Full Speed Ahead!

{Resource Handbook}

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Session 1: Business as Usual
Additional Context: Frank Pick, a Marketing Genius

Drawing of proportions for Johnston's roundel, c1925.
Taken from the London Transport Museum's Online Collection (Reference number: 2000/9202)

A Transportation Champion

One of the undeniable champions of public transportation in London was Frank Pick (1878-1941). For much of his career, Pick was the marketing director for the London Underground, and under his careful watch the network grew into the worldwide brand recognized today. Instrumental to Pick's success was his masterful use of marketing to rebrand the London Underground; one could go so far as to say Pick literally transformed the way the public perceived, and ultimately used, London's transportation infrastructure.

Pick's use of Posters

To ensure the Underground got its message across, Pick relied heavily on posters. He revolutionized station design, restricting the spaces companies could use for advertisements and putting official posters in illuminated, prominent cases in all stations. Eventually these posters became so popular and recognizable some of the most famous artists of the day contributed their talents to the endeavor; such professionals included Fred Taylor, Laura Knight, CRW Nevinson and Edward McKnight. By instructing artists to focus on specific destinations in their work and not on the vehicle used to reach them, Pick managed to convince daily train and bus commuters that the same company that brought them into work could also take them on leisurely trips to relaxing spots throughout the city or to the country for holiday.

Roundels, Architecture, and Maps

Pick's legacy is present in several other crucial elements of London's transportation infrastructure. The classic typeface seen on roundels was developed by Edward Johnston and commissioned by Pick. In fact, Pick was so impressed with Johnston's work the pair continued to collaborate and eventually unified all of the Underground with a redesigned roundel, the emblematic red and blue roundel still used today. Other icons that came into fame under Pick's watch were the station designs of Charles Holden, showcased on the then brand-new Jubilee extension line, and electronics-inspired tube map of Harry Beck. The later has actually been imitated by transportation networks all around the world, including those of New York City, Sydney, and Stockholm.

Advertising Done Well

And so Frank Pick ushered in an era of prominence which London's public transportation industry still enjoys today. Pick's marketing techniques were so successful that they actually shaped the future of the London Underground and became a permanent part of the company's culture and image. That is the power of advertising done well.

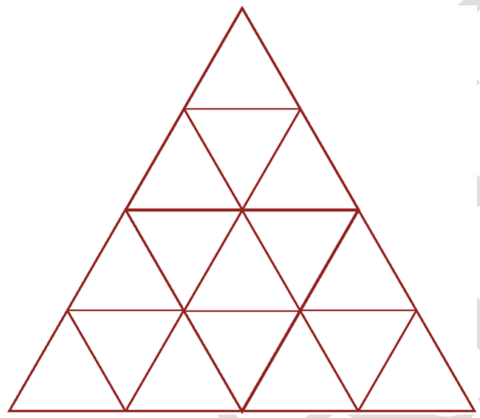
Creative Problems

1. **Electric Bulbs**

   There are three switches outside a closed room. There are three lamps inside the room. You can flip the switches as much as you want while the door is closed, but then you must enter just once and determine which switch is connected to which lamp. How can you do it?

2. **Counting Triangles**

   How many triangles do you see?

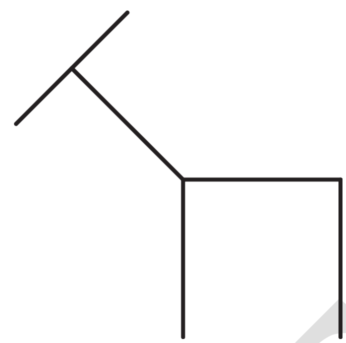


3. **The Candle Problem**

   You are given a candle, a box of thumbtacks, and a box of matches, and asked to fix the lit candle to the wall so that it will not drip wax onto the table below.

4. **Giraffe Problem**

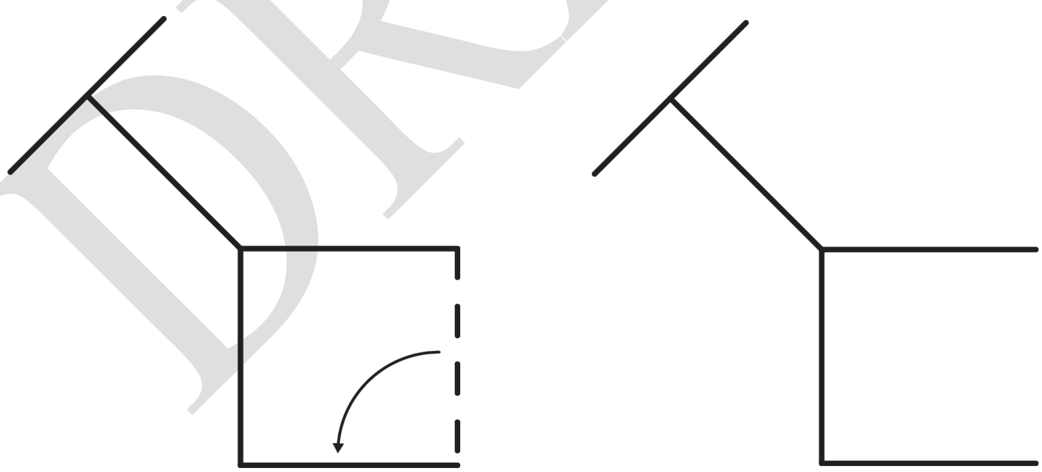
Five matchsticks were placed so as to form the figure of a giraffe as is shown in the diagram below. Can you move just one matchstick so that the shape of the giraffe is retained intact but is rotated or reflected?



Solutions to the Creative Problems

1. Switch the first one on for a minute, then turn it off and turn the second one on. Enter the room and feel the two bulbs are off. The warm one was turned on by the first switch, the light that is on is connected to the second, and the other to the third.
2. 27 triangles
3. See image

4. See image



Transport Transaction Game

Student Worksheet

Player breakdown: Minimum of 4 companies

Time Estimate: 30 minutes

Goal: The company with the most completed contracts wins!

Roles:

1. Teacher:
    - Transport for London Official
    - Keeps track of transactions between the companies on the whiteboard, chalkboard, or Excel File
2. Student teams:
    - Specialized companies that all have resources

Set Up:

Prep (needs 5-10 minutes)

Photocopy the tracking sheet so each company has one. Cut out the resources, contracts, and company specializations from the back of this packet. Put them in a hat or a bowl.

How to Play:

Choose several different cards equal to the number of companies for each category: resources, contracts, and company specializations. Each company will randomly draw for a card from each of the categories.

Company specializations will be put into a hat. A representative from each team will pull out a specialization, then a starting resource, and a contract. Each company begins the game with £ 1000. Then they will form a company name and begin strategizing the best way to complete their contracts. The company with the most contracts completed wins. However, if two companies have the same amount of contracts, then the company with the most money wins. All deals struck are final.

To complete a deal, a company must gather the right amount of resources to produce a commodity. Similarly a company needs to collect all of the commodities to complete a contract. An example: Company A specializes in biofuels. They have a contract to build an oyster card system. The oyster card system needs composites and computers. Composites need one textile and one biodegradable plastic. Computers need one metal and one biodegradable plastic. Therefore Company A needs to get three biodegradable plastics, two metals, and one textile to complete their oyster card system contract. To do this, they will have to negotiate with other companies to gain these resources.

Company Specializations:

- Metals
- Biodegradable Plastic
- Biofuels
- Textiles

Resources:

- Biofuels
- Biodegradable Plastics
- Metal
- Textiles

Commodities:

- Engines
- Composites
- Computers
- Tyres/Tires

Contracts:

BUS

- Tyres
  - Biodegradable Plastics
  - Metal
- Engine
  - Metal
  - Biofuels

TRAIN

- Engine
  - Biofuels
  - Metal
- Composites
  - Textiles
  - Biodegradable Plastics

BICYCLE

- Composites
  - Textiles
  - Biodegradable Plastics
- Tyres/Tires
  - Biodegradable Plastics
  - Metal

FERRY

- Engine
  - Metal
  - Biofuels
- Computer
  - Metal
  - Biodegradable Plastics

OYSTER CARD SYSTEM

- Computer
  - Metal
  - Biodegradable Plastics
- Composites
  - Textiles
  - Biodegradable Plastics

Company Specializations

Metals

Biodegradable Plastics

Biofuels

Textiles

Contracts

BUS CONTRACT: (£ 1000)

You have been tasked to build a **Bus**. The following commodities are needed to build this contract: Tyres and Engine. Tyres are made from biodegradable plastics and metal. Engines are made from biofuels and metal.

Train Contract: (£ 1000)

You have been tasked to build a **Train**. The following commodities are needed to build this contract: Engine and Composites. Engines are made from biofuels and metal. Composites are made from textiles and biodegradable plastics.

Bicycle Contract: (£ 1000)

You have been tasked to build a **Bicycle**. The following commodities are needed to build this contract: Tyres and Composites. Tyres are made from biodegradable plastics and metal. Composites are made from textiles and biodegradable plastics.

Ferry Contract: (£ 1000)

You have been tasked to build a **Ferry**. The following commodities are needed to build this contract: Engine and Computer. Engines are made from biofuels and metal. Computer are made from metal and biodegradable plastics.

Oyster Card System Contract: (£ 1000)

You have been tasked to build an **Oyster Card System**. The following commodities are needed to build this contract: Computer and Composites. Computer are made from metal and biodegradable plastics. Composites are made from textiles and biodegradable plastics.

Transport Transaction

Tracking sheet

Our company name is:

Our slogan is:

Our goal is to:

Monetary Funds include:

Our resources:

Our commodity:

Contracts Completed:

1)

2)

3)

4)

5)

6)

7)

8)

Final Resources:

Final Monetary Funds:

RESOURCES

1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC
1 TEXTILE	1 METAL	1 BIOFUELS	1 BIODEGRADABLE PLASTIC

Commodities

1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER
1 TYRES	1 COMPOSITES	1 ENGINE	1 COMPUTER

Citation(s)

"Frank Pick, a Marketing Genius" copyrighted images courtesy of the London Transport Museum.

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Session 2: Train of Thought

Additional Context: The Early Underground

Construction of the Metropolitan Railway, or what we call the London Underground, began in 1860. When construction was completed, it became the world's first underground railway. The line quickly served its intended purpose, to relieve traffic in the streets of London as well as transport passengers from London's mainline stations to the city.

Completing tunnelling along Praed street, Paddington for the Metropolitan Railway's Kensington extension, c1866. Taken from the London Transport Museum's Online Collection (Reference: 1981/535)

More than 2,000 navvies built the railway by hand with what is known as the 'cut and cover' method. Essentially, the track was laid in shallow cuttings dug along streets, which were then covered with a roof to make a tunnel. Despite the inherent danger of this technique, only a few accidents occurred. In 1863, the first section of the railway opened and ran from Paddington to Farringdon. The railway was an engineering success and extremely popular.

Metropolitan Railway A class 4-4-0T steam locomotive No. 23, 1866.
Taken from the London Transport Museum's Online Collection (Reference: 1998/37950)

The Metropolitan Railway company made many efforts to reduce the steam and smoke from underground trains. They tested multiple different methods, such as a fireless train that ran on hot bricks. In the end, the company decided to use conventional steam engines, but with some special modifications. These engines had special pipes that could condense exhaust into side tanks of cold water. They also avoided using coal to limit the amount of smoke produced. Instead, they used coke. With the help of 'blow holes' (holes in the tunnel to let steam escape) in the Circle line, they were able to slightly limit the steam in tunnels. However, the final solution to the problem of smoke in the rail lines was the trains' electrification in 1905. To learn more about the London Underground, please view the London Transport Museum's Online Gallery.

Additional Context: Aerodynamics

Aerodynamics is the study of the way gases interact with bodies traveling through them. When we observe the effects of aerodynamics such as a plane flying in the sky or a flag waving in the wind we are seeing the effects of several different types of flow. There are three types of flow: laminar, turbulent, and transitional. Each are outlined below, but there is a lot more to them than is discussed here.

Laminar Flow

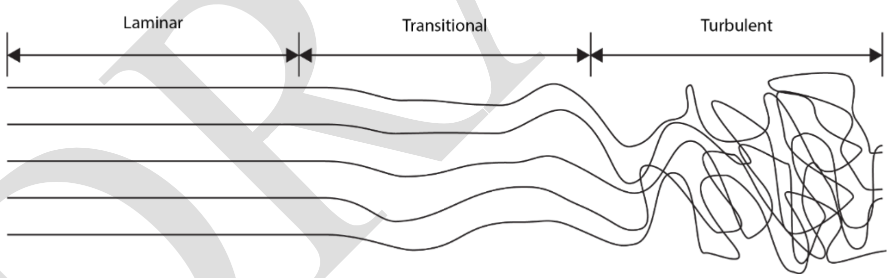
Laminar flow generally occurs at low speeds. It can be thought of conceptually as sheets which stack upon each other and are compressed or stretched towards and away from another depending on the shape of the object passing through them.

Turbulent Flow

Turbulent flow occurs most often at high speeds. In this type, flow becomes unpredictable as the molecules in the fluid take on erratic motions and form vortices comprised of eddies and wakes. This can contribute to the overall drag the object experiences as it passes through the fluid.

