Reverse Engineering

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Reverse Engineering an Inkjet Printer

We are Team Byte (21549F) and are part of Queen Elizabeth's school and we have reverse engineered an inkjet printer. Specifically the HP photosmart C3100 printer. In this presentation, we have discovered how a printer works and how it uses the mistakes of the human body to create what we see on a piece of paper. We explain the main uses of a printer and why this invention is so useful to modern day society. In our main section about the printer we discuss:

VEX - ONLINE CHALLENGES - REVERSE ENGINEERING

1.0 - The Summary Report

The definition of a printer is a machine used for printing text or pictures. This is the base of what it does, but how it does it is a whole new load of information. The printer is now a staple of human life, used in workplaces, schools, and even VEX competitions. It allowed for the printing press, which spread news to the world. Instead of writing with a pen, you could print it in minutes!

Why did we choose a printer? Our team discussed what to reverse engineer for some time, we started off by mind mapping our ideas and what we thought would be most suitable to reverse engineer. After we had finished we all brought our ideas together and slowly took away the ones we thought were not as good as options. At this point we had around 10 ideas including a computer, a games console, toy car, lamp, watch, some others and obviously the printer. From this point we decided to look more closely with practicality and how much we could talk about. We looked into specifics for each of the options considering their strengths and weaknesses to pick the best option. In the end we chose the idea of the printer as what happens inside is more than what meets the eye. With many functions, this household item is quite fascinating. When looking further in depth we also realised how a printer is created to trick your eyes to create the colours displayed even using offset lithography to create the colours displayed on a piece of paper. Additionally, we were intrigued by how a printer uses light and electricity to create what we see on the page. This is why we chose a printer

We are going to be disassembling The HP Photosmart C3100 All-in-One Printer. It is 44 x 25.9 x 16.97cm and weighs 4.5kg. It is an inkjet printer and has a 48-bit colour, and 8-bit grayscale. This equates to around 256 shades of grey. It has around 4800 x 1200 DPI (Dots per Inch) when printing colour. This printer is capable, despite being old, can serve a household for their printing needs.

The printer has many parts which we researched about, ranging from the ink cartridge, to server motors, to ink nozzles. There are a variety of parts in this printer, in a variety of sizes, some ranging from a few micrometres to long belts, it is interesting to see this complex system

Aside from the knowledge we gained about this item we also learnt about teamwork, good research and presentation. We found out it was really challenging to find very specific questions on the web about our printer, so we had to dig in ourselves. We realised using key words and using the ‘control + f’ function we could quickly find what we needed. We realised how to split work evenly, and plan for the future. We learnt about safety and of course, the genius engineering behind the printer.

Word count: 496

2.0 - An introduction to the Printer and its uses

Printer

A printer is a hardware device that takes electronically data from a computer or any other device and then converts this into a physical form. This device in particular is capable of accepting text and graphic outputs from a computer and transferring this as information displayed on A4 paper. Currently, printers are becoming more and more advanced and to this point in time we can use them for scanning, photocopying and as well as that they can also fax. There are two main types of printers: laser jet printer and an inkjet printer.

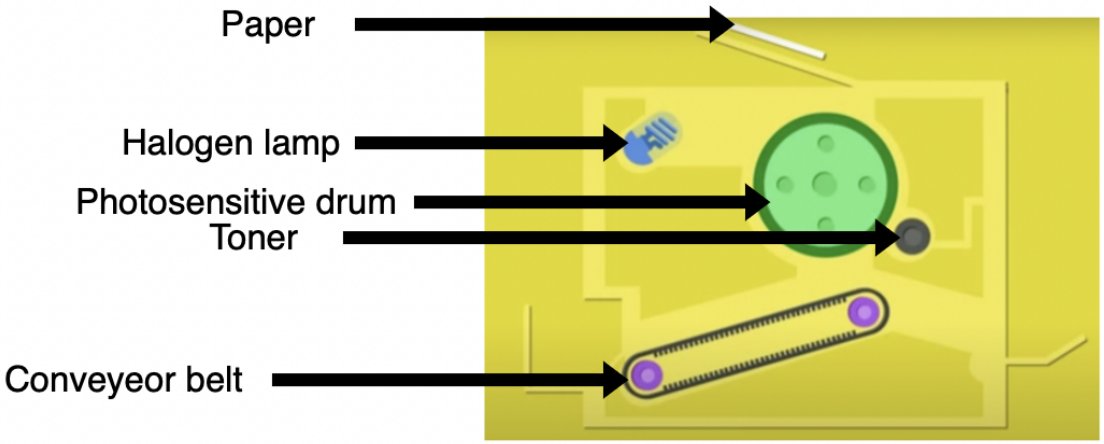
Scanning

Technology has been invented over centuries to make tasks easier and gives humans many benefits. On a daily basis, humans commit many actions however with technology this has become increasingly easier over the years. Printers are now developed to also have scanning features to archive certain documents to make sure they do not get lost. In the situation of a company the loss of such documents could lead to thousands of pounds being lost just due to a missing document. At home or for daily work, this scanning feature is also great in saving a few seconds of somebody’s day by enabling them to make a copy of a document without having to

access their computer first. This is done by storing a digital copy of the original image where it then transmits the information onto the computer.

Photocopying

Photocopiers are incredibly useful in day to day use with their ability to produce duplicates of a document instantly and for very little cost. This is incredibly useful for certain circumstances such as newspapers or magazines where several thousands are required and to print off each one would be an incredibly painstaking job. Photocopiers make this job way easier and more practical for everyday usage. Photocopying is more complicated than what meets the eye. All we see is the image transferred onto another piece of paper but what goes on inside the machine is more complicated. There are many parts to a photocopier : halogen lamp, photosensitive drum, toner, a conveyer belt and a corona wire. These are all essential in a photocopier to allow it to function.



