Animating Spintronics

A dissertation submitted to The University of Manchester for the degree of Master of Science in the Faculty of Computer Science

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memory block block that carry the data or information. 5, 25, 26, 29, 30, 38–40

Acronyms

API Application Programming Interface. 21, 41

array DBMSs Array Database Management Systems. 10

CGI Computer Generated Imaging. 19, 43

DRAM Dynamic Random Access Memory. 15

FPS Frame Per Second. 40, 43

GUI Graphical User Interface. 44

IoT Internet of Things. 10

MRAM Magnetoresistive Random Access Memory. 10, 15, 44

RAM Random Access Memory. 15, 18

SRAM Static Random Access Memory. 15

ABSTRACT

Computer animation is a process that generating a series of animated images. Three-dimensional animation, also known as 3D animation, is the main form in modern computer animation. When it comes to complicated objects or physical phenomena, animation provides convenience, which makes it easy to be observed and understood by learners.

Spintronics is the study on the intrinsic spin of electrons and the magnetic moment generated by them, as well as its fundamental electronic charge in solid-state devices, also known as SSD. This is one of the new technologies that offer real promise for enhanced device performance.[1]

Spintronics is one of the new technologies that offer real promise for enhanced device performance. Since this physical technique is difficult to understand and worldwide there are limited examples which utilise this method, in this project, an animation with demonstrating teaching purpose is designed. This would contain a basic working process of magnetic racetrack memory device which is based on spintronics technique.

DECLARATION

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning

I want to thank my supervisor Christoforos for all his advice and enthusiasm throughout the project.

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1 Introduction

Big data nowadays is taking a vital character in the current society. It is a field that systematically extracts and processes information from huge data sets that are too large or complicated to be dealt with by traditional data processing application software. Big data is currently exploited on lots of applications or software that rely on the statistical information, referring to the use of user behaviour analytics, predictive analytics, or other specific data analytics methods that needs to retrieve information from data sets. The data sets provided for the above purposes commonly do not have a particular size and since the type of the data could be in any kind of realms. Big data technique can also be used for analysing trends of some numerical-dominated realms such as business stock prices, medical diseases distribution and criminal prediction.

The volume of the data sets increases rapidly as the data and information are collected by numerous information-sensing Internet of Things (IoT) devices such as mobile devices. Since the 1980s, worldwide people's average technological capacity to store information roughly doubled every 40 months[2]. Until 2012, 2.5 exabytes (2.5×10^{18} bytes) are generated every day[3]. According to the report from an International Data Group, it predicts that the global data volume would increase exponentially from 4.4 zettabytes (4.4×10^{21} bytes) to 44 zettabytes from 2013 to 2020. IDC also predicts that by 2025, the amount of data would increase up to 163 zettabytes[4].

Relational database management system and software nowadays often have difficulty dealing with big data, as the work requires a good strategy for processing a large amount of data in high efficiency, as well as the support from advanced devices in the hardware hierarchy. In the software aspect, massively parallel processing algorithms like MapReduce and technology like Array Database Management Systems (array DBMSs) can be used for handling big data. In the hardware aspect, innovative storage devices, which have greater potentials to manage and process big data than the currently used devices, should be designed and applied to computers.

Spintronics memories, as one of the novel memory management techniques, arise and are applied to lots of computational data storage devices that are closely related to and cleverly applied with electronics and magnetism techniques. However, as a new technology for memory storage, devices based on spintronics are expected to have a good performance in dealing with data and an increase in data storage capacity while keeping the devices to physically reduce in size as well as the consumption of energy[5].

For example, Magnetoresistive Random Access Memory (MRAM), as a product developed based on the spintronics technique, possesses a fast speed for reading and writing data, which ensures a high efficiency when a large amount of data is encountered. The high density and low power requirement properties of MRAM also save the demand for space and energy[6]. As spintronics memory is too innovative, some devices are still in development such as racetrack memory, which could have greater potential for big data management in the future.

1.1 Project aim

In this project, magnetic racetrack memory is chosen to be animated, inspired by the research on big data and the idea of array DBMSs. The goal of this project is to deliver an animation that demonstrates the basic functionality of a spintronic device such as a racetrack memory, magnetic random access memory, spin torque oscillator or nanowire. The animation should be able to present the essential features so that would be appropriate for people in the general public who are interested in scientific innovation. The animation created can also include interactive functionalities which allows viewers to focus on particular aspects of the device.