Transitional Flow

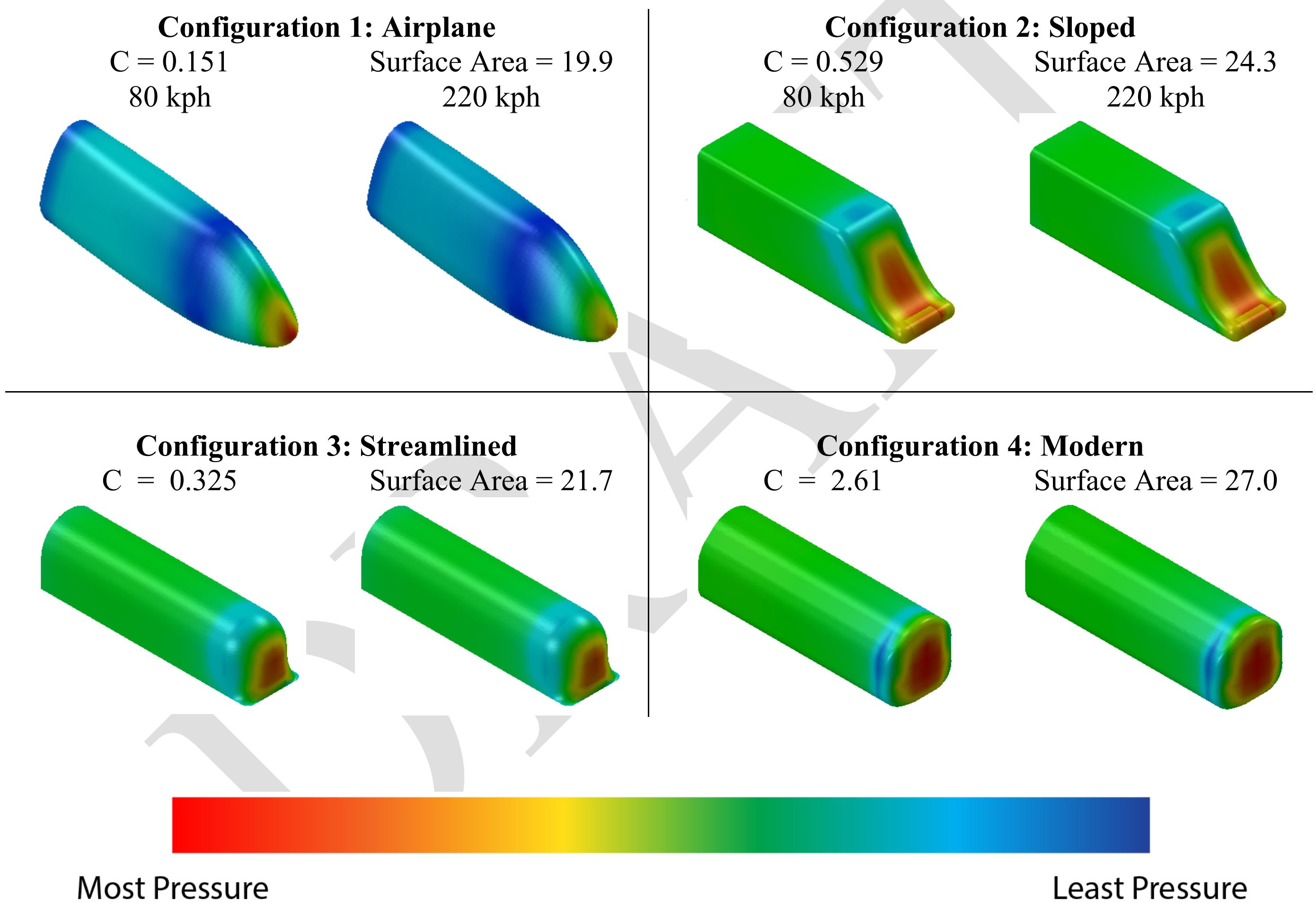
Transitional flow is a combination of turbulent and laminar flow and occurs at the transition between them.



Engineers use wind tunnels and sophisticated computer models to simulate how real trains will function. An important part of this process is optimizing the design of the head and tail of the trains to reduce drag, thus saving energy and improving the train's performance. The drag force can be determined using the following equation where C is the drag coefficient, ρ is the density of the fluid the object travels through, v is the velocity of the object or the fluid, and A is the surface area.

$$F_{drag} = -\frac{1}{2} C\rho A v^2$$

The force is multiplied by a minus sign because the drag force always opposes the direction of travel just as friction does. The drag coefficient is determined experimentally because it is almost impossible to predict how complex geometries will behave in fluids. Below are various designs simulated traveling at 80 kph and 220 kph. Notice that the larger the surface area is, the larger the drag coefficient becomes. Each simulation is scaled to show where the most and least pressure is on the model; therefore, the colors correspond to different pressures in each simulation. The units have been left off since the size of each design is relative.



In underground subways, the trains do not travel fast enough for the drag to have a considerable effect on the train's performance. However, in the 1930s, engineers around the world were designing streamlined vehicles with this in mind. In fact, one London tube prototype train, shown below on the left, from 1935 was designed with a rounded front and rear to make the train more aerodynamic. Configuration 3 is inspired by that design. Engineers soon realized this had little effect on the train's performance at subway speeds and opted to use a simpler train design, shown below on the right, to reduce manufacturing costs. Though your train will be a tube train as well, remember force is proportional to mass and acceleration. If you have a very light train, as yours may be, drag will have a greater effect.

Additional Context: Propulsion and Braking

Most modern subway trains are powered by electricity. The rails are connected to a power source along the track and the train's wheels complete a circuit which drives the motors on board each train. This prevents trains from having to burn fuels in traditional combustion engines which exhaust fumes harmful to passengers. Though this is the primary method used by underground trains around the world, be creative and consider normally implausible methods, such as fans, balloons, railguns, rubber bands, torsion springs, or cable systems.

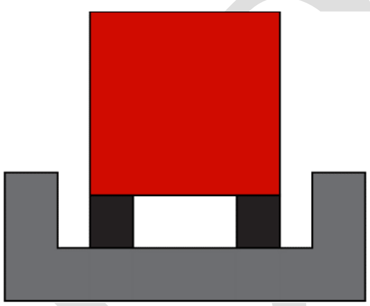
Similarly, make sure your train can stop. A runaway train is a recipe for disaster. Think about possible methods to slow your train down, such as magnetic braking or high friction surfaces. Modern trains use either air brakes or vacuum brakes, but both work on similar principles. Shown in the diagrams below are the different states an air brake system may be in. When the driver applies the brakes, the air flows out the brake pipe line allowing air from the reservoir to fill the brake cylinder applying the brake. On the other hand to release the brakes, air pumped into the brake pipe moves the valve to allow air from the brake cylinder to flow out the exhaust and extending the spring. An intermediate state is possible when pressure in the brake pipe is equalized with that in the valve preventing air from flowing in or out of the brake cylinder. These systems allow compartments which become detached from one another to automatically brake by severing the brake pipe. Vacuum brakes work identically, but operate on a lack of pressure, as opposed to air brakes.

Additional Context: Track Design

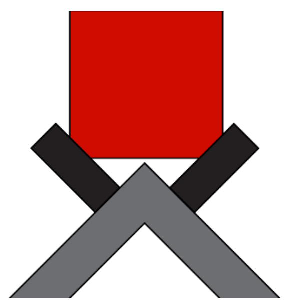
Your track design will largely influence the type of train you plan to design. Most trains, especially in the tube, use two rails which the train rides atop. However, many high speed trains are maglevs, meaning they use magnets to suspend the trains for ultra-low friction. One particular train in Germany, called the Wuppertal Suspension Railway, has the train hanging underneath the track. You can see a picture of this train below.

Below are some possible track designs, but be creative and see if you can design a better one or maybe a hybrid of two.

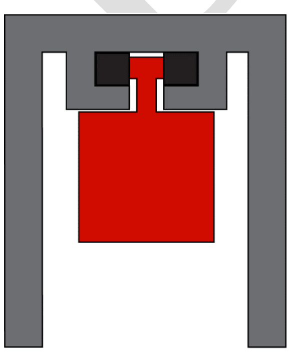
Traditional Track



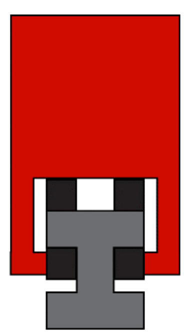
Angled Track



Hanging Track



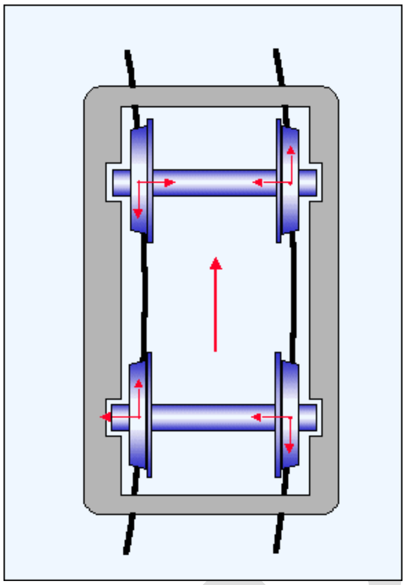
I-Beam Track



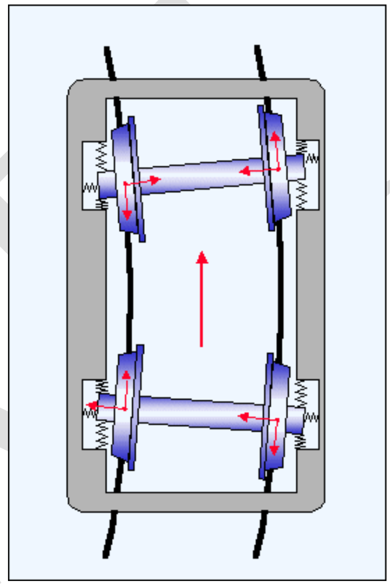
Additional Context: Bogies

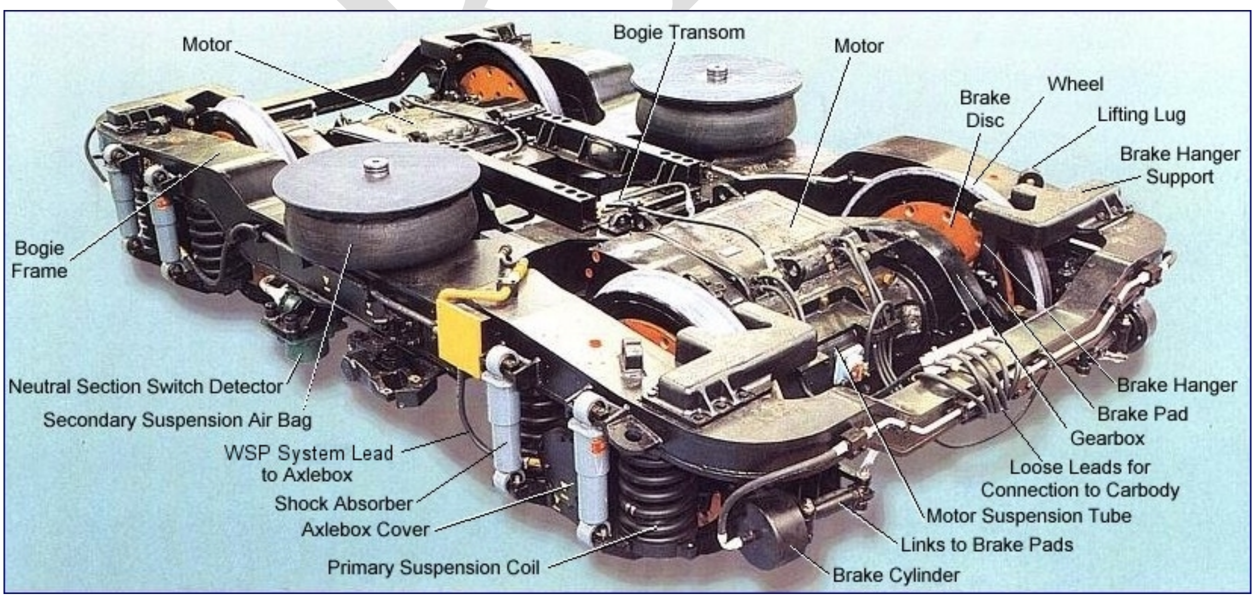
Bogies, also called trucks, are the part of the train which connect the body to the wheels. Bogies are highly engineered to include the wheels, suspension, sensing equipment, brakes, and motors. The image below shows a typical bogie and the various components inside. They generally have four wheels and steerable bogies, seen to the right of traditional bogies, allow the wheels to angle slightly for easier travel across curved track.

Non-Steerable Bogies



Steerable Bogies





Citation(s)

"The Early Underground" copyrighted images courtesy of the London Transport Museum.

- August 1, 2013, The Kaiserwagen, Retrieved from: https://en.wikipedia.org/wiki/Wuppertal_Suspension_Railway#/media/File:Wuppertal_kaiserwagen.jpg

- November 13, 1936, Retrieved from: http://www.ltmcollection.org/photos/photo/photo.html?_IXSR_=8LTLoXQoRgf&_IXMAXHITS_=1&IXinv=1998/89338&IXsummary=results/results&IXsearch=1935&_IXFIRST_=70

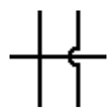
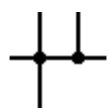
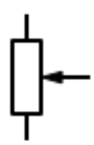
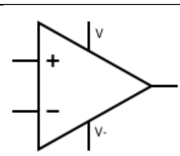
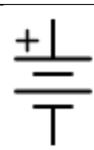
- April 19, 2012, Farrindon Station MMB 22 S-Stock, Retrieved from: http://upload.wikimedia.org/wikipedia/commons/c/c5/Farringdon_station_MMB_22_S-Stock.jpg

Session 3: Mixed Signals

Reference Material: Circuit Elements

One of the most important parts of a railway system is signaling. Train safety and management depends on it. In order to understand how signaling works, it is important to first understand how a circuit works.

Components in the Circuit

Name	Symbol	Description
Wire		Conducts electrical current.
Unconnected Wire		Wires are not connected.
Connected Wire		Connected wires are distinguished by black dots or nodes.
Resistor		Restricts current flow.
Potentiometer		Changes voltage output of wiper depending on position of knob
Photoresistor/Light Dependent Resistor(LDR)		Changes resistance based on light exposure.
Light Emitting Diode (LED)		Form of diode which emits light when current is passed through it.
Operational Amplifier (Op Amp)		Has two inputs, an inverting (-) and non-inverting (+), and an output. Must be connected to power and ground as well.
Battery		Provides power to the circuit with constant voltage.