Firstly the paper with all the information travels down into the photocopier, over here is the halogen lamp which uses light to detect the information. It has an intense beam of light which scans the document from top to bottom, this light also gets reflected onto the photosensitive drum. As light waves are reflected by the colour white, the light has no impact, however for other colours such as black which are less reflective. The photosensitive drum is a metal roller which is electrostatically charged. With electrons on the outside and protons on the inside which balance each other out. It is attached to a high voltage wire called the Corona wire which has around 9 - 13 kV supplying all the power required. The photosensitive drum is coated with a chemical called selenium. It is a semiconductor which gives it the properties to be an insulator in the dark and a conductor when there is light. Now when this light falls upon the photosensitive drum the areas of the photoconductor which were exposed to the light becomes conductive and gets discharged and the area not exposed to the drum remains negatively charged therefore we get an electrical shadow. This is like a pretend version of the document but created by electrons.

When this drum rotates around it carries it to the toner which is positively charged. Positive particles from the toner are attracted to the negative ones on the photosensitive drum and therefore attach on to balance. A blank sheet of paper is placed on the conveyor belt where as it moves along it is given a stronger electrical charge than the one on the photosensitive drum. As the two parts cross each other the protons move onto the paper where it finally moves through two hot rollers which fuse the toner particles onto the paper. This is why there is a warm sensation on the paper after the entire process is finished. It is now permanently fused onto the paper, this is photocopying. This process happens extremely quickly to produce many copies.

Fax

Fax also known as telecopying is the telephonic transmission of scanned documents either text or images, usually to a telephone number associated with a printer or other output device. The original document is scanned with a fax machine which converts the document into a bitmap. In this form the information is transmitted as electrical signals through a telephone system. It is then reconverted and then turned back into the original copy. Currently all modems (a hardware device that converts data from a digital format into another format that is suitable for an analog transmission) are all capable of receiving fax data and with a household item such as a printer being capable of doing this action makes it a lot easier for many people. It helps keep paperwork simple and helps create a record, so you know everything is safe and secured. This is useful as when last minute negotiations get made with another company. The updated documents can easily get faxed over without running back to the office to print the new papers. Furthermore, they also have cheap costs and are multifunctional machines such as printers.

Why did we choose a printer? Our team discussed what to reverse engineer for some time, we started off by mind mapping our ideas and what we thought would be most suitable to reverse engineer. After we had finished we all brought our ideas together and slowly took away the ones we thought were not as good as options. At this point we had around 10 ideas including a computer, washing machine, toy car, lamp, watch, some others and obviously the printer. From this point we decided to look more closely with practicality and how much we could talk about. Furthermore we looked into specifics for each of the options considering their strengths and weaknesses to pick the best option. In the end we chose the idea of the printer as what happens inside is more than what meets the eye. With many functions, this household item is quite fascinating. When looking further in depth we also realised

how a printer is created to trick your eyes to create the colours displayed even using offset lithography to create the colours displayed on a piece of paper. Additionally, we were intrigued by how a printer uses light waves and electricity to create what we see on the page. This is why we decided to choose a printer to reverse engineer.

3.0 - External Anatomy

Figure 2.1 - View of printer

Figure 2.2 - Top view

Figure 2.3 - Side view

Figure 2.4 - Bottom view

Figure 2.5 - Paper exit and intake

Figure 2.5 - LAN and power connector

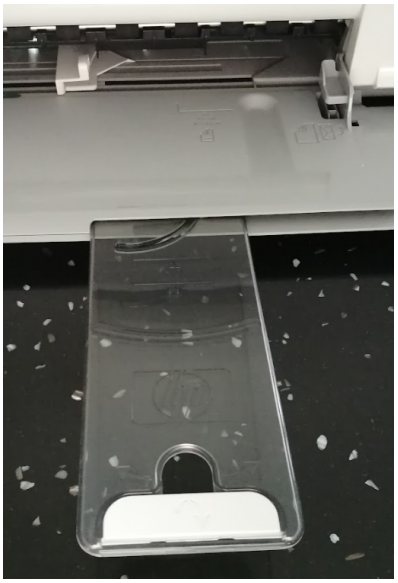


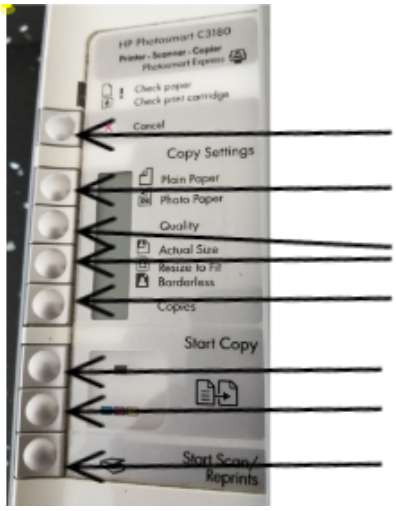
Figure 2.5 - Paper tray extender

Figure 2.6 - On button + Photosmart Express button (left) + Proof Sheet button (right)

Figure 2.7 - self-adhesive Label Roll

Figure 2.8 - AC Power adapter

Figure 2.9 - Barcode



Cancel button – stops a task or resets settings

Paper type button – Change to match the paper loaded (plain or photo)

Quality button – Changes the quality of the paper

Size button – Changes the image size (100%, resize to fit, Borderless)

Copies button – selects the desired number of copies

Start Copy Black button – makes a black and white copy

Start copy colour – makes a colour copy

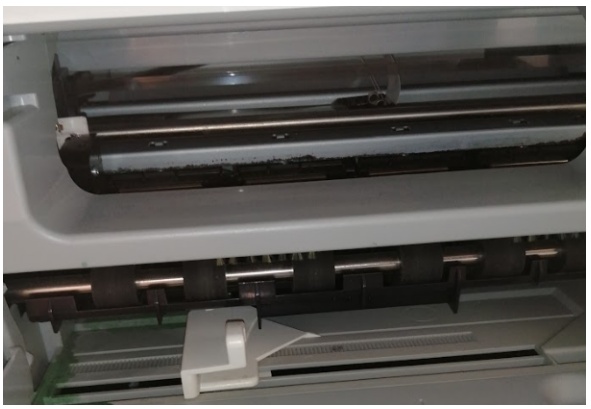
Start Scan button – Starts a scan

Figure 2.10 - Control Centre

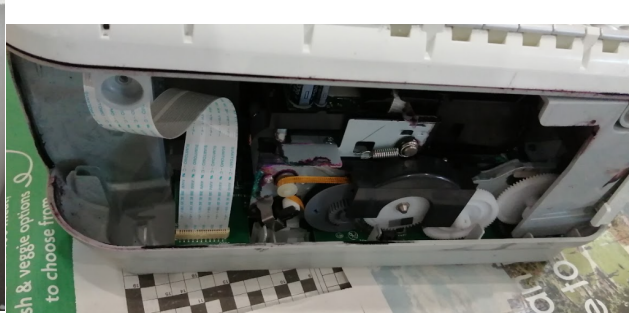
4.0 Disassembly Process

Step 1: Ensure to wear safety equipment such as safety goggles and gloves
Must have responsible adult supervision throughout the process
Printer must be assembled in a clear space
All cables must be disconnected from electrical outlets