In the implementation aspect, the most essential target is to understand the physical principle of spintronics so that the magnetic racetrack memory device with a correct and clear working flow can be displayed. On the other hand, in order to design an efficient and effective algorithm for the animation, a thorough understanding of the connection among components created by the integrated development environment is vital.

1.2 Challenges of the project

Animating spintronics is interdisciplinary work. Knowledge of both computer science and physics are required. To be more specific, it is important to know how the information in a computer is written into a memory device and how does the process of reading or writing memory relate to electromagnetism. It is also important to be proficient to use related integrated development environment and programming languages to achieve the animation effect so that the desired physical phenomena can be displayed with high quality and correctness. On the other hand, in the physical aspect, it is important to beforehand resolve the related questions like how the current and magnetic field affect each other and what are the roles of magnetic polarities and the electrodes in a spintronics device.

Besides the requirement of adequate knowledge of physics including electricity and magnetism, which needs a large amount of research, the method of evaluating this scientific visualisation is another difficult aspect that needs to be considered.

Floyd claims that lack of information about visualisation strategies would make the application of visualisation difficult[7]. As a computer science student, the integration of visualisation and computation should be concentrated on, as well as the usability of the visualisation systems. However, evaluation on whether the data or information being visualised are conveyed accurately would be a grand challenge because the animation provides a visual experience for adopters and the responses vary depending on different individuals. From all those responses, the evaluation is limited by the subjectivity, hence an appropriate arrangement for the responses is required. Additionally, the usability of information visualisation tools can be measured in a laboratory environment, but to be more convincing, it is better to demonstrate the utility in a real setting, which is a given application domain and set of users. It is also a good idea to prepare different realistic tasks for the spintronics device to execute so that to demonstrate to the users since that makes the visualisation application more convincing[8].

In addition, most of the racetrack memory devices published in the academic paper or news are still in the concept level, where only the theoretical structure can be exhibited, as well as its simple working process. The researches on the racetrack memory devices are limited as the concept and the technique is so innovative that there are few computer storage devices are build or published based on this technique. Thus, to build up a racetrack memory device animation, a relatively complete understanding of this device is required, and the process of researching the limited information becomes another challenging point.

One more problem that is required to be considered is the way of the presentation of the device. Since the project is in the form of animation, it needs to be exhibited to users. Two methods are considered: the project can be made into a video, or be uploaded online as an interactive program. For the former, the quality of the video becomes another important indicator of the project as the video needs a proper order to demonstrate each component of the device with the help of the script explanation. Other elements that could potentially improve the quality of the video such as dub, subtitle and background music should also be thought about. For the latter, if the project is uploaded online as a program, a proper introduction of the device is required and the program should be interactive so that the users can manipulate the displayed device. The instruction of use for the program should be listed at the same place for users to understand how to interact with the device.

The implementation would try to resolve these challenges as much as possible, as some of these are the inevitable issues that are necessary to be solved, yet some of the solutions could be discarded as they could be too strict and infeasible such as building up an experimental environment with a real setting, including the simulation of the various intensity of current passing through a device, to test the accuracy of the animation.

1.3 Work preparation

1.3.1 Referable valid model

Most of the currently existing products are presented as a whole whereas the examples of the basic model working with the magnet are relatively rare. According to the model proposed by the S.S.P.Parkin team, the structure of the basic model is simple which contains three components: the writing element, the reading element and the magnet, also known as the racetrack in this case.

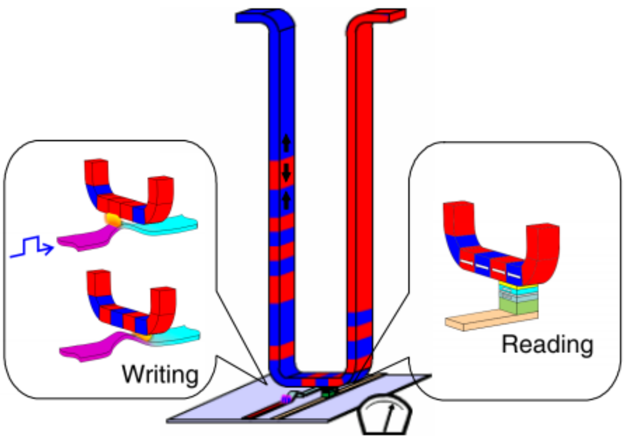


Figure 1: Image borrowed from L. Thomas, et al[9]. The basic structure of the magnetic racetrack memory.