Circuits

A circuit can be described as a cyclical path around which electricity flows from the positive terminal of a battery to the negative terminal of a battery. It is accustom to denote the positive terminal of the battery with a plus sign, +, and a red wire while the negative terminal is denoted by the negative sign, -, and a black wire. In order for a current to flow through a circuit, it must be closed (i.e. the path between the batteries terminals must be connected). If the path between terminals is not connected then the circuit is called open. A short circuit occurs when the resistance in an open circuit is zero (be sure to avoid this).

An especially important concept is power and ground. Power is generally very intuitive for people to grasp because it is the highest voltage in the circuit. However ground is a little more complex. Ground doesn't have to be 0 volts. Simply put, it can be anything so long as it is the lowest voltage in the circuit. The various notations for power and ground are noted below.

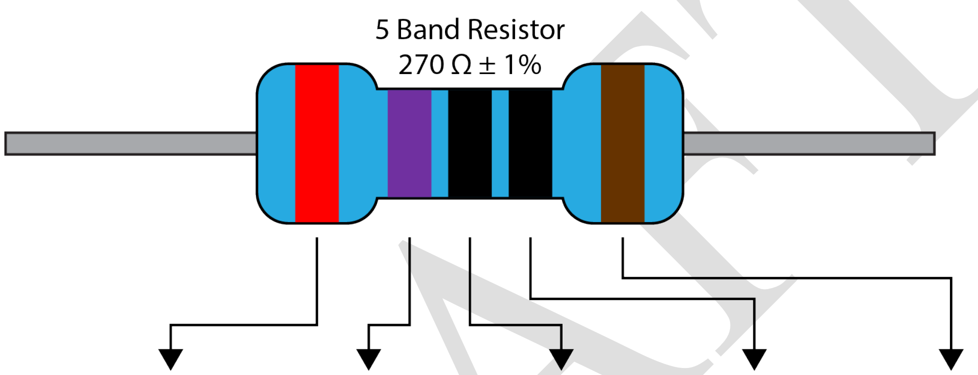
Power supply voltage	PWR	V_{CC}	V_{DD}	V+	V_{S+}	V_{cc+}
Negative supply voltage	GND	V_{EE}	V_{SS}	V-	V_{S-}	V_{cc-}

Resistors

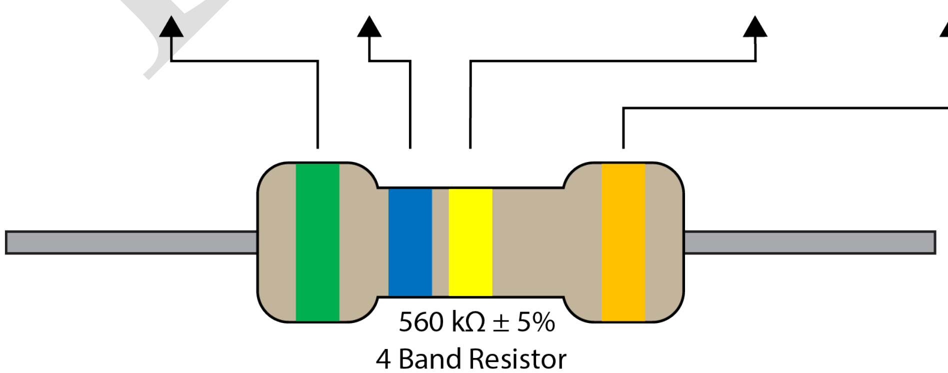
Resistors restrict the current flow through circuits. When a resistor is connected to a circuit and electricity is passed through it, there will be a voltage drop across the circuit. This can be found using the relation between resistance (R), current (i), and voltage (V) in Ohm's Law.

$$V = iR$$

Resistors are measured in Ohms. The higher the resistors value in Ohms, that the less current will flow through it (assuming you have a fixed voltage source). They can be anywhere from a couple of Ohms to millions of Ohms or even greater. You can determine the resistance of resistors using the chart of band colors below.

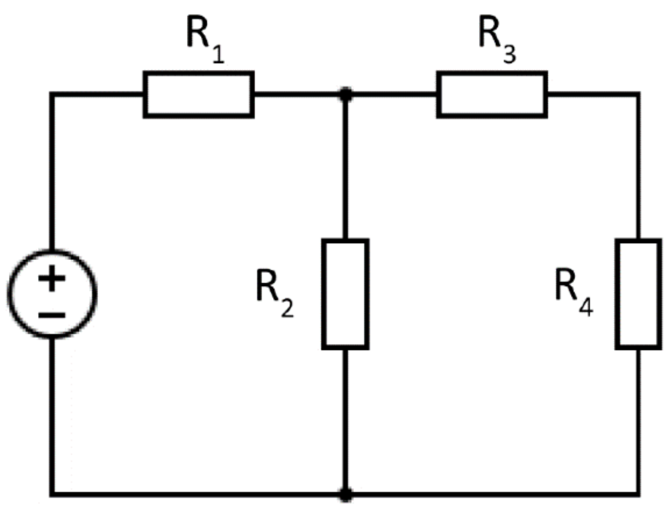


Color	1st Band	2nd Band	3rd Band	Multiplier	Tolerance
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1%
Red	2	2	2	100Ω	± 2%
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	± 0.5%
Blue	6	6	6	1MΩ	± 0.25%
Violet	7	7	7	10MΩ	± 0.10%
Grey	8	8	8		± 0.05%
White	9	9	9		
Gold				0.1Ω	± 5%
Silver					± 10%



Parallel and Series

As can be seen in the diagram of the circuit there are both series and parallel combinations of resistors. The resistors R_2 is in parallel with R_3 and R_4. R_3 is in series with R_4, and R_1 is in series with all other resistors. Though this example uses resistors, the concept of parallel and series applies to any component though the equations below are specific to resistors. You will not be asked to calculate their equivalent resistance, but it can be found for any combination of resistors using the equations. The symbol denotes a summation. If for example, you have three resistors in parallel, your sum would be $\sum \frac{1}{R_n} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$. Likewise, for three resistors in series it would be $\sum R_n = R_1 + R_2 + R_3$.



Equivalent Parallel Resistance

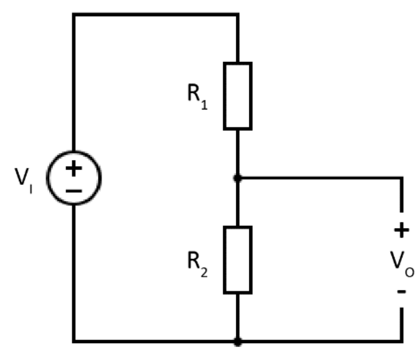
$$R_{eq} = \frac{1}{\sum \frac{1}{R_n}}$$

Equivalent Series Resistance

$$R_{eq} = \sum R_n$$

Voltage Dividers

Voltage Dividers are one of the simplest and most important circuits to learn. Theses circuits can take a large voltage and turn it into a smaller voltage. In this activity, the voltage divider allows us to convert the change in resistance of the photoresistor to a change in voltage for the input to the operational amplifier. The equation below relates the output voltage to the input voltage. You will not have to do any calculations for this activity but note that R_1 will be the photoresistor and R_2 a regular resistor.



$$V_O = V_I \frac{R_2}{R_1 + R_2}$$

Potentiometers

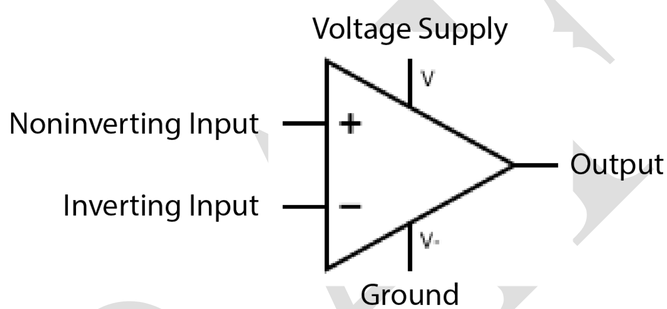
Potentiometers are extremely useful and common electrical components. By turning the knob, the voltage will change on the middle pin called the wiper. Potentiometers work on the concept of voltage dividers. However, for a potentiometer $R_1 + R_2 = R_{Potentiometer}$. Potentiometers like resistors have no direction, but remember to connect the left and right pins to power and ground.

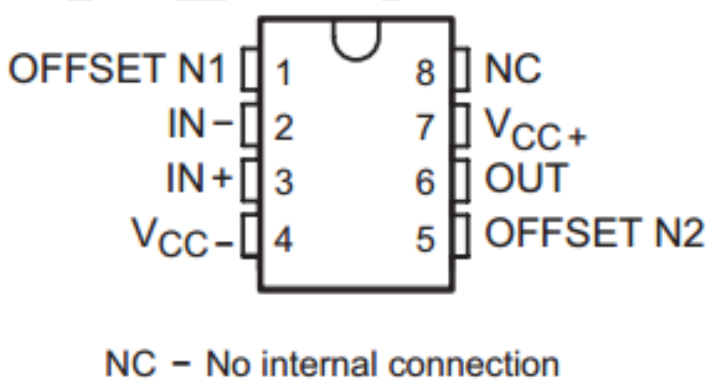
Photoresistors

Photoresistors are one component which can be used to detect light in a circuit. When in darkness, its resistance will be highest. When illuminated, its resistance will be lowest. Its change in resistance coupled with a voltage divider will allow you to change the voltage to the operational amplifier's noninverting input.

Operational Amplifiers

Operational amplifiers, op amps for short, are used in many manors. In this activity, it is used to compare the difference in voltage between two inputs and output a HIGH (on) or LOW (off) depending on which voltage is greater. An op amp requires the connection of at minimum five pins. Here you will connect the power and ground to provide electricity to the chip via V_{CC+} and V_{CC-}. In the final circuit, the wiper pin of the potentiometer should be connected to the inverting input (IN-) and the voltage divider wire from the photoresistor section should be connected to the non-inverting input (IN+). In the example chip below, you may ignore the OFFSET N1 and N2 pins as they are not important for your activity. You will need to look up the datasheet for you particular chip by doing an internet search for the text written on the top of it. Then find a picture similar to the example one below for information on each pin.

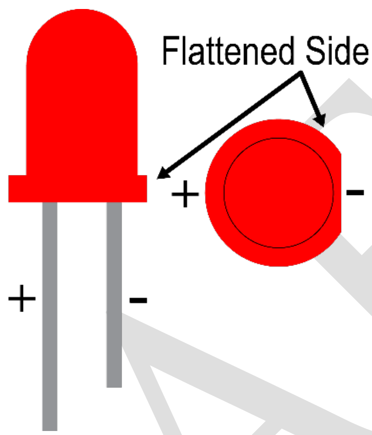




Chip Diagram for TL081CP

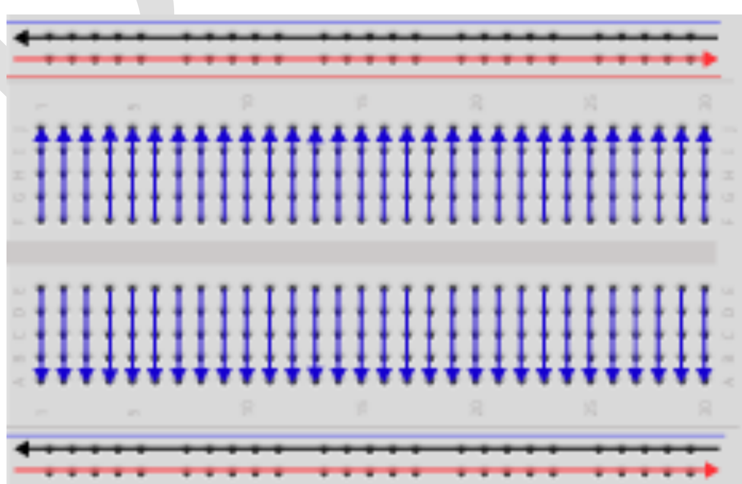
LEDs

Light emitting diodes, or LEDs, are a special type of diode which emit light when current is passed through them. Diodes unlike many common electrical components have a specific direction and burn out if they are placed incorrectly. On the circuit diagram symbol the flat line denotes the side which goes to ground. When looking at the actual component the side with the shorter wire is ground and the longer is power. This ground side of the LED will also be flattened.



Breadboards

Breadboards are extremely useful for rapid prototyping of electrical circuits. They come in various sizes but they all work the same. The vertical strips of holes on either side, sometimes only one side, are connected together as power and ground rails. Connecting any of these pins will result in all of the other inline pins being connected to the same source. In the middle of the board there are of rows. Each row on each side are connected together. Refer to the diagram below for a clearer picture of the connections on a breadboard.



Session 4: Rail Lines and Line Graphs

Additional Context: Signaling

In the early days of railways (in the 1830s and 1840s), there was no fixed signaling. Train drivers had to keep their eyes open for another train so they could stop before colliding with it. However, several accidents illustrated that this was not the best method for signaling trains as it was (and is) quite difficult to stop a train within the driver's sight distance.

Time Interval System

In order to counteract this problem, London Underground attempted the Time Interval System which was a system where the trains were only allowed to run at full speed for ten minutes, or a ten-minute headway, after the previous one had left the station. Policemen used red, yellow, and green flags to inform drivers when to proceed. A red flag was shown for the first five minutes after a train had departed. If a train arrived after five minutes, a yellow flag was shown to the driver. The green flag was given after a full ten minutes had passed. What do you think were some potential issues with this system? How dangerous was it? Think about this for a moment.