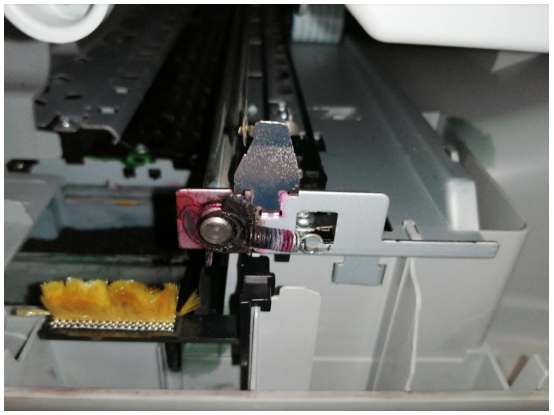
Step 2: Open the print cartridge door



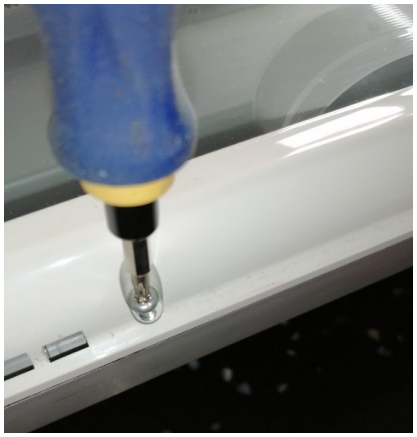
Step 3: Open the screws on the side of the printer



Step 4: Open the other side of the printer



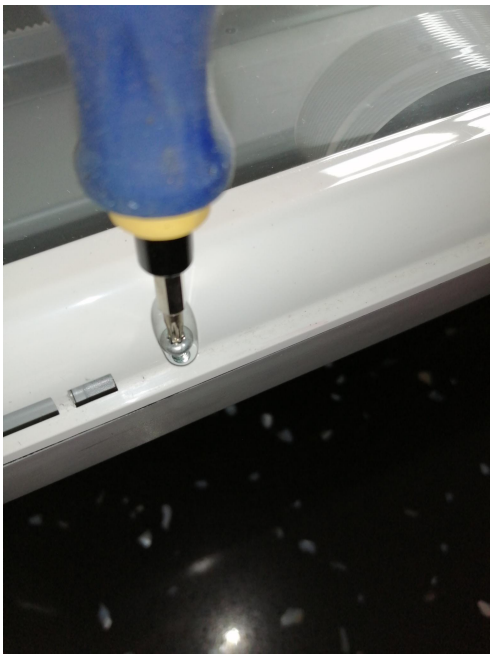
Step 5: Remove the top panel



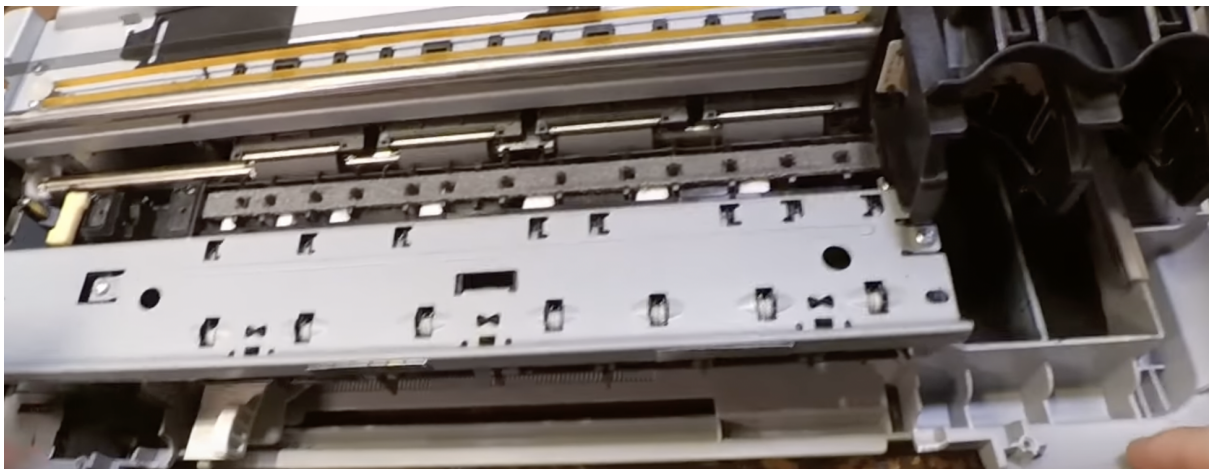
Step 6: Remove the panel below that it should come off smoothly

Step 7: Remove the on button

Step 8: If there are any screws anywhere try to unscrew them and take the plastic walls of the printer off.



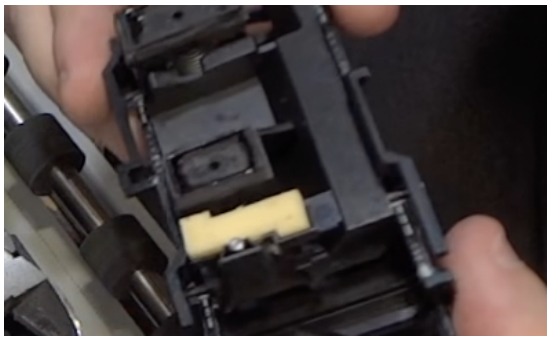
Step 9: After removing all of the plastic you then want to remove any motherboards or chips that are hanging it should end up like this



