times the cable diameter for fiber)—bending fiber too sharply causes the glass to crack or the light to escape.
- Fiber connections require absolute cleanliness because microscopic dust particles on the glass end can block light transmission completely.
- **Fusion splicing** permanently joins two fibers by melting them together (strongest, lowest loss), while **mechanical splicing** uses alignment fixtures (faster, easier, slightly higher loss).
- Never look directly into the end of an active fiber optic cable—the infrared laser light is invisible but can cause permanent eye damage.

Safety First!

Always use a fiber optic power meter to verify a fiber is not active before inspecting it. Treat every fiber as if it's carrying laser light.

Fiber Distribution Panels

- **Fiber distribution panels** serve the same role as patch panels for copper, providing organized termination points for fiber cables.
- **Splice trays** hold spliced fiber connections and protect them from damage, allowing for organized storage of excess fiber length.
- **Adapter panels** provide connector ports (SC, LC, etc.) for patch cable connections, allowing flexible reconfiguration.
- Proper cable management is even more critical with fiber because the cables are more delicate and bending restrictions are stricter.

Fiber Distribution Panel

Splice Tray
(protected splices)

Adapter Ports (SC, LC, etc.)

Cable Management