More information of the model can be obtained from the research carried out from the company IBM, which introduce the functionality of the components of the racetrack memory in a form of online article and YouTube video respectively[1].

[1]IBM Introduces Racetrack Memory Concept https://www.youtube.com/watch?v=zIjK1dMdTGY

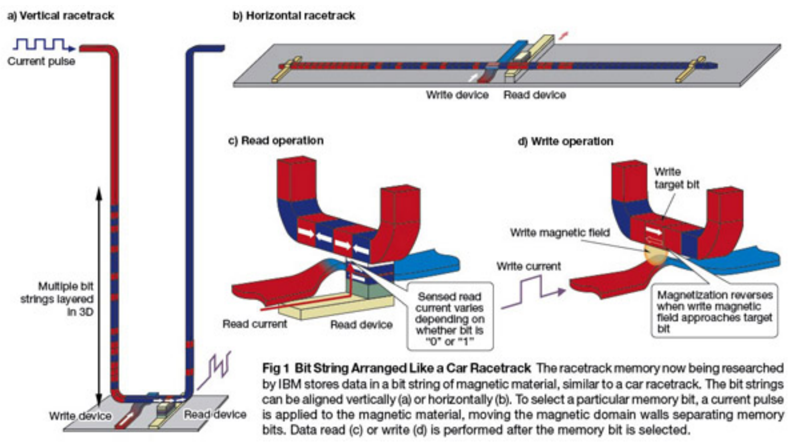


Figure 2: Image borrowed from J.Hruska[10]. Detail structure of the magnetic racetrack memory.

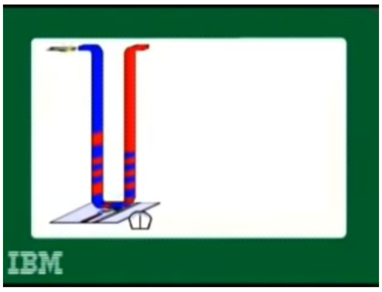


Figure 3: Screenshot from YouTube. IBM publishes the idea of applying the magnetic racetrack memory on the computer memory device.

These published models encourage the idea of how to construct the racetrack memory device, thus the following process of animating would be built based on them.

1.3.2 Designing the algorithm

As the project mainly focuses on the visual presentation of the racetrack memory device, the consideration of the algorithm would be rather simple. The algorithm should achieve 2 main aspects: firstly, the correct working process of the racetrack memory device should be presented, which requires a thorough understanding of the physical principle behind the devices; secondly, the computational cost of the program should be considered since the quality of the animation and the efficiency of the script is another important point that should be thought about.

1.4 Brief outline for each sections

In this section, some content of the following sections, where the whole process of research, as well as the implementation of the animation, would be briefly outlined.

In the background section, the concept of computational data storage, spintronics and scientific visualisation will be introduced. Researches on these topics are done to better understand the method for implementation, including how the information or data are recorded in computer devices, different types of computer memory devices, the reason and demand for developing a magnetic electronic kind of devices. How the scientific visualisation method would be helpful for the general public to learn a science domain would also be discussed.

In the methodologies section, brief introductions on several tools for animating, game developing, modelling and rendering would be brought out. Then the comparison among them would be simply discussed so that one of them can be selected as the main developing tool. The fundamental strategy of how to implement the animation would also be mentioned in the animating aspect and the programming aspect.

In the implementation section, the detail of how the animation is developed would be illustrated. This will contain the detail of modelling and how the models are combined; why the invisible elements of the device need to be presented and how they can be presented; the logicality of the working flow of the device and how to develop the algorithm for that; the animating process based on the researches and algorithm; how to improve the acceptance for users to use the animation to learn knowledge.

In the evaluation section, questions about how well the animation was done would be discussed. This would contain the evaluation in the physical aspect and the visual aspect. Several input patterns would be tried to test the correctness of the implemented racetrack memory. The device would also be compared with the currently existing models and a discussion about how the implemented one provides a better experience would be carried out. On the other hand, due to the subjectivity property of the responses from users who have watched the animation, a questionnaire would also be designed so that the evaluation can be quantified according to the result of the survey. Then a statistical analysis for the obtained result would be carried out, including the discussion about the reason on the distribution pattern.