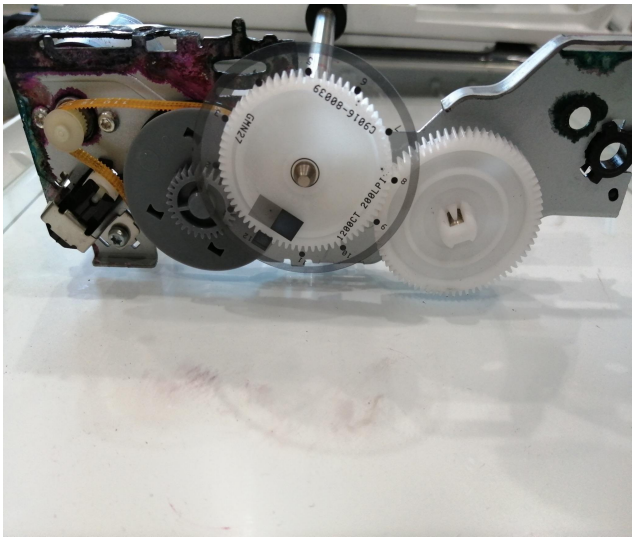
Step 10: Remove the screws attaching the belt and pulley mechanisms and take it out this will also include the printhead and the moveable arm when you take this part out.

Insert picture here:

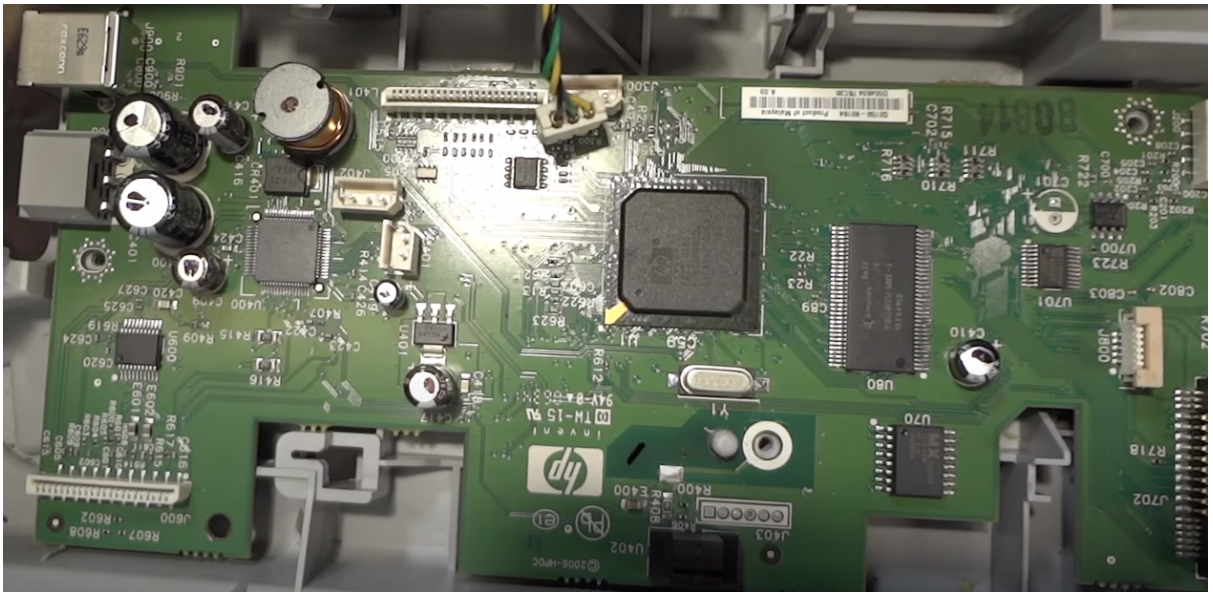
Step 11: Then you want to remove the main tank



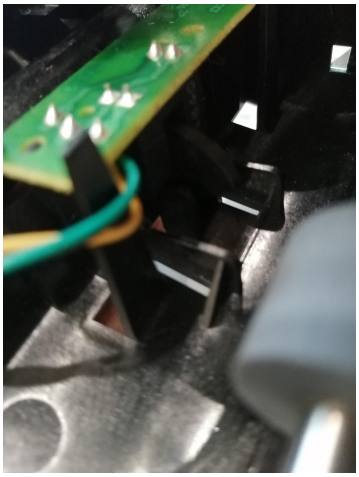
Step 12: Then you remove the roller arrangements alongside the gear system and the motor that runs from the feedback circuit.

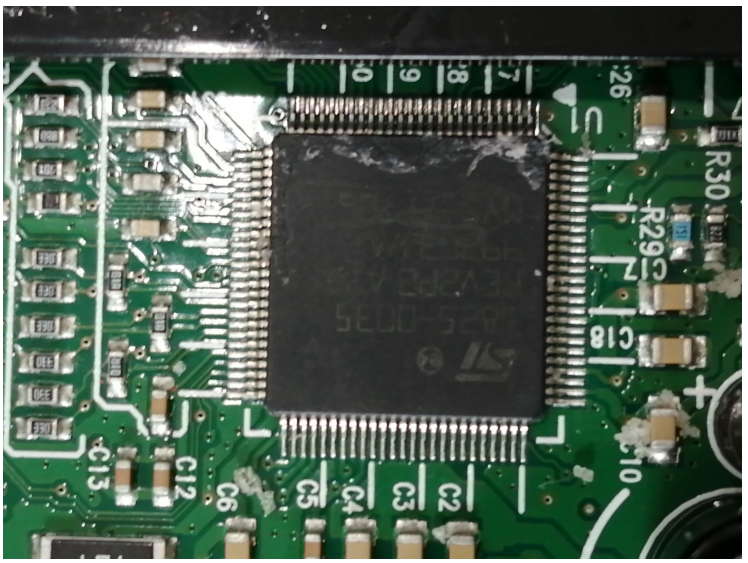


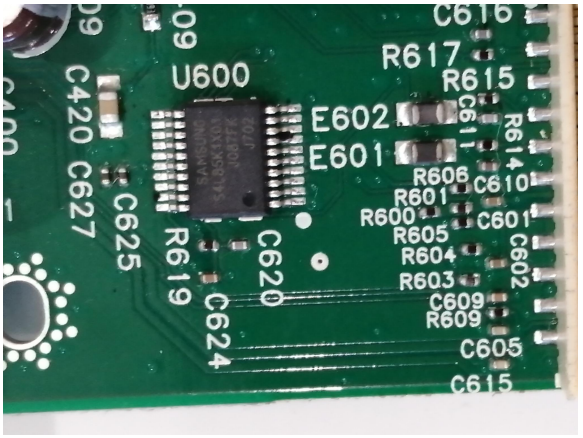
Step 13: Then you want to remove the feedback circuit that will contain the SD chip and processing chip.