As you probably had already guessed, the Time Interval System was incredibly dangerous! Early trains were unreliable and would often break down between stations. The speed at which trains were running could not be guaranteed which resulted in many rear-end collisions. Another problem was line capacity. Even if all trains could be relied upon to travel at perfect conditions (no fluctuations in speed or unexpected stops), signal engineers still needed to run more trains on the line. Increasing the amount of trains on the line made the number of accidents increase in response. Eventually, they came up with fixed signaling which they hoped would finally fix the system.

The Golden Rule of Signaling

The basic rule of signaling is to divide the tracks into sections to ensure that only one train was allowed in one block at a time. Each block is protected by a fixed signal placed at its entrance so that a driver of an approaching train could see it. If the section is clear, the signal will show a "Proceed" indication. This indication used to be a raised semaphore arm; however, now it is a green light or green "aspect". If the block was occupied, then the signal will show a "Stop" indication, which is usually a red aspect. The next train will wait until the train in front has left the section.

The first mechanical signals in the UK appeared in 1841. In 1860, a signal box with levers controlling remote signals and points replaced these mechanical signals. Originally, the passage of each train was visually tracked by the signalman. When the train had cleared his section, the signalman would inform the signal box on the approach side that his block was free so that another train could go through. These messages were transmitted using an electric telegraph. The use of the electric "block telegraph" to pass messages and signal interlocking, which will be discussed further in depth later on, was introduced in the UK by the Regulation of Railways Act of 1889.

Distant Signals

Distant signals were introduced so that the driver could stop in time if the next stop signal was at danger. Positioning of these signals depended on visibility, curvature, maximum permitted speed, and a calculation of the train's ability to stop. Like the stop signals, distant signals were semaphores originally. They showed a green light at night if their stop signal was also green and yellow if the stop signal was red.

Additional Context: Track Circuits

Today, trains are monitored by track circuits. The London Underground was the first large-scale user of this system, applying it from 1904 to 1906. Low voltage currents are applied to the rails to cause a signal to show a “proceed” aspect. The current flow will be interrupted by the wheels of the train. This will cause the signal protecting the section to show a “stop” command (a red aspect or a stop signal). A “proceed” signal will only be displayed if the current does flow. Diagrams of Unoccupied and Occupied Blocks are provided below in Figures 1 and 2 respectively. A block section is separated electronically from neighboring sections by insulated joints in the rails. However, nowadays, more recent installations are electronics which allow jointless track circuits. In fact, some areas of the circuit allow signals, known as semi-automatic signals, to be held manually at red from a control center even if the section is clear.

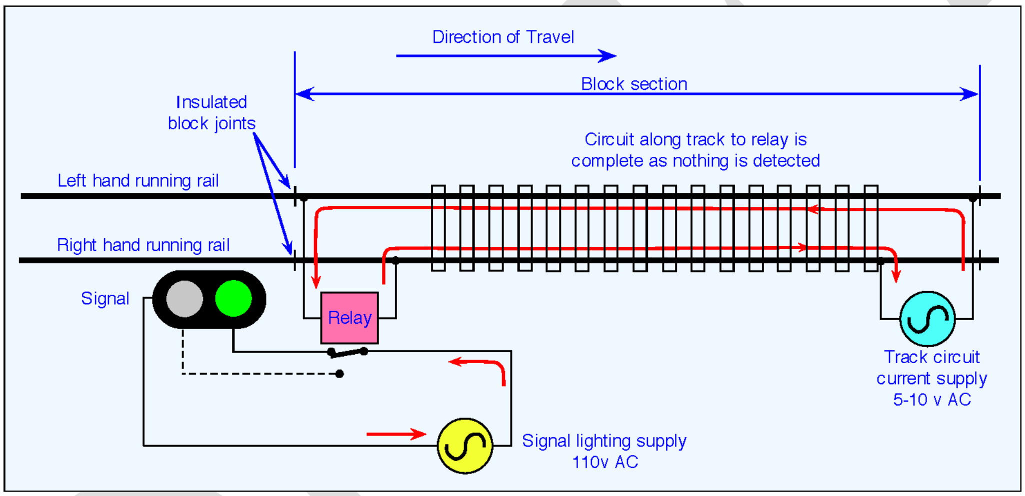


Figure 1: Unoccupied Block

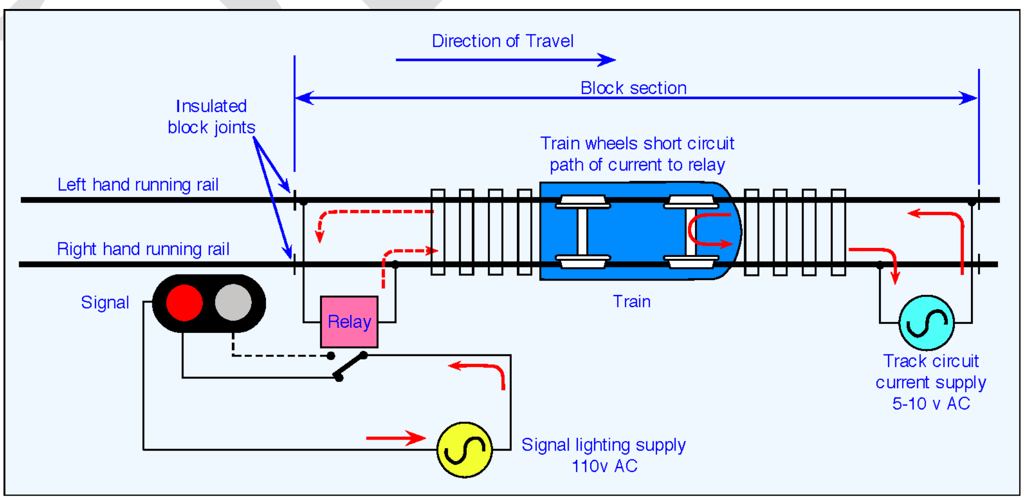


Figure 2: Occupied Block

Blocks

Railway tracks are divided into sections, or blocks, to ensure there is always enough space between trains and to avoid possible collisions. Each block is protected by a signal placed at its entrance. If the section is occupied by a train, the signal will be red. If the section is clear, the signal will be green. See Figure 3 to view this concept pictorially.

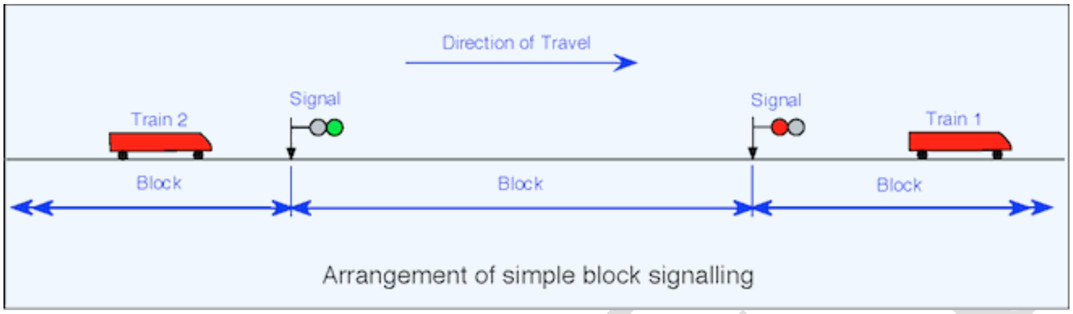


Figure 3: Simplified Block Diagram

Multi-Aspect Signals

There needed to be a new signals system for a train driving over 50 km/h because the driver needs a sufficient amount of time before he can stop. This led to distant signals, or caution signals, which were placed far enough back from the signal protecting the entrance to the block to give the driver a warning and a safe braking distance. Each signal was a multi-aspect signal and would show a red, yellow, or green aspect. Examples of multi-aspect signals includes a three-aspect signal and a four-aspect signal.

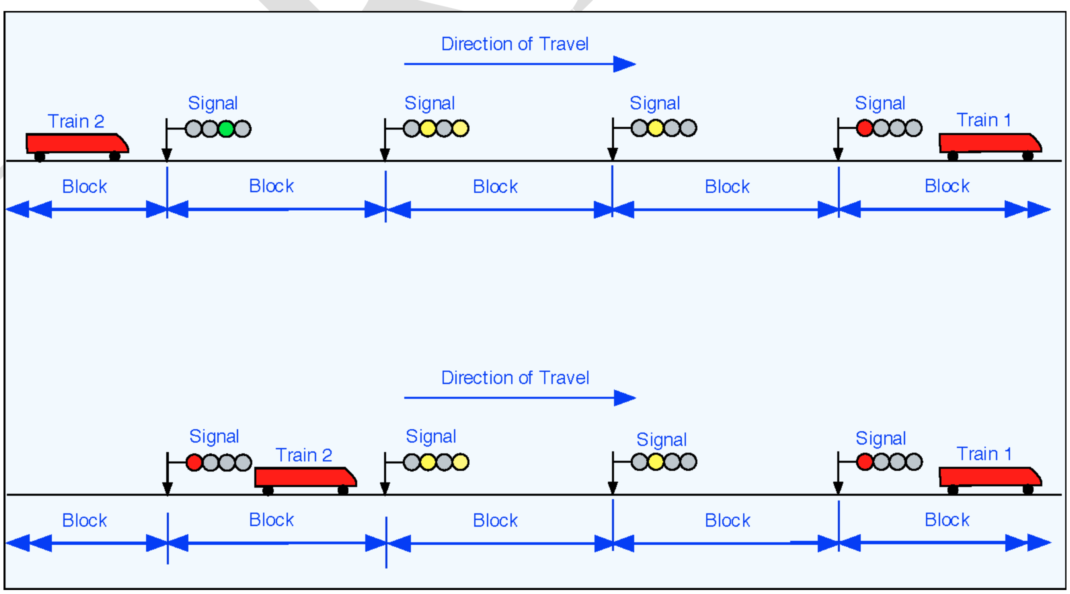


Figure 4: Four Aspect Block Signaling

Four-Aspect Signaling

The most commonly used multi-aspect signaling in the UK is a four-aspect system. It works similarly to the 3-aspect system, except they include two warnings (a double yellow and then a single yellow) before a red signal. This provides an early warning to higher speed trains so that they can prepare to stop. Figure 4 shows four-aspect signals with a high speed train with three clear blocks ahead (in the upper diagram) and a slower train with two clear blocks ahead of it (in the lower diagram). Lower speed trains can run closer together so more trains can be operated over a given section of line.

Reference Material: Fundamental Physics Equations

Included here are some of the fundamental equations of physics. Students should be familiar with these relationships, but this sheet may serve as a useful reminder of some of their details. Note that some of these same equations are behind the complex train graphs shown in this problem.

Table of Prefixes

Prefix and Abbreviation	Meaning	Example
giga- (G-)	1*10^9	1 Gg = 1,000,000,000 g
mega- (M-)	1*10^6	1 Mg = 1,000,000 g
kilo- (k-)	1*10^3	1 kg = 1,000 g
-	1	1 g
mili- (m-)	1*10^-3	1 mg = .001 g
micro- (-)	1*10^-6	1 g = .000 001 g
nano- (n-)	1*10^-9	1 ng = .000 000 001 g

Basic Kinematic Equations

- Let
    - x = displacement
    - v = velocity
    - a = acceleration
    - t = time

  Assume acceleration is constant.

$$x = x_o + v_o * t + \frac{1}{2} a * t^2$$

$$x = x_o + v_{avg} * t = \frac{1}{2}(v + v_o) * t$$

$$x = x_o + v * t - \frac{1}{2} a * t^2$$

$$v = v_o + a * t$$

$$v^2 = {v_o}^2 + 2a(x - x_o)$$

Basic Energy Equations

- Let
  - m = mass
  - v = velocity
  - g = gravity
  - h = height
  - k = spring constant
  - x = displacement

$$Kinetic\ Energy = KE = \frac{1}{2} * m * v^2$$

$$Potential\ Spring\ Energy = SE = \frac{1}{2} * k * x^2$$

$$Potential\ Gravitational\ Energy = GE = m * g * h$$

Basic Momentum Equation

- Let
  - m = mass
  - v = velocity
  - p = momentum

$$p = m * v$$

Newton's Second Law of Motion

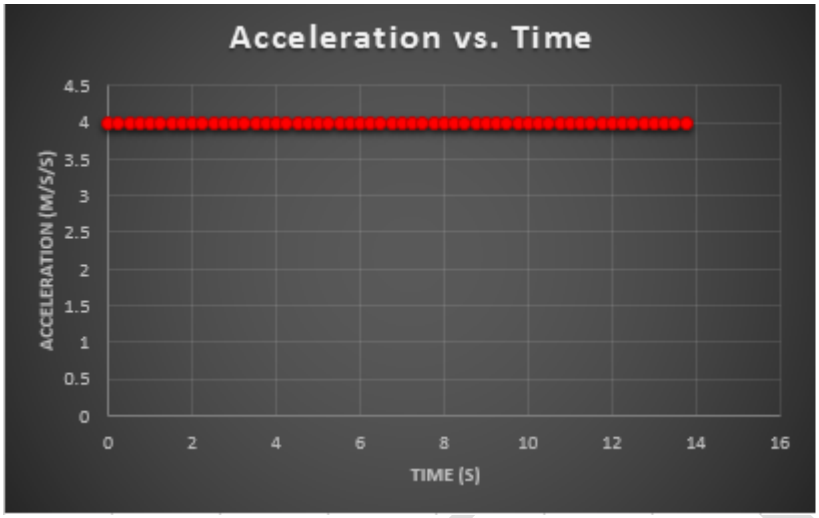
- Let
  - m = mass
  - a = acceleration
  - F = force