In the reflection section, ideas of modification on the animation, model construction and the method of presentation would be discussed, including a comparison between the developed version and an inaccurate discarded version. Some ideas of modification on the current implemented models would also be listed. The extra ideas are not implemented due to the limit of time, whilst they are good for improving the user experience to some extent. Limitation of the project would also be mentioned concerning the animation, spintronics, and computer storage aspects. At the end of the reflection section, the method of how to demonstrate the project would be discussed, which includes the reasons for the decision and the advantages and disadvantages of the methods considered.

In the future work section, ideas of further development on the animation and the racetrack memory device would be introduced, where some of these may be difficult to implement. Many different kinds of ideas would be discussed as the racetrack memory is still in development, that indicates the unpredictable future directions and potentials of this device. The animation would still be the theme concentrated on, whilst the ideas or methods of further developing and demonstrating could be different from the current version.

2 Background

2.1 Computational data storage

In the computer science field, information or data would be recorded into a memory cell, also known as a binary cell, where each cell stores one bit of the binary information - either 1 or 0[11].All text information such as a sentence strings, characters or digits can be encoded as a sequence of numbers by referring the American Standard Code for Information Interchange, ASCII table in short[2]. The encoded numbers can then be converted into binary bits to be accepted by the binary cells in the computer memory device.

Computer memory possesses various properties, including that the devices could be either volatile or non-volatile. Volatile memory requires power to maintain the stored information, that when the power is shut off the data inside the memory would be lost. Dynamic Random Access Memory (DRAM) and Static Random Access Memory (SRAM) are two typical examples of volatile memory. On the contrary, non-volatile memory would maintain the content even the power is lost[12]. Examples of non-volatile memory devices include ferroelectric RAM and most types of magnetic computer storage devices such as MRAM.[13]

Magnetic computer storage, as a typical non-volatile memory, stores data or information on a magnetised medium, which uses various patterns of magnetisation in a magnetisable material. The information inside the storage can be accessed using one or more read/write heads. Hard disks are widely used as the magnetic storage media to store computer data as well as audio and video signals. As the storage medium moves past the read-and-write head devices, information is written to or read from the medium as the operation between it and the heads is very close. The instantaneous magnetisation of the material under the heads would be detected or modified, where the two magnetic polarities would be used for representing the binary signal 1 or 0 in computer respectively.

The magnetic material can be regarded as consisting of many small magnetic regions, which is magnetic domains and each of them has a mostly uniform magnetisation intensity. The magnetic domain is formed by the magnetic particles inside the magnetic region because of the poly-crystalline property of the material.

A write head magnetises a region with its strong magnetic field generated by the current passing through it, and a read head detects the magnetisation of the regions, determining the polarities of them and transfers the signals to other related processing components, as shown in Figure 4. Early hard disk drives used an electromagnet to magnetise the region and then to read the magnetic field by using electromagnetic induction, that is, the storage manipulation is executed by the same component. With the increase of the data density, magnetoresistance is used by the read heads, where the electrical resistance of the head changed according to the strength of the magnetism. Spintronics concept is utilised in this development, wherein the read heads, the magnetoresistive effect was much more significant. The heads nowadays are different from past devices. The magnetoresistive read components and thin-film inductive write components are separate, while still keep a very close distance to each other[14].

Computer memory storage devices show the potential of being manipulated under electricity or magnetism or both. The amount of memory with a scaling of the device is the main question that is being worked on, in other words, more infor-