Step 14: Continue taking pieces out now as most of the necessary pieces have already been removed however there are many more chips inside

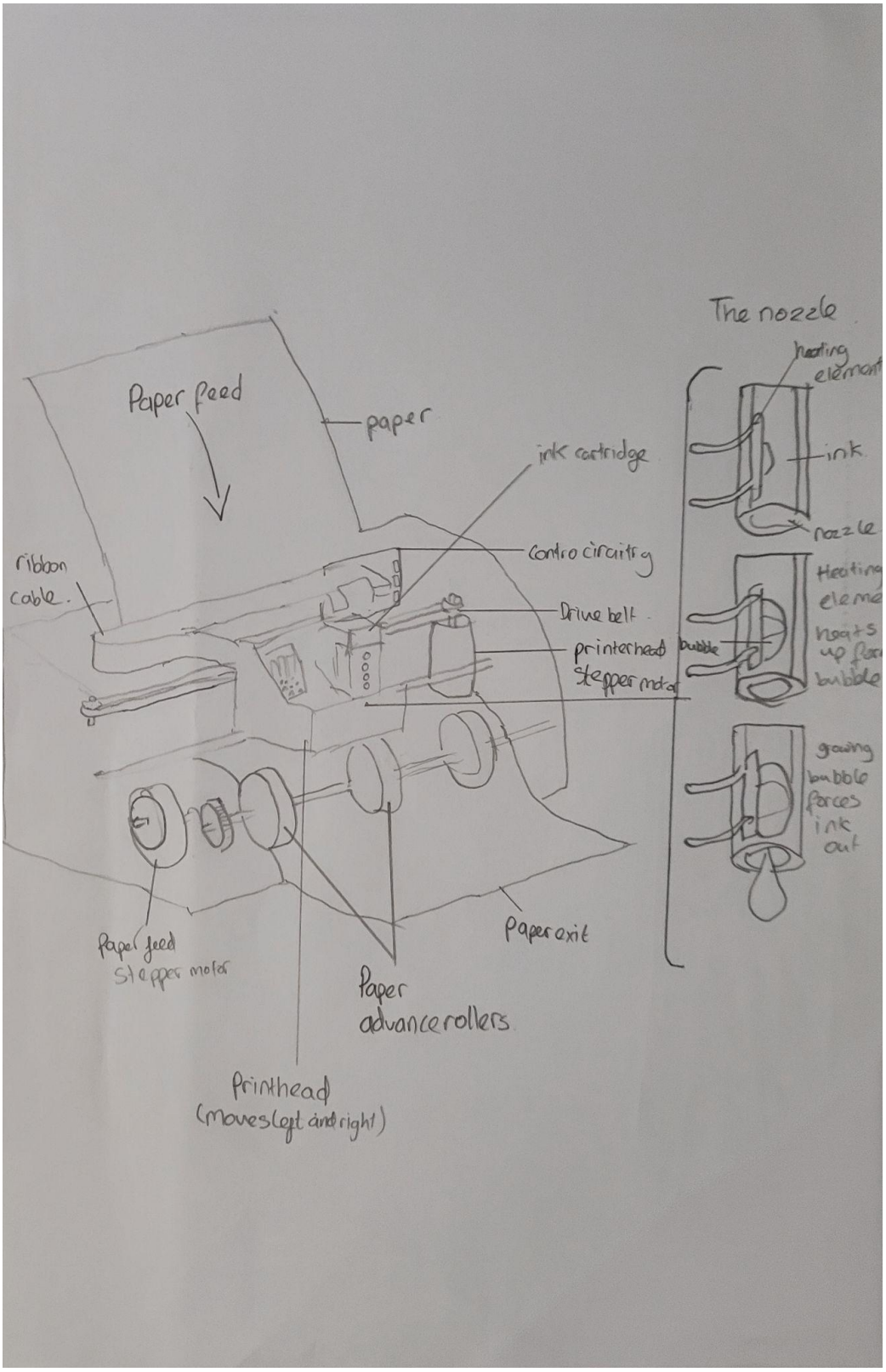


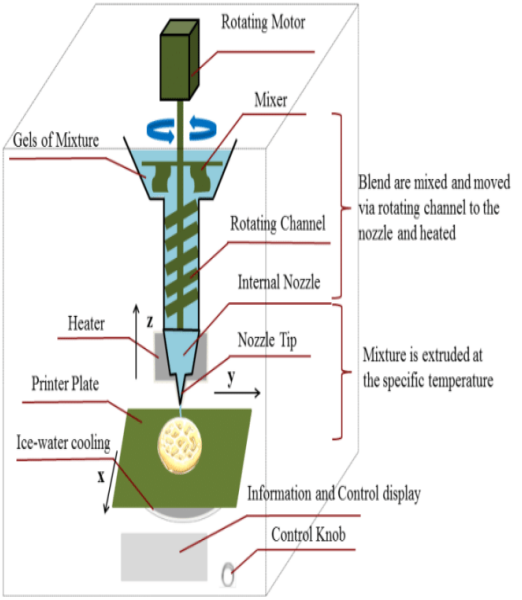
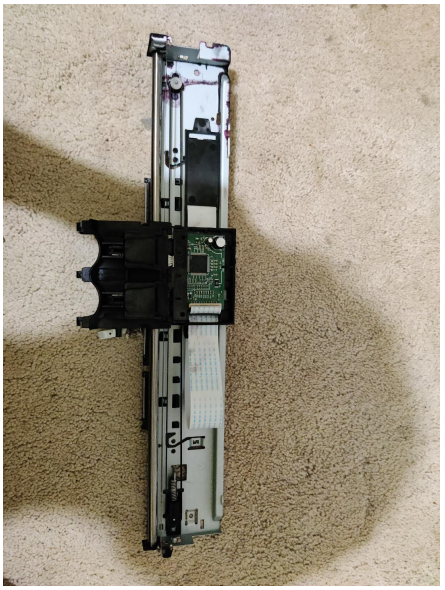