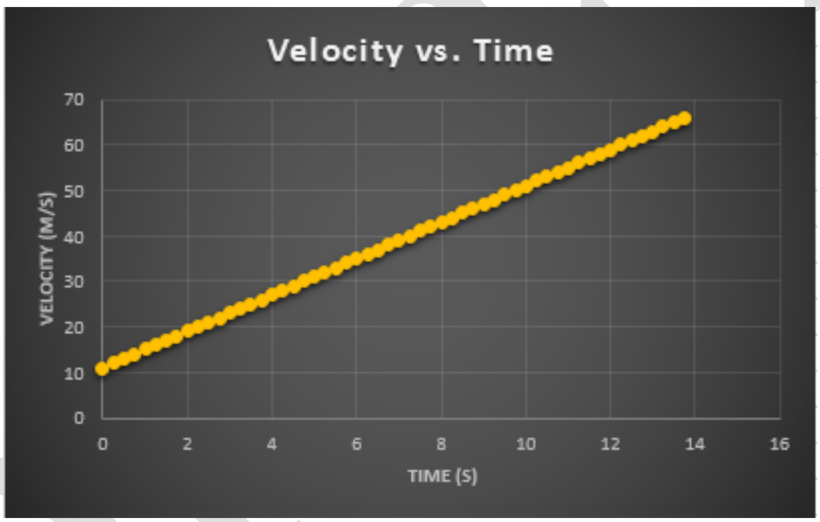
$$F = m * a$$

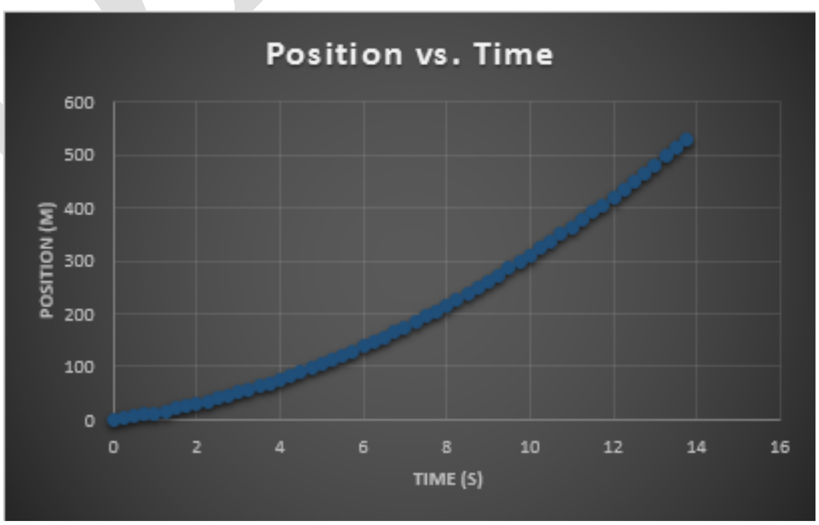
Reference Material: Fundamental Physics Relationships

Note that position vs. time, velocity vs. time, and acceleration vs. time graphs are all related. If acceleration is constant and positive at a given time, the velocity vs. time graph will have a constant positive slope and the position vs. time graph will be a parabola (concave up). Conversely, if acceleration is constant and negative at a given time, the velocity vs. time graph will have a constant negative slope and the position vs. time graph will be a parabola (concave down). These concepts are illustrated below.

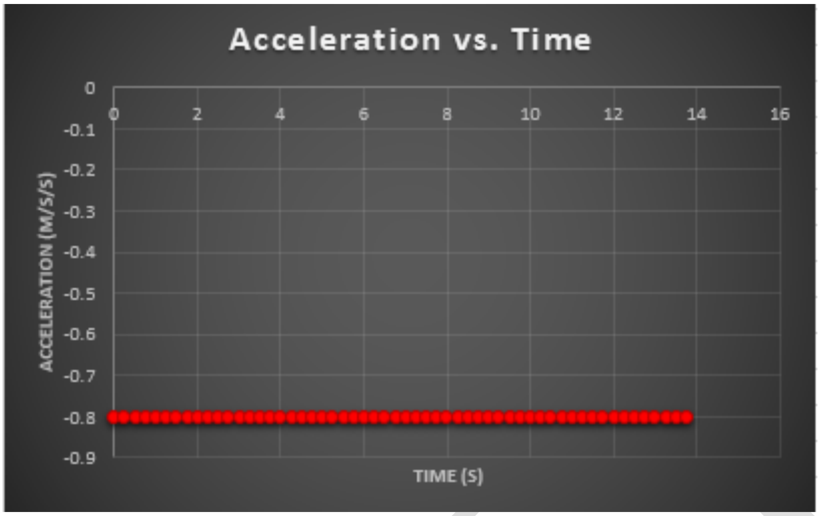
Example: Constant Positive Acceleration

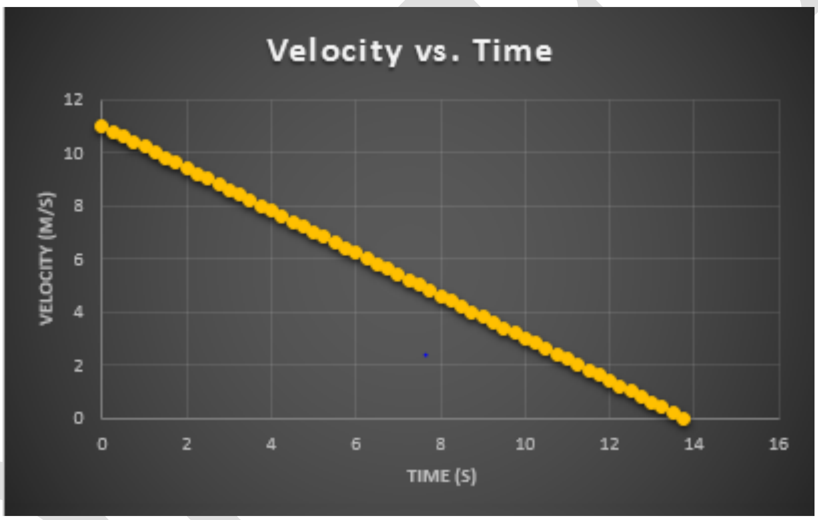


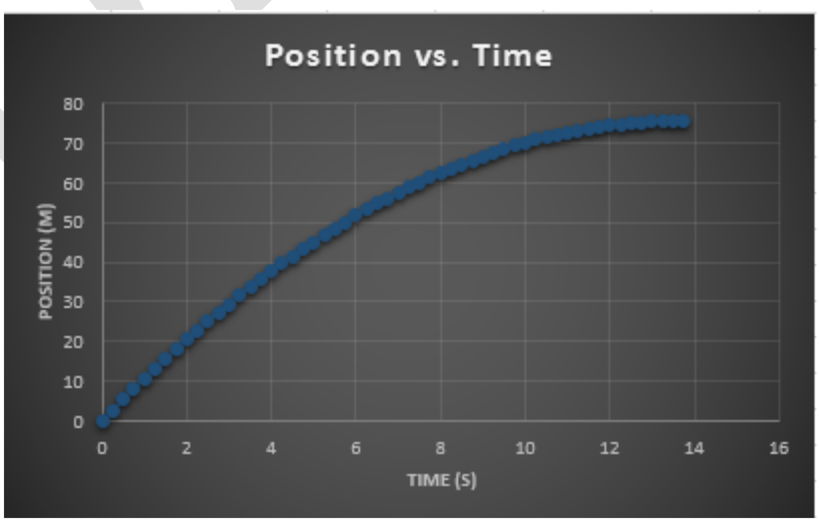




Example: Constant Negative Acceleration







Citation(s)

“Signaling” copyrighted images courtesy of Railway Technical Web Pages

- Railway Technical. (2014, December 9). Railway Technical Web Pages. Retrieved June 4, 2015, from http://railway-technical.com/stations.shtml#Station-Design

Session 5: Mind the Gap

Additional Context: Bridges

Used since ancient times, bridges are structures that provide passage over an obstacle, such as a valley or river. Some of the greatest bridges still standing today were built by Roman engineers. Pont du Gard (pictured above), spanning 272 metres, is an example of a Roman bridge. With the introduction of arches, the Romans revolutionized bridge building. Arched bridges allowed a downward force to be directed through the bridge's supports. Human civilizations employed this engineering feat for the next thousand years.

When designing a bridge, experts say that it's important to have a good understanding of BATS. BATS, is an acronym for the key structural components of bridges, **beams**, **arches**, **trusses**, and **suspensions**. Combinations of these four elements allow for various bridge designs from arch bridges and suspension bridges to side-spar cable-stayed bridges. The difference between these bridges is the length they can cross in a single span, which is defined as the distance between two bridge supports (physical braces that connect the bridge to the surface below).

Definitions

- **Stress** is the pressure or tension exerted on a material object.

$$\sigma = \frac{Force}{Area\ of\ the\ Cross\ Section}$$

Stress is measured in newtons per square meter, or pascals. This formula explains why thin objects break so easily: they have an extremely low cross-sectional area, so stress in the body is very high. Of course, the opposite is true for very large objects. So, ultimately stress causes an element to fail, not necessarily the force it experiences; engineers must consider both the forces present in bridge beams as well as their size and shape in order to create safe infrastructure. Examples of stress are **compressive, tensile, torsional** and **shear stress**; they are caused by compressive forces, tensile forces, moments, and sliding forces (forces acting parallel to a cross section) respectively.

- **Tension** is the state of being stretched. For example: What happens to a rope when you play a game of tug-of-war?

- **Compression** is the action of reducing an object in volume. For example: What happens when you push down on a spring? It becomes smaller and more compressed. You will even feel a force pushing back on you.

- **Moments** form as an element is bent or twisted. If you hold a heavy weight in your hand, your wrist will bend downwards; this is because a moment, or bending force, has formed in your wrist. Bridges usually cannot bend as well as your joints, so engineers must perform very precise calculations of moments to ensure no excessive stresses form as a result of these reactions. Note that moments and torque are very similar, and, for the purposes of this program, can be considered synonymous.
- **Dead load** is the result of the forces present in a structure by virtue of its own mass and geometry.
- **Live load** is the result of the forces present on a structure as it is in use. For example, on a bridge, this might be cars, pedestrians, snow, wind, etc.
- **Buckling** occurs when compression overcomes an object's ability to endure that force.
- **Snapping** occurs when tension overcomes an object's ability to handle the lengthening of the force. Let us go back to the game of tug of war. If both teams pull too hard, the rope will snap!

- **Trusses** are structures made of elements supported at two points. The ability of engineers to design trusses to support compressive and tensile loads as well as moments has made them critical to bridge design. Usually trusses are arranged into triangular shapes as triangles are easy to form out of metal beams and distribute loads evenly and predictably among their members.

Table of Bridge Designs

Bridge	**Description**
Beam/Girder	• The simplest bridge design. These bridges need a rigid horizontal structure and two supports for the bridge to rest on at each end. o These components directly support the downward weight of the bridge and any traffic travelling over it. o Generally made out of concrete or steel o Height and size are controlled by the distance the beam can span • Example: The Waterloo bridge
Truss	• Product of the Industrial Revolution • Adapted the beam bridge by adding more trusses. Can have a thorough truss (above the bridge) or a deck truss (beneath the bridge) • Example: The Millennium (Wobbly) bridge
Arch	• Distributes compression throughout its entire form. • Tension is negligible thanks to the arch (dissipates force outwards) • The greater degree of curvature, the greater the effects of tension on the underside of bridges. • Example: The Pont du Gard
Suspension	• A beam bridge with two towers, anchorages, supporting cables, and a deck truss. o Towers support the weight and dissipate the compression o Supporting cables receive the bridge's tension forces. o Deck truss is a supporting truss system beneath the bridge. Helps to stiffen the deck and keeps the roadway from snapping. • Can cross distances between 610 and 2,134 meters • Example: The Golden Gate Bridge in San Francisco
Cable Stayed	• Adapted from suspension bridge. First built in Europe after the end of World War II. • These bridges have a bridge with a tower, deck, and supporting cables. • Tower absorbs compressional forces • Example: The Dartford Crossing bridge

Citation(s)

- Introduction to Simple Truss Analysis. (n.d.). Retrieved June 4, 2015, from http://www.aboutcivil.org/simpl-truss-analysis-methods.html

- Lamb, R., & Morrissey, M. (n.d.). How Bridges Work. Retrieved June 2, 2015, from http://science.howstuffworks.com/engineering/civil/bridge.htm

Session 6: Tunnel Vision

Definitions

- **Shafts** - Vertical openings. They are often dug by hand or with boring equipment
- **Ventilation shaft** - Vertical passages used in mines and tunnels to replace stale underground air with fresh air
- **Portal** - The opening of a tunnel
- **Crown** - The top half and "roof" of a tunnel
- **Invert** - The bottom half and "floor" of a tunnel
- **Statics** - The branch of mechanics concerned with bodies at rest and forces in equilibrium.
- **Driving** - Engineers refer to advancing a tunnel as driving
- **Stand-up time** - The amount of time a tunnel will support itself without any additional structures. Knowing this time enables engineers to determine how much material they can excavate before they must add supports

Classification	Description	Example
Mining tunnels	These tunnels are cheap, temporary structures built to let miners access valuable resources. They are usually dark, cramped, and can use wooden supports.	Coal mines of West Virginia, USA
Public works tunnels	These tunnels are used to transport water, gas, sewage, electrical lines, etc. to and from urban areas.	The Romans included tunnels in their aqueducts, transporting water from mountain springs into the heart of Rome.
Transportation tunnels	Every day millions, if not billions, of people travel through tunnels, either on trains, on foot, or in cars.	The Chunnel, also known as the Channel Tunnel, links Britain with Continental Europe via several parallel rail lines.