[2]ASCII table - http://www.asciitable.com/

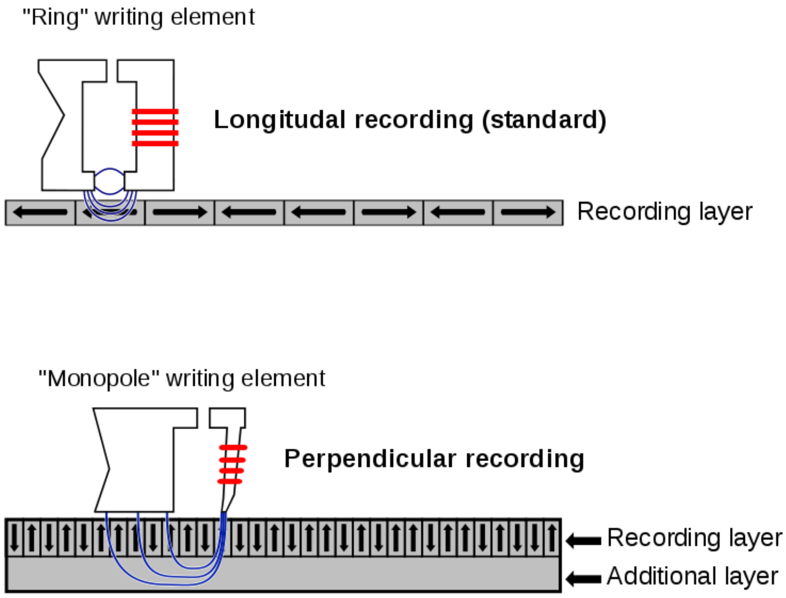


Figure 4: Image borrowed from Wikipedia[15]. An example concept of magnetic storage devices

mation or data is desired to stored while reducing or maintaining the size of the device.

2.2 Spintronics,nanowire and racetrack memory

Spintronics was discovered in the 1980s where the concerning spin-dependent electron transport phenomena were observed in solid-state devices. In 1985, Johnson and Silsbee found the spin-polarised electron injection from a ferromagnetic metal to a normal metal[16], and in 1988 Albert Fert et al discovered the giant magnetoresistance[17]. In 1990, with the proposal of a pin field-effect-transistor by Datta and Das, semiconductors for spintronics began to be used[18]. Different from the traditional electronics, spintronics includes both charge state and electron spins, which shows potential for implications in the efficiency of data storage and transfer[19].

With the spin-logic, non-volatile devices which enable scaling are being extensively studied, as well as the use of techniques based on spin-transfer torque. Devices that use spin and magnets for information processing have been proposed[20].

Racetrack memory, as an experimental non-volatile memory device, was proposed by physicist Stuart Parkin from a team of IBM's Almaden Research Centre[21].

A racetrack memory "unit" consists of a magnetic wire, a reading element and a writing element, where a spin-coherent electric current is applied on a nanowire. A nanowire is a nanostructure, with the diameter of the order of a nanometre (1×10^{-9}). Due to the speciality of the nanowire, that some properties of the nanowire can not be observed in bulk materials, it becomes a great material for conducting, semiconducting and insulating[22]. Nanowires, therefore, shows great potential to be the components of developing computer memory devices. Scientists from the University of Pennsylvania have developed nanowires that can store and retrieve computer data a thousand times faster than existing portable memory devices such as Flash memory and microdrives[23]. Devices developed based on nanowires shows performance using less power and space than the current memory technologies while possessing a high memory transferring speed. Racetrack memory devices, which exploits nanowires, hence have similar properties at these aspects. An electric pulse would as well be applied on the side of the magnet, which causes the magnetic domains inside the magnet moving from one side to the other depending on the direction of the pulse. As the current is passed through the nanowire, the domains pass through the magnetic reading and writing elements near the magnet. The intersected magnetic domain blocks would be altered to record the pattern of bits. A complete race track memory device should be made up of many such "unit"s. To be supplementary, the magnet, tracks of writing component and reading components are all nanoscopic.

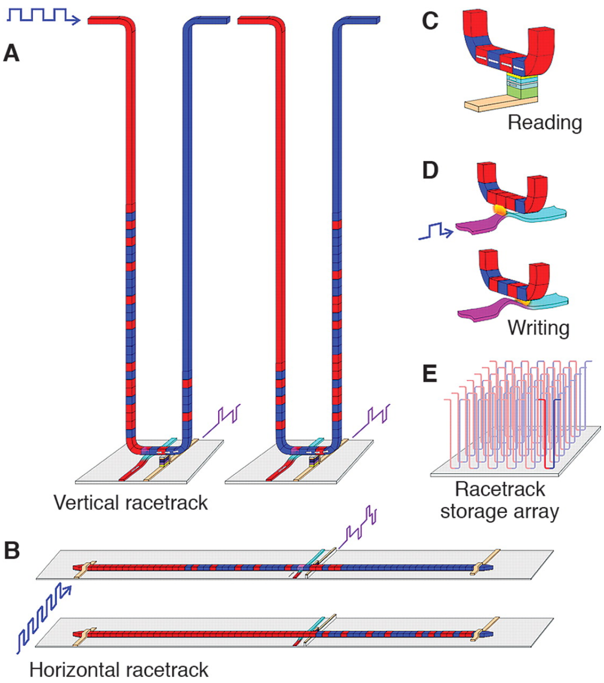


Figure 5: Image borrowed from S. S. P. Parkin[24].(A)Overview of the vertical magnetic racetrack memory structure(B) Horizontal structure of the magnetic racetrack memory (E) The design of a dense racetrack memory storage array