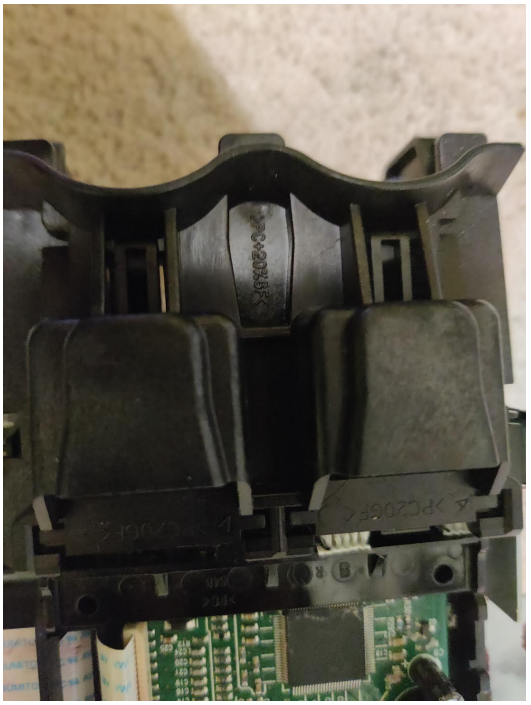
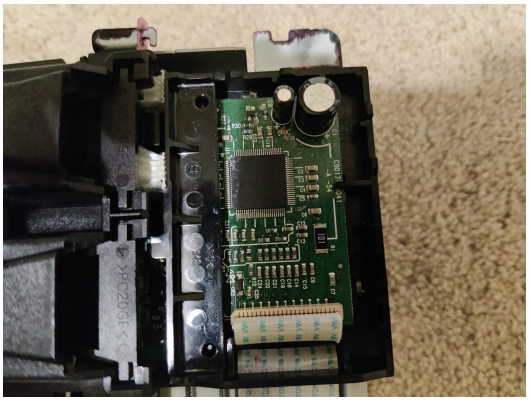


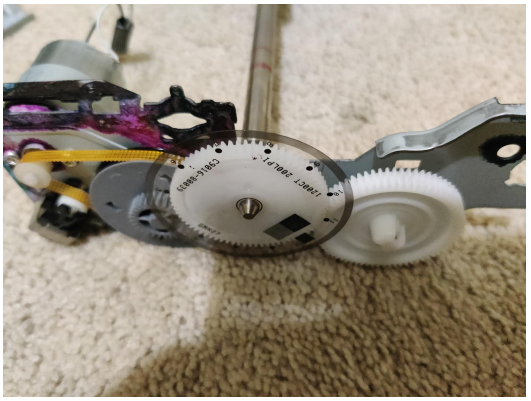
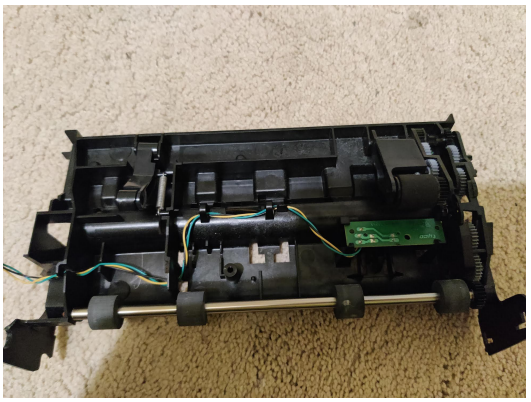
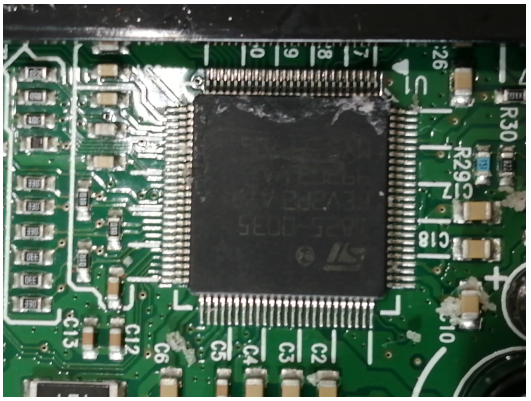
5.0 - Internal anatomy

Firstly we needed to identify all of the parts inside the printer, and its function. Below is a drawing which we made of the inner parts of an inkjet printer. It shows all the parts and how they are positioned. We then have a table which explains each part in depth, and an explanation of how they work together


Paper feed
paper
ink cartridge
control circuitry
ribbon cable
Drive belt
printerhead stepper motor
Paper feed stepper motor
Paper exit
Paper advance rollers
Printhead (moves left and right)
The nozzle
heating element
ink
nozzle
bubble
Heating
heats up
bubble
growing bubble forces ink out

Inkjet nozzle	This puts the ink onto the paper. These nozzles are around 10 micrometres in diameter, 10 times smaller than a human hair! They put tiny drops of ink onto a page which makes up the print. They work by using a heating element to blow a bubble which lets a drop of ink out.	
Ink cartridge	The ink cartridge is where the ink is stored. There are 4 colours, cyan, yellow, purple and black. Cyan yellow and purple can create almost any colour with different amounts, but it is very difficult to create black, which is why black ink is also stored	
Drive Belt and sliding rod	A belt is used to attach the print head to the stepper motor. The sliding rod is how it moves across the page	

DC motor	The stepper motor allows the print head to move back and forth across the page.	
Printhead	This is the main part of the inkjet printer. This houses the series of nozzles which spray ink.	
Moveable arm	The moveable arm connects the printhead to the Driver belt.	

Gear system	These are operated by the electric stepper motor to turn rollers that advance the page through the system	
Rollers	These advance the page throughout the system	 
Motherboard No.1	The motherboard is the control centre of the printer, which tells it what to do. It sends signals to all the other components and makes the printer work	

LAN and power connector	This connects the printer to electricity (which the printer runs on) and the wifi network to allow the documents to be sent from your device to the printer	

All of the components allow a printer to function and carry out its job, however the most important job a printer has, is to print using ink. It uses the printer circulation path which is a specific way of how ink from an inkjet printer reaches all the way to the nozzle.