Method	Description	Example
Fire-Setting	Inducing thermal stresses in rock can cause is to become brittle and shatter. By rapidly heating and cooling a rock face it becomes relatively easy to advance, or drive, a tunnel.	Romans used this technique to construct the aqueducts mentioned above.
Cut-and-cover	Here workers literally dig a trench, construct or install a section of the tunnel, then convert the completed structure. Obviously, this method has a huge impact on areas along the path of the tunnel.	The first few lines of the London Underground were constructed using this method; some 2,000 workers dug the necessarily trench by hand. Today, this technique is used on many underwater lines, where silt can be easily dredged. In these scenarios sections of tunnel are floated above the trench, filled with water, sent into the trench, joined by underwater workers, and finally drained of excess water. This technique was used during the construction of the Ted Williams Tunnel in Boston's "Big Dig".
Shielding (for soft ground)	When tunneling through soft ground, engineers must cope with a short stand-up time; cave-ins are a constant concern. Therefore, diggers must constantly reinforce areas as they dig. They remove a small amount of earth before covering the affected area with a board. Once the entire face of the tunnel has been excavated and covered large machines then push the protecting boards forward, and the process is repeated.	Marc Isambard Brunel first introduced this method in 1825 with a rectangular pedestrian tunnel beneath the Thames. Peter M. Barlow and James Henry Greathead applied the Brunel method to cylindrical tunnels in 1874 as part of the construction of the London Underground. Since then the method spread throughout the world, ultimately returning to London as the tunnel boring machines used in the Crossrail lines shield the tunnel as they dig.
Jumbos (for hard rock)	A jumbo is scaffolding placed at the cutting face of the tunnel. Workers use the platform to drill deep holes into the rock, stuff them with explosive charges, then blast away the rock, excavating the broken rock only after clearing the noxious smoke.	This process is also used for mining and making roads through mountains.
Full face method (for	This technique is reserved for either tunnels with a small diameter or tunnels	This technique is used heavily with Tunnel Boring Machines as these

hard rock)	going through strong materials. Here excavation is simultaneously being done on the entire rock face, not just a small section which is later reinforced. The material must be firm enough to support itself for this to be a viable option.	machines excavate all the way across their massive diameter.
Top-heading-and-bench (for soft ground and rock)	A smaller tunnel is dug first, known as a heading, along the crown of the tunnel, then a lower part of the tunnel is dug, called a bench. This repeats until the tunnel's full diameter has been excavated. Many benches can be created, depending on the desired size of the tunnel. A clear benefit of this technique is that it lets engineers test the quality of the ground ahead of the tunnel.	Perhaps this method was utilized during the historically sensitive phases of the Crossrail initiative. Slowing the digging to allow for archaeologists to examine individual layers of rock may have preserved many different types of artifacts.
Tunnel boring machines (for soft rock)	Tunnel boring machines, or TBMs, are massive devices that cut full cylindrical shafts through rock. They have disk cutters at their rotating front ends, conveyor belts to remove muck from the active end, and a massive mechanism to install shielding as the machine advances. Thus these machines can literally create a nearly finished tunnel in one pass.	The effectiveness and speed of TBMs has made them incredibly popular in recent years. The Crossrail project uses eight TBMs which can generate 100 m of new tunnel in a week. The Chunnel project used as many as 11 TBMs; French teams competed with English teams to see who could reach the middle of the English Channel first.
Tunnel jacking (for soft ground)	Powerful jacks advance a hollow metal box through the earth almost like a cookie cutter. The enclosed dirt is carted away and the exposed faces are reinforced.	This technique was used Boston's "Big Dig" as a way to drive the tunnel without damaging surrounding infrastructure.
Future	Advancements in tunnel-boring machines, research into ultrasonic imaging, and developments in waterjet cutting and concrete composition all have the potential to make tunnels larger, easier to produce, and safer.	

Additional Context: The Crossrail Initiative

Crossrail, Europe's current largest infrastructure project, will reduce traveler's journey time, ease congestion, and improve connections between Heathrow and Paddington. It is projected to open in 2018 and is predicted to increase the miles of tunnels in London's rail-based transport network by 10 percent- the largest increase since World War II. It is estimated that the Crossrail endeavor will add 42 billion pounds to the UK economy and create thousands of jobs and training opportunities throughout London.

The Tracks

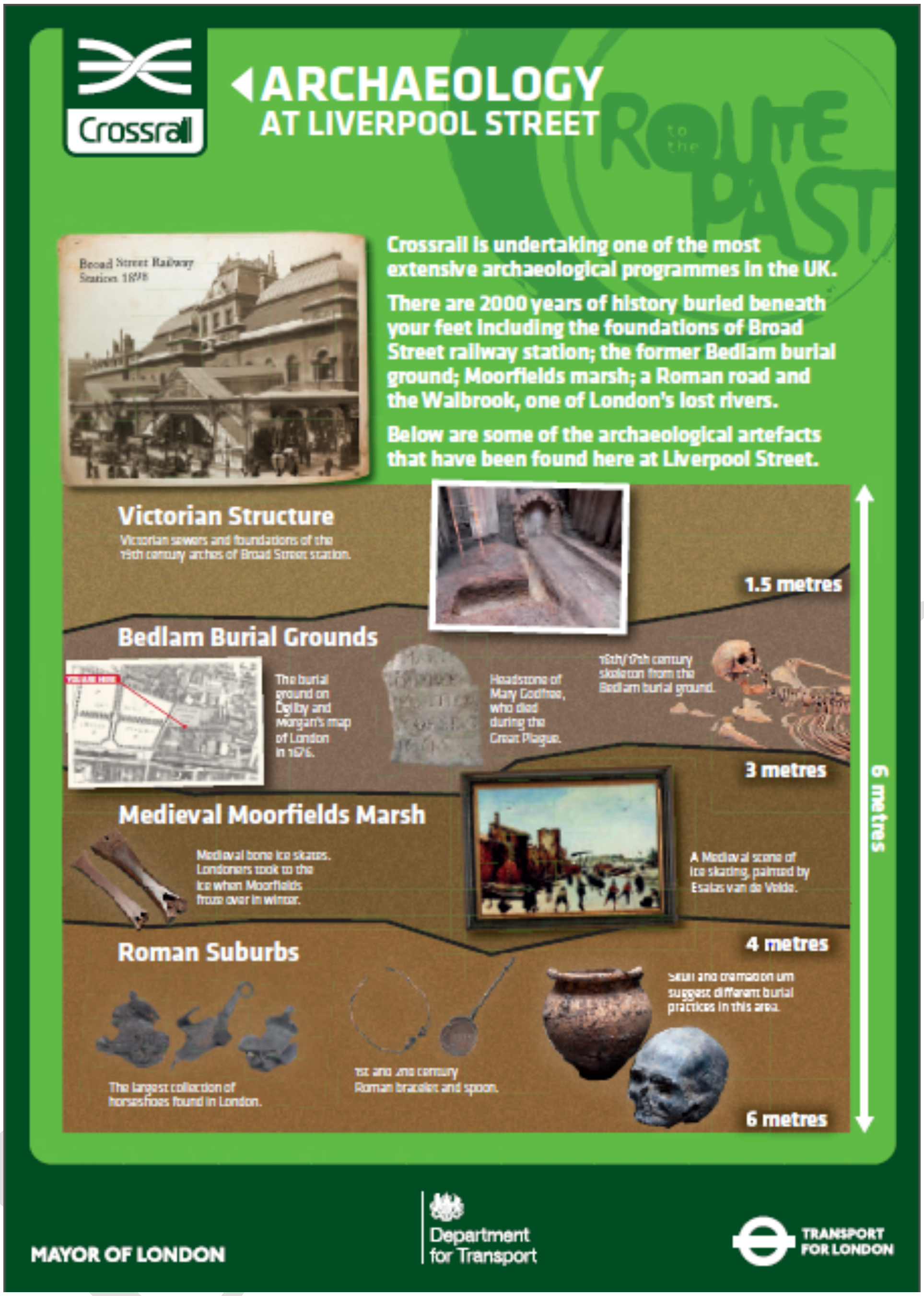
- 10 new Crossrail stations will be built at Paddington, Bond Street, Tottenham Court Road, Farringdon, Liverpool Street, Whitechapel, Canary Wharf, Custom House, Woolwich, and Abbey Wood.
- The new stations will be connected by 21 km of twin bore tunnels under central London to the 30 existing Network rail stations from Reading to Abbey Wood.
- As of June 2nd, 2015, the train tunnels are 90% complete. Tunneling should finish in spring of 2016.

The Trains

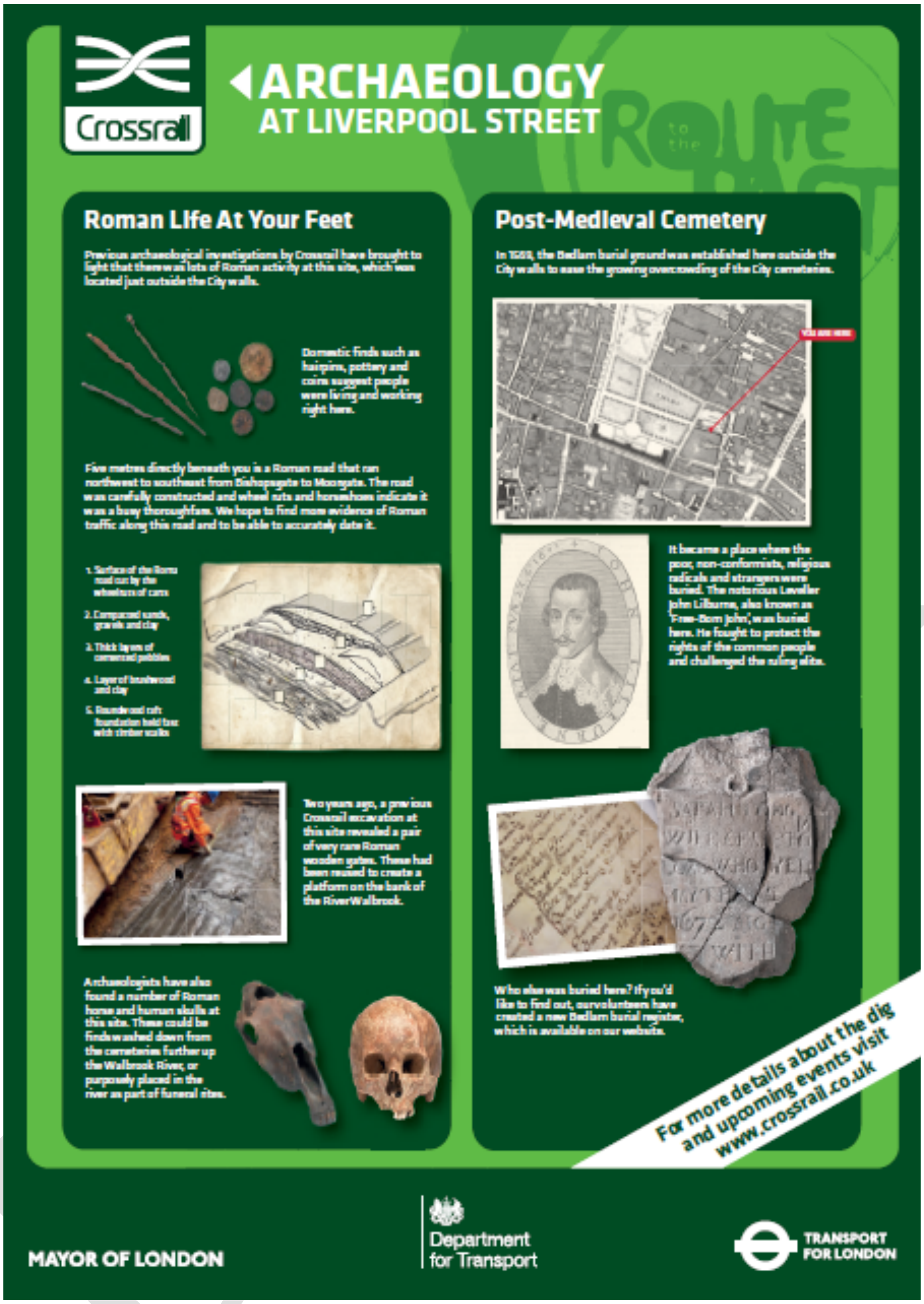
- Each train will be around 200 meters long
- Each train will accommodate roughly 1,500 passengers
- It is estimated that roughly 200 million passengers will use Crossrail each year

Crossrail's Archaeological Finds

In March 2015, Crossrail found a new archaeological site at Liverpool Street which reveals about 2,000 years of London's past ranging from the Roman Times to the Victorian Era. This site is now known as the Bedlam Burial Ground. Crossrail has sixty archaeologists working on the site. The archaeologists have found a Roman road running through the site as well as over 3,000 skeletons. To dig deeper into Crossrail's archaeological exploration, please view the informative pages provided by Crossrail shown below.