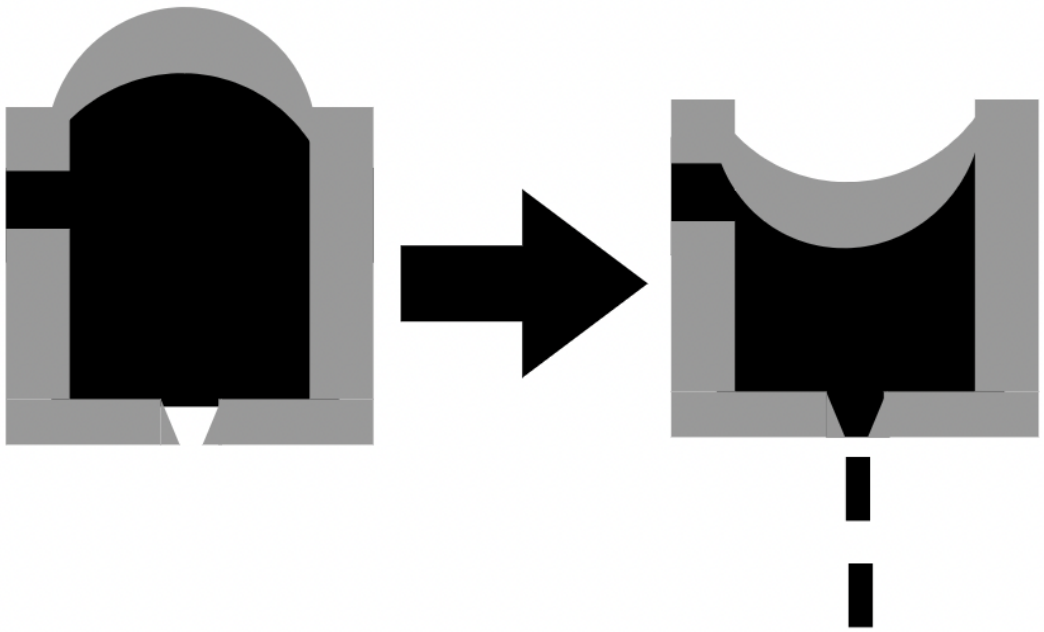
1) **The main tank** - Stores the ink used in printing. Ink recovered from the gutter is also returned here.
2) **The pump** - Pressurised and feeds the ink from the main tank to the printhead.
3) Decompression Valve - Adjusts the ink pressure
4) **Piezoelectric element** - Applies a negative electric charge to the ink particles created from the ink stream.
5) **Nozzle** - Where the ink is used to then be printed onto a piece of paper
6) **Electrostatic sensor** - Monitors whether the ink particles have the proper electrostatic charge in them.
7) **Deflecting electrode plates** - Generates a magnetic field between the electrode plates to deflect ink particles according to their charge. This directs ink particles onto the print target.
8) **Gutter** - Collects the ink particles that are not used in printing.
9) **The pump** - Retrieves the ink particles from the gutter and feeds them to the main tank.

Then the process is repeated where the ink comes back to the main tank and the process continues until all printing is finished. All the printing occurs at the nozzle and the cycle then restarts. It is important for the ink to have an electric charge as in order to control the motion of ink droplets, they must be given an electric charge. Static electricity causes ink drops to stick to the printhead, eventually clogging nozzles and causing printhead damage. It can also damage sensitive printer electronics, sensors, and controllers. This is why an electric charge is given to the ink so that it prevents all of this from occurring, without this negative charge the printer would fail and possibly blow up due to overheating and the dried ink may cause a reaction with the heat from the heating sensors causing the entire printer to fail. The electrode plates have a magnetic field which redirect the ink drops to turn so that they align onto the paper. This is to ensure that the ink droplets lands in that specific spot so that the print is not messed up.

The printhead of the inkjet printer also works in different ways. It either follows DOD which is drop on demand or continuous; these are both for how the printhead forces the nozzles to drop the ink. Drop on demand is exactly what the name states it is why the printhead chooses what time the ink drops from the nozzles. This is a non-binary process that is less common but is more precise and saves more ink. By choosing when to drop the ink it saves ink drops rather than the continuous method that constantly fires the ink. This is where the

ink always drops, however some of the ink from some nozzles is not required and therefore goes into the gutter where it returns back to the main tank. However sometimes it is not the case where they go back into the gutter but instead an electromagnetic charge or air redirects the ink drops to go into the right spots. This is the older technology used more commonly in the past and currently drop on demand printers are on track to surpass them as they save more ink and more printing companies are moving to this type of inkjet printers.

There are two main types of printheads, thermal and piezo printheads. The thermal printhead uses the bubble method of heating up the ink(more is explained later on) whereas the piezo printhead works by adding voltage to a piezoelectric material which causes the material to change shape. The piezo material is behind a chamber filled with ink, as it changes shape the movement forces the ink out of the nozzle.



Piezo printhead - the top part changes shape forcing the ink out of the nozzle

Microchips

A microchip (also called a chip, a computer chip, an integrated circuit or IC) is a set of electronic circuits on a small flat piece of silicon. On the chip, transistors act as miniature electrical switches that can turn a current on or off.

Logic chips are the ‘brains’ of electronic devices − they process information to complete a task. Among Logic chips, CPUs (central processing units) are the ‘original’ chips, first designed in the 1960s. But there are also processors with specific functionality in mind. Memory chips store information. There are two types of Memory chips: DRAM (Dynamic Random Access Memory), which are the ‘working memory’ chips that only save data while the device’s power is turned on, and NAND Flash, which save data even after the device is turned off. For example, DRAM helps to run programs on your device, whereas NAND stores

your photos. Whereas DRAM is fast, NAND is slow to read and write data.such as GPUs (graphical processing units, which are optimised for visual display) and NPUs (neural processing units, designed for deep and machine learning applications).

In a printer they use an integrated circuit rather than many microchips some of these are the feedback circuit which takes in all the information from the brain to calculate the fastest possible route to print everything onto the page.

6.0 - How does it work?

Printers are engineered extraordinarily with many small mechanisms allowing the entire printer to come together. Many people assume that as computers or displays use RGB colours that printers will do the same to create the colour that we see. Instead when these colours mix it will create a muddy version of the colour not creating the colour that we see displayed on computers. To fix this they use offset lithography which uses the secondary colours: cyan, magenta and yellow. Using these colours as well as black the printer can create any colour we desire.