Crossrail
ARCHAEOLOGY
AT LIVERPOOL STREET
to the
ROUTE
PAST
Broad Street Railway Station 1898
Crossrail is undertaking one of the most extensive archaeological programmes in the UK.
There are 2000 years of history buried beneath your feet including the foundations of Broad Street railway station; the former Bedlam burial ground; Moorfields marsh; a Roman road and the Walbrook, one of London's lost rivers.
Below are some of the archaeological artefacts that have been found here at Liverpool Street.
Victorian Structure
Victorian sewers and foundations of the 19th century arches of Broad Street station.
1.5 metres
Bedlam Burial Grounds
The burial ground on Ogilby and Morgan's map of London in 1676.
Headstone of Mary Godfree, who died during the Great Plague.
16th/17th century skeleton from the Bedlam burial ground.
3 metres
Medieval Moorfields Marsh
Medieval bone ice skates. Londoners took to the ice when Moorfields froze over in winter.
A Medieval scene of ice skating, painted by Esaias van de Velde.
4 metres
Roman Suburbs
Skull and cremation urn suggest different burial practices in this area.
The largest collection of horseshoes found in London.
1st and 2nd century Roman bracelet and spoon.
6 metres
6 metres
MAYOR OF LONDON
Department for Transport
TRANSPORT FOR LONDON


Crossrail
ARCHAEOLOGY
AT LIVERPOOL STREET
Route to the Past
Roman Life At Your Feet
Previous archaeological investigations by Crossrail have brought to light that there was lots of Roman activity at this site, which was located just outside the City walls.
Domestic finds such as hairpins, pottery and coins suggest people were living and working right here.
Five metres directly beneath you is a Roman road that ran northwest to southeast from Bishopsgate to Moorgate. The road was carefully constructed and wheel ruts and horseshoes indicate it was a busy thoroughfare. We hope to find more evidence of Roman traffic along this road and to be able to accurately date it.
2. Compacted sands, gravels and clay
3. Thick layers of cemented pebbles
4. Layer of brushwood and clay
5. Roundwood raft foundation held fast with timber stakes
Two years ago, a previous Crossrail excavation at this site revealed a pair of very rare Roman wooden gates. These had been reused to create a platform on the bank of the River Walbrook.
Archaeologists have also found a number of Roman horse and human skulls at this site. These could be finds washed down from the cemeteries further up the Walbrook River, or purposely placed in the river as part of funeral rites.
Post-Medieval Cemetery
In 1569, the Bedlam burial ground was established here outside the City walls to ease the growing overcrowding of the City cemeteries.
It became a place where the poor, non-conformists, religious radicals and strangers were buried. The notorious Leveller John Lilburne, also known as 'Free-Born John', was buried here. He fought to protect the rights of the common people and challenged the ruling elite.
Who else was buried here? If you'd like to find out, our volunteers have created a new Bedlam burial register, which is available on our website.
For more details about the dig and upcoming events visit www.crossrail.co.uk
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ARCHAEOLOGY AT LIVERPOOL STREET

ROUTE to the PAST

Bedlam Burial Ground

Historic research tells us that the 'New Churchyard' later known as the Bedlam Burial Ground was established in 1569. "The plot, about an acre in all, was walled in and the level raised by dumping earth and rubbish from cellar and well diggings in the City." The considerable cost of the walling and making up was paid by Alderman Sir Thomas Rowe.

Excavation of the burial ground. The cemetery wall is visible at rear

Evidence for these ancient works show a dense pattern of timber (elm) piles was driven into clays and silts on the edge of the Walbrook River. This formed the foundation for the brick cemetery wall that survived to a height of several brick courses. Within the area of the burial ground a thick layer of imported soil was placed to raise the land level. The earliest burials are found to cut through this soil. Finds were diverse and included a rare 16th century Venetian Gold Ducat.

Elm timber piles from the 16th century cemetery wall foundation at Bedlam Burial Ground being recorded

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ARCHAEOLOGY AT LIVERPOOL STREET

ROUTE to the PAST

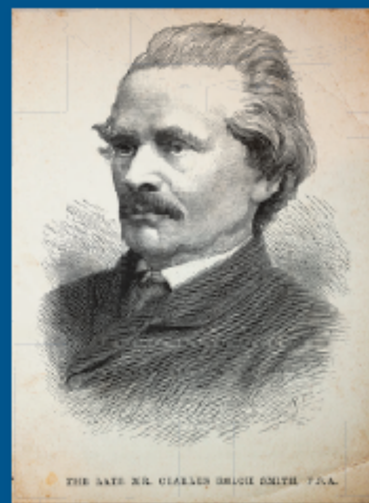
Bedlam Burial Ground

More than 10,000 people were buried in the new cemetery. As it was not attached to a particular parish church, no single burial register exists. Instead, entries like 'buried at Bedlam', or 'New Churchyard', are spread across different parish records.

Biographic detail rarely survives in the archaeology at this site. However, partial gravestones have been found re-used in the foundations of the cemetery wall.

Charles Roach Smith (1807-1890) was a pioneering London archaeologist and founder of the British Archaeological Association. He lived at No. 5 Liverpool Street where he made the following curious observation.

"Opposite my house on the other side of the street was a long dead wall, which separated the street from a long piece of garden ground. When my man buried in it a deceased favourite cat, he said he came upon the remains of human skeletons. A few years later the cat's coffin and epitaph were bought before the directors of the North London and Great Eastern Railway as a very puzzling discovery!"



©Illustrated London News Ltd/Mary Evans

We now know that apart from Roach's cat, construction works for the building of Broad Street Station had encountered the Bedlam cemetery remains in the 1860s.

A rare Venetian gold ducat of Doge Leonardo Loredan, AD 1501-21 Obverse: the Doge kneels before St Mark Reverse: Christ 'ego sum lux mundi' (I am the light of the world)

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Citation(s)

- Crossrail. (2015). Welcome to Crossrail. Retrieved June 4, 2015, from http://www.crossrail.co.uk/

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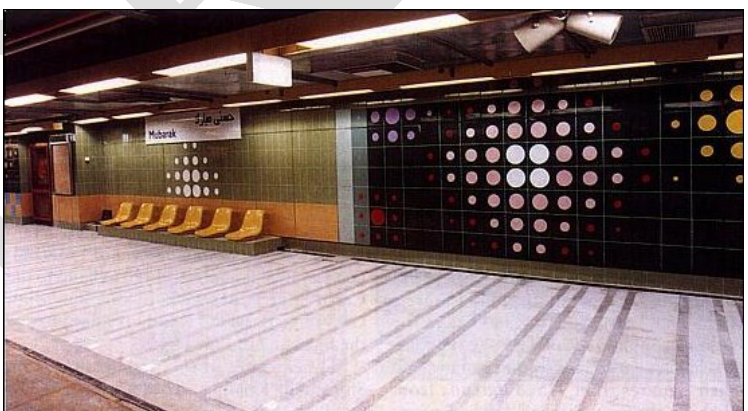
Session 7: Station Fixation

Additional Context: Station Artwork

The majority of the London Underground's tube stations have their own unique personalities, oftentimes featuring famous artist's' work or displaying an interesting architectural feature. Stations can also be set apart by an iconic image as well, such as the silhouette of Sherlock Holmes seen at the Baker Street station (Bakerloo line). However, London Underground is not the only tube system that showcases unique station architecture and design. Some examples of good station design are included below in Figures 1 to 3.

A new underground station on the metro system of Santiago, Chile. A combination of striking architecture and subdued lighting combine to give a pleasing overall finish. The use of upper level galleries, visible to the left and right, is unusual but adds to the feeling of accessibility.

Figure 1, Architecture: This photo is of an underground metro station in Santiago, Chile. The station is quite striking with its unique architecture and lighting. This station uses upper level galleries (which is unusual) to add to the feeling of accessibility.



An example of a wide station platform (Cairo Metro, Egypt) designed to accommodate large numbers of passengers boarding and alighting at the same time. Note that there are no supporting columns to limit circulation or visibility on the platform. There are a few seats for waiting passengers but these are arranged to prevent a person lying down on them. Vagrants sheltering in stations in a serious problem in some cities and has to be discouraged.

Figure 2, Platform: This photo was taken at a Cairo Metro station in Egypt. It is an example of a wide station platform which is designed to accommodate large numbers of passengers boarding and leaving at the same time. Note: there are no supporting columns to limit circulation or visibility on the platform. There some seats for waiting passengers but these are arranged to keep a person from lying down on them.

Madrid, Spain, offers an example of a light, airy station concourse with faregate lines dividing the "paid" and "unpaid" areas. The ticket office is located in the centre of the gate line so it can be used by passengers in both areas. The lightweight steel structure over the escalators in the foreground carries CCTV cameras and loudspeakers.

Figure 3, Concourse Design: The photo was taken in Madrid, Spain. It offers an example of a light, airy station concourse with fare gate lines dividing the “paid” and “unpaid” areas. The ticket office is located at the center of the gate line so it can be used by passengers in both areas. The lightweight steel structure over the escalators (bottom left of photo) allows CCTV (Closed Circuit Television) cameras and loudspeakers to be hung.

Citation(s)

“Station Artwork” and “Station Design” copyrighted images courtesy of Railway Technical Web Pages.

- Railway Technical. (2014, December 9). Railway Technical Web Pages. Retrieved June 4, 2015, from http://railway-technical.com/stations.shtml#Station-Design

DRAFT

Session 8: Time is of the Essence

There are many descriptions of the CPM (Critical Path Method) algorithm available online, from the original published paper onwards. Mosaic, a company working in project management, has a large list of scheduling-related papers. “Basic CPM Calculations” is a good resource to expand the given exercises to include more detail on the calculations and changes to the process. It provides modifications to the method that accommodate more complex scheduling scenarios. The Above and Beyond section in the Teacher Handbook for this session has some of these modifications. The basic calculations paper can be found here: http://www.mosaicprojects.com.au/pdf/schedule_calculations.pdf

Critical Path Information:

History and Summary

The Critical Path Method (CPM) is a method of mathematical analysis to shorten the completion time of large projects. It was developed in the 1950’s by Morgan Walker and James Kelly. Walker worked at DuPont, an American chemical company, where managers were looking for uses for their ‘UNIVAC1” computer, with an interest in planning, scheduling, and estimation. CPM has been used in engineering, software development, construction, and research projects, and for other projects with many components. A related method of project modeling was used to plan the 1968 Winter Olympics, from 1965 onwards.

The Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT) are related algorithms to schedule a large number of activities, some of which depend on a previous activity being finished.

Definitions

- **Project** - A large, complex goal that can be broken down into specific activities.
- **Activity** - A task in the project. Each activity has a duration, and a (possibly empty) set of activities that must be completed before it can begin.
- **Network diagram** - A way of representing the activities in a project to show the order they must be completed in, and the timings involved.
- **Path** - A sequence of activities in the networking diagram
- **Critical Path** - The path through the networking diagram from start to finish with the longest total time. This determines the project's duration.

Basic Steps to the Critical Path Method (CPM) are as follows:

1. Define the activities in the project, activities that must precede these activities, and the duration of each activity.
2. Create a network diagram to display the activities clearly and determine the project's duration.
3. Determine the duration of the project, and the critical path.

Theater Production

Student Worksheet

Definitions

Project - A large, complex goal that can be broken down into specific activities.

Activity - A task in the project. Each activity has a duration, and a (possibly empty) set of activities that must be completed before it can begin.

Network diagram - A way of representing the activities in a project to show the order they must be completed in, and the timings involved.

Basic Steps to the Critical Path Method (CPM) are as follows:

1. Define the activities in the project, activities that must precede these activities, and the duration of each activity.
2. Create a network diagram to display the activities clearly and determine the project's duration.
3. Determine the duration of the project, and the critical path.

This example determines the total time required to produce a theater performance.

Define the Activities, Dependencies, and Durations

The activities, their dependencies, and their durations are provided.

Activity Name	Activity identifier	Preceding activities	Duration (Days)
Choose designers	A	-	5
Choose crew	B	-	5
Choose cast	C	-	3
Rehearsals	D	C	19
Design set	E	A	10
Build set	F	B,E	9
Technical run-through	G	F	1
Actor run-through	H	D	2

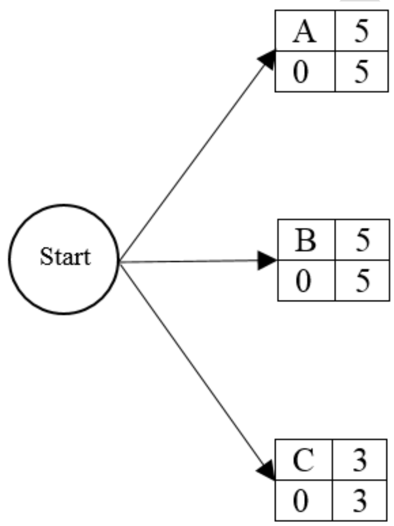
Create a Network Diagram

Each activity will be represented by its letter ID, the earliest time it can begin, the time it will finish, and its duration, in the following format:

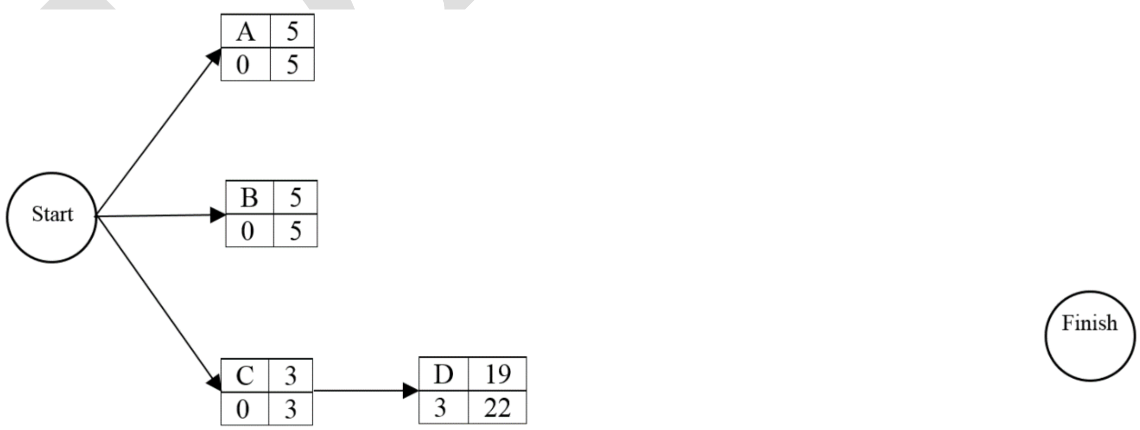
ID	Duration
Start	Finish

Formats will vary across different sources.

Network diagrams begin with the start node at the left edge. The next step is to add activities that do not depend on completion of a previous activity. This is completed in the diagram below.



Now, add in activities depending on a previous activity. The activity's start time will be the end time of the previous activity, and the end time can be determined from its duration.



Complete the diagram above by placing the remaining activities. What happens when an activity has multiple preceding activities?

After all activities are added, the activity or activities that have no activity depending on their completion are connected to the finish node. The finish time of the project should be written in the finish node. The project is complete when the last activity has ended.

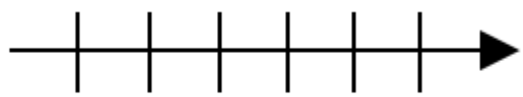
Determine the Critical Path

Definitions

Path - A sequence of activities in the networking diagram

Critical Path - The path through the networking diagram from start to finish with the longest total time. This determines the project's duration.

Determine the critical path by starting at the finish node and moving backwards to the start node. When there are two or more preceding activities to choose from, as there are at the finish node, choose the one with the latest finish time. Mark the arrows between activities you encounter as follows:



Identify the critical path on the diagram above.

Station Design

Student Worksheet

Consider the following table of activities to construct a railway station.

Activity	Activity identifier	Preceding activities	Duration (days)
Foundation	A	-	30
Core structure	B	A	16
Roofing and siding work	C	B	20
Install windows	D	C	5
Electricity	E	B	12
Plumbing	F	B	10
Insulation	G	E, F	4
Install interior walls	H	G	10
Finish flooring	I	G	14
Plumbing and electrical fixtures	J	H	7
Painting and décor	K	I, J	5
Shops set-up	L	D, K	4

Create a network diagram for this simplified building schedule of a station.

What is the total time estimate for the project? Which activities are on the critical path? Mark the critical path on your diagram.

Questions

Consider these questions independently of one another, working from the initial schedule. (When looking at the flooring strike, do not consider the safety violation in the electrical work.) Keep in mind how you arrive at your answers.

1. The inspection of the electrical work reveals a safety violation that takes three days to fix. How does this impact the total project time?

2. The workers hired for the flooring go on strike, causing a delay of four days. How does this impact the total project time?
3. Under pressure to finish the station, one of the managers brings in a larger and more efficient crew to install fixtures, reducing the time required from seven days to two. How much time is saved by this over the entire project?
4. There is a shortage on the materials used for siding on the station’s exterior. How many days can the siding be delayed by without delaying the entire project?

Float Time

Student Worksheet

Delays are part of any large project. It is important to know how a delay will impact your project's schedule, and be able to find this information easily even in a project with many activities.

To expand the networking diagram to reflect how long an activity can be delayed without slowing the project, a new node format is needed:

EST	ID		EFT
LST	DUR	Float	LFT

Definitions

EST and **EFT** - Early start and finish time estimates for the activity. These are the start and finish time estimates calculated previously.

LST and **LFT** - Late start and finish time estimates for the activity. These are the latest time values for the activity to start and finish without delaying the project's finish time.

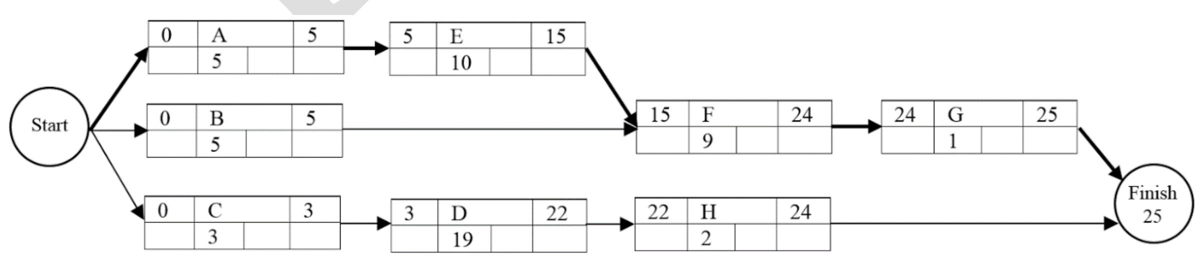
Float - The amount of time that an activity can be shifted by without delaying the project's finish time.

Theater Example, Revisited

Calculate the LFT and LST for each activity, then the float. Start with G and H, and work towards the start. The LFT for G and H is 25.

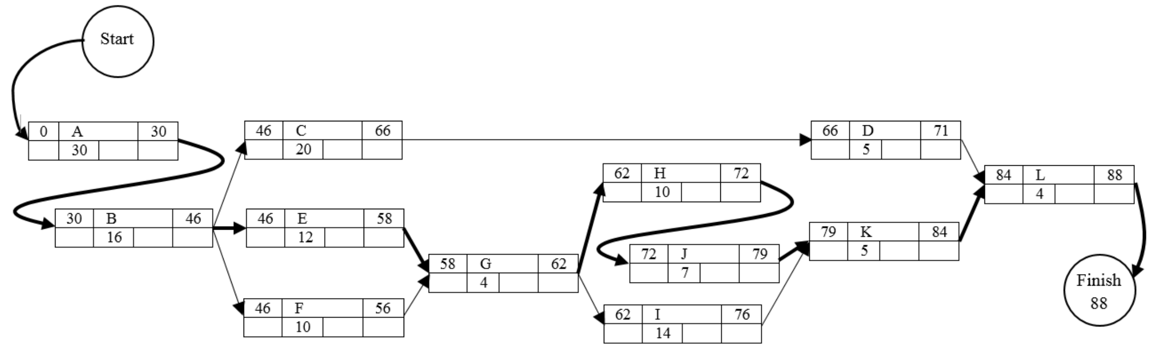
Find the LFT and LST for G and H. From the definition of float given above, what is the float time for G and H? What is the calculation you are using to determine float?

What happens when an activity has multiple activities depending on its completion, as in the start node?



Now Try On Your Own

Determine the LFT, LST, and float for each activity in the diagram below, which represents the station design project, in your company.



Critical Path Method Supplemental Explanation

Teacher Reference Sheet

This example determines the total time required to produce a theater performance.

Define the Activities, Dependencies, and Durations.

Activity Name	Activity identifier	Preceding activities	Duration (Days)
Choose designers	A	-	5
Choose crew	B	-	5
Choose cast	C	-	3
Rehearsals	D	C	19
Design set	E	A	10
Build set	F	C,E	9
Technical run-through	G	F	1
Actor run-through	H	D	2

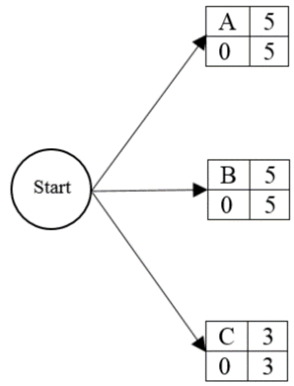
Create a Network Diagram

Each activity will be represented by its letter ID, the earliest time it can begin, the time it will finish, and its duration, in the following format:

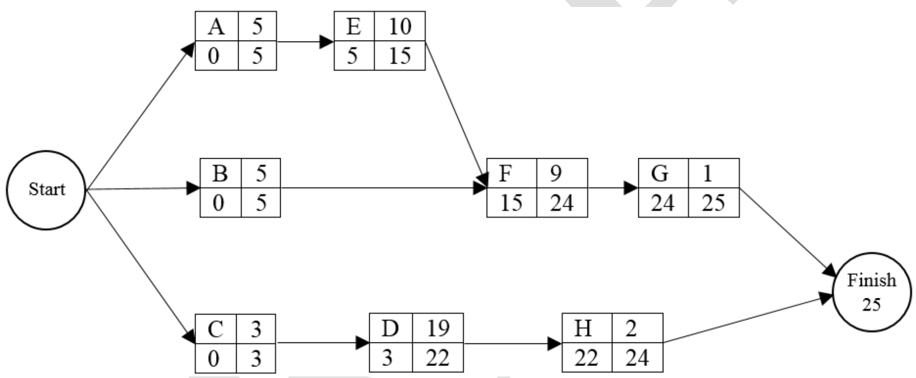
ID	Duration
Start	Finish

Formats will vary across different sources.

Place the start node at the left edge of the diagram. Add activities that do not depend on completion of a previous activity. The finish time for an activity is the sum of its start time and duration.

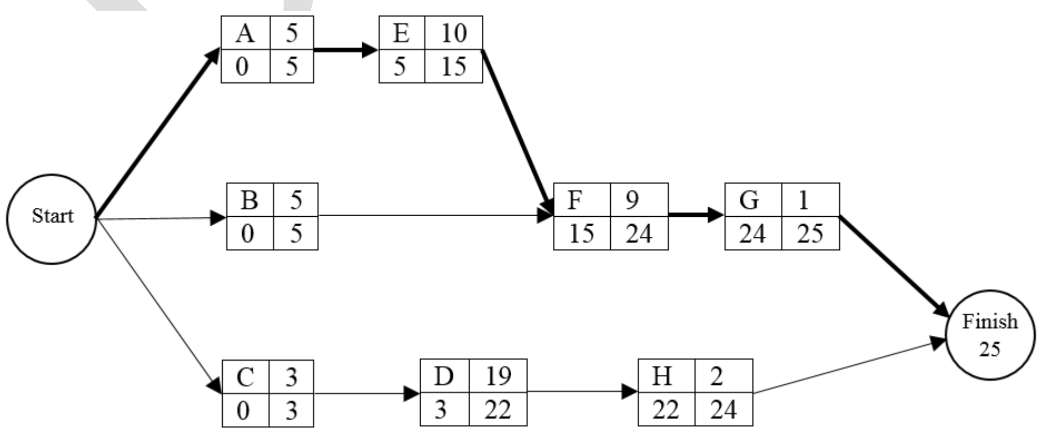


Add in activities depending on a previous activity. The activity's start time will be the end time of the previous activity. If an activity has more than one preceding activity, use the maximum of their end times. After all activities are added, the activity or activities that have no activity depending on their completion are connected to the finish node. The finish node has the finish time of the project, determined by the maximum end time of the activities leading to it.



Determine the Critical Path

Determine the critical path by working backwards from the finish node, to the start node. When there are two or more preceding activities, choose the one with the latest finish time. The critical path is marked in bold below.



Float Time Supplemental Explanation

Teacher Reference Sheet

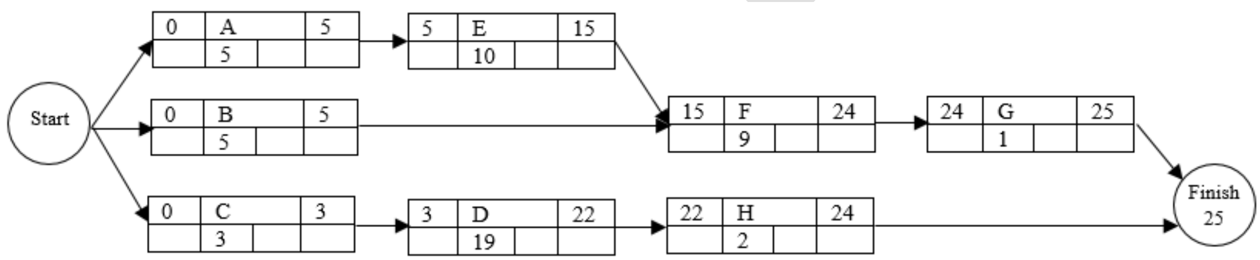
To expand the networking diagram to reflect how long an activity can be delayed without delaying the project, a new node format is needed:

EST	ID		EFT
LST	DUR	Float	LFT

EST and EFT are the early start and finish time estimates for the activity. These are the start and finish time estimates calculated previously.

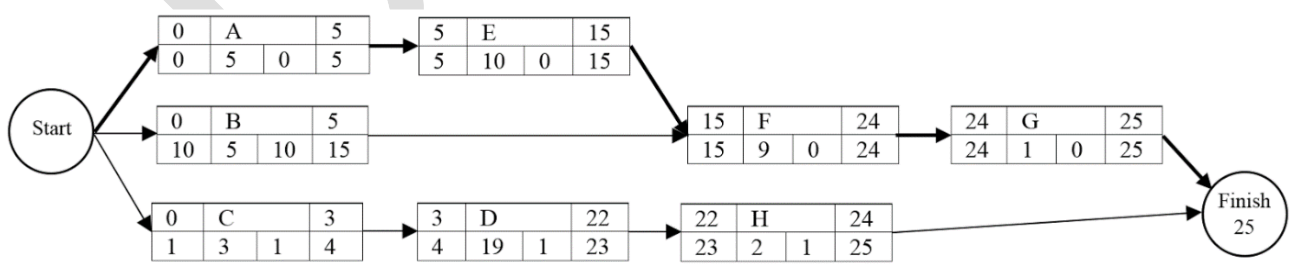
LST and LFT are the late start and finish time estimates for the activity. These are the latest time values for the activity to start and finish without delaying the project's finish time.

Float is the amount of time that an activity can be shifted by without delaying the project's finish time.



Working from the finish backwards, the LFT is determined by the LST of the activity directly after it, or the finish time if it has no subsequent activity. If an activity has multiple subsequent activities, use the one with the earliest LST. The LST is the difference between the LFT and the activity's duration, and the float is the difference between the EST and LST.

For reference: LST = LFT - duration; Float = LST - EST



Activities that are on the critical path will have a float time of zero. Any delay on the longest sequence of activities will cause a delay in the project's completion. If an activity does start late, the float for other activities may be affected. In this case, if C is delayed by one time unit, then D and H will be starting at their late start times, and have zero float.

Citation(s)

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- Basic CPM Calculations. (2014). Retrieved June 8, 2015, from http://www.mosaicprojects.com.au/pdf/schedule_calculations.pdf

- Michallon, A. (2005). Xth Winter Olympic Games Official Report. Retrieved June 4, 2015, from http://library.la84.org/6oic/OfficialReports/1968/or1968.pdf

Session 9: Show Time

There are no additional resources for this activity.

Session 10: A Journey Back in Time

There are no additional resources for this activity.