In our case we used a photosmart C3100 printer by HP. It is an older model of a printer however it is an inkjet printer that has coloured prints. The printer has many different areas to it but the main mechanism that allows the entire printer to function is how the ink is released and gets on the paper. This is done using a nozzle which controls the amount of ink being dropped instead of running continuously. The drops are in dots that are so small that when we see them on a piece of paper it does not appear like that - this is our eyes tricking us and our brain processing the information that we require which ends up being the picture displayed as one continuous image. The nozzle has a small circumference and back pressure inside it makes sure the ink will not leak out allowing for a precise image. To release the ink there are small heating resistors which are so sensitive that when heated can reach up to 100 degrees celsius per microsecond. For safety reasons we do not have a picture of one but have a visual display of one. When requiring a certain nozzle to drop ink, power needs to be supplied to the one respectively, the ink will then heat up and vaporise causing a bubble to form. This bubble then acts as a piston to push the ink out of the nozzle where it then hits the paper and the drop is completed. Then the heat is turned off causing the bubble to contract, this back pressure causes the ink to come back up and suck outside air into the nozzle. As fresh ink flows back in the surface tension will push this air back out allowing the new ink to settle in its place.

To build a proper printer the ink head is connected to a printhead with a connection pipe that allows for new ink to flow into the inkhead. It is placed on a horizontal rod which it is free to move on. It uses a belt and pulley mechanism to move across the rod, this is all powered using a stepper motor. The printhead is connected onto the belt using a moveable arm that allows the head to move left or right in accordance with the belt. The printhead has around 2100 nozzles to drop the ink on the paper as it makes its way from left to right and then right to left following this pattern to the end of the piece of paper. To move the paper it uses a stepper motor and 2 supportive roller arrangements on a gear system to move the paper

downwards. When printing the printhead follows a precise path which is calculated before printing it can do this as it is controlled by a stepper motor and a feedback circuit.

When printing we use offset lithography as I stated before this is because when mixing the ink together we use the subtractive colour method that combines the colours together so that when we look at it from a molecular level the colours obstruct each other. This is different when using light as we use the additive colour method which creates the perfect colours that are displayed. As each colour absorbs all other colours but reflects its own a colour such as red will reflect red but if we add the colour blue then some of the red may pass through another red molecule or it will hit against a blue molecule where the end result will be black due to this our eyes perceive the colour as a muddy colour due to the presence of black. To fix this we simply need to invert the colours which are the secondary colours: cyan, yellow and magenta also known as cym colours. Now when printing we can combine these colours and create our colour with no problem as they have properties of both colours it allows light of both red, blue and green to pass through preventing the creation of black. This creates a perfect version of the colour we were aiming for. To create different shades of a colour our eyes trick us this is done by the spacing of the dots. The bigger the spacing creates a lighter colour and to create darker shades drops of black are added in between the green drops which trick our eyes into perceiving a darker colour. This is why we use cmyk colours where k stands for key representing black.

7.0 - Conclusion

In conclusion, we as a team have learnt how to reverse engineer a printer and understood the fascinating mechanisms that allow a printer to function. Using offset lithography to produce the colour that we see on a print as well as understanding how a printer plays with our eyes to create different shades of colour. In the end, we were all fascinated on how a printer works and even thought of how to evaluate the printer.

When evaluating a printer there are 5 things to take into consideration:

- Size and speed
- Image quality
- Media handling
- Ease of usage
- Ink usage

Size and Speed

The speed of printing and how if someone wanted to print off a document with 100 pages it would take an extremely long time compared to when printing 1 or 2 pages which takes around a minute. To help solve this problem we thought about adding another printhead and a belt and pulley mechanism behind the first one. In this case it would be bigger and more expensive cost wise due to more manufacturing however there would be less time spent on printing as we have 2 printheads dropping ink at the same time to speed up the process. This would be more useful in instances such as offices where more documents are required to be printed to speed up time.

Image quality

On a current inkjet printer the printing quality is 1200 x 1440 dots per inch this is good quality for paper sized 5 x 7 inches however for larger sized paper we require more dots per inch to make a good image quality. With a low printing quality the image will not look good and be off the main image. When evaluating we decided as a team the image quality is good however if we want to add more nozzles for better printing quality then the manufacturing cost will go up. As most people print in A4 we found that the printing quality is good for the printer.

Price

The price of the HP photosmart c3100 has a price range of $80 - $150 which is cheap for most printers however it is an older model of a printer, this printer is slightly unadvanced from newer printers. However as a group we all agreed this is a suitable price range for this printer for people who don't require professional printing but rather simple coloured print for their daily needs.

Ease of usage

This printer is quite easy to use having only 3 main functions, printing, photocopying and fax which are all incredibly useful in many cases. It has an instruction manual come with it as well as online resources on how to fix this printer in case it ever stops working. This printer is incredibly easy to use however we thought it can be evaluated by making it more user friendly. We plan on doing this by adding sounds to it to tell blind people when the print is read as well as this on the keypad we aim to add braille to help blind people in case of printing. This allows our project to be accessible for a larger audience.

Ink usage

The ink usage in this printer is not the best as it uses the continuous method instead if drop on demand, this wastes ink as it then goes into the gutter where it is recycled into the main tank this wastes some ink as some is randomly flown off during this process and can also mess us the print however very slightly that usual our eyes do not spot this difference. In our opinion the method of drop on demand is better as it saves more ink and also has less chance of clogging up the printer.

8.0 - References

When reverse engineering this printer we used a video by Ondrej Janovec on youtube - https://www.youtube.com/watch?v=xhxv1TqbJAE which is the complete dismantling process of the printer.

For the majority of our information we used the internet for secondary research however one of our group members also found a book in their local library on how different mechanisms in this world work. In this we learnt about the belt and pulley mechanism that is inside the printer.

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https://www.linkedin.com/pulse/anatomy-inkjet-head-nigel-heywood

Additionally for some of the drawing we used an online website - https://app.diagrams.net

This is all of our references that we have used for reverse engineering a printer, it consists mainly of websites and youtube videos. We made sure to use reliable sources and cross-checked the information to make sure it was factual.