Magnetic racetrack memory is similar to the idea of a shifting register where the data blocks are moved along the racetrack to interfere with the corresponding reading and writing elements. The moving direction of the magnetic domain along the magnet and nanowires caused by the current can be determined by Fleming's right-hand rule rules[25] if considered in a simple way, whilst the actual physical principle is more complicated. To be further, The direction of the movement of the domain walls is independent of the magnetic charge of the domain wall which enables the entire sequence of domain walls to be moved along the magnet. Domain walls are shifted along the racetrack by current pulses which use the spin-momentum transfer phenomenon[26]. Spin-momentum transfer torque effect is when an unpolarised current is passed through the fixed layer whose spin imparts an angular momentum which results in a spin-polarised current. This current, when passed through the free layer, transfers its angular momentum resulting in a change in the free layer's orientation[19].

The writing element uses several different methods to achieve altering the domain walls which includes using the self-field of current passed along the neighbouring nanowires or using the spin-momentum transfer torque effect from the current injected into the racetrack [26]. The two types of polar, caused by the positive and negative electrode, matches the bits types in the computer storage devices.

A magnetic tunnel junction magnetoresistive sensing devices are used as the reading element for the racetrack memory. This device consists of an insulating barrier that is sandwiched between two ferromagnetic layers of different coercivities. A capping layer that has conducting property is attached to one of the ferromagnets as most of them have oxidising nature[27].

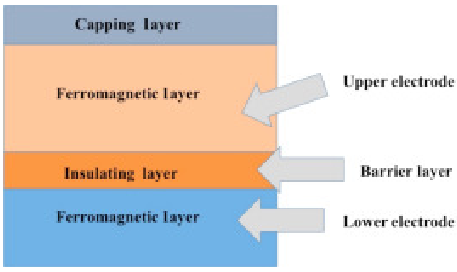


Figure 6: Image borrowed from J.P.Singh et al[27]. A schematic of a typical magnetic tunnel junction device.

The discovery and development of spintronics devices enable the improvement of the performance of computer storage devices. The spin valve as the first device enables a thousandfold increase in the storage capacity of magnetic hard disk drives. The magnetic tunnel junction as the second device is in the process of supplanting the spin-valve, as it has a higher signal, which stands for higher efficiency. The magnetic tunnel junctions also form the basis of modern magnetoresistive RAMs, where the magnetic moment of on electrode is used to store a data bit. Modern hard disk drives use a single magnetic tunnel junction element to store and read one bit, whereas the racetrack memory device can achieve manipulating ten to hundred times of that amount because of its composite structure. This depends on the number of the "unit"s and domain walls that a racetrack memory device would contain.

Racetrack memory, as an innovative type of computer data storage concept, is acknowledged by a lot of authoritative institutions and experts including IBM as mentioned. Yassine Quessab, a postdoctoral fellow at New York University's Center for Quantum Phenomena, claims that racetrack memory could supplant the current method for big data storage because it has an increased density of data storage, more efficient operation and consumes less energy than the current methods[28]. In the traditional data storage method like an old musical cassette tape, the data reading and storing is achieved by moving material, which is the tape in this case, with a motor across a reader, and then by decoding the written information on the material the sound can be reproduced. Racetrack memory, on the contrary, manipulates the data in the other way round, where the material keeps stationary, and the information itself is moved across the reading element and the writing element so that all the mechanical components would not be moved[29].The mechanism increases the reading and writing speed of the memory device, which could potentially achieve a new type of computer data storage with higher efficiency and lower energy consumption.

2.3 Background of scientific visualisation

Scientific visualisation is an interdisciplinary branch of science which stands for visualising the scientific phenomena such as physical domain and numerical statistics.

This technique is also considered as a subset of computer graphics because they are implemented by the use of various tools including programming languages and integrated development environments. Scientific visualisation aims for graphically illustrating the scientific data so that scientists can understand and retrieve information from the data[30].

One of the earliest examples of scientific visualisation was sculpted in clay in 1874 by James Clerk Maxwell - Maxwell's thermodynamic surface[31]. This shows the potential demand for scientific visualisation at an early stage. Computer graphics techniques satisfy this requirement nicely due to the convenience and efficiency that computer graphics would provide[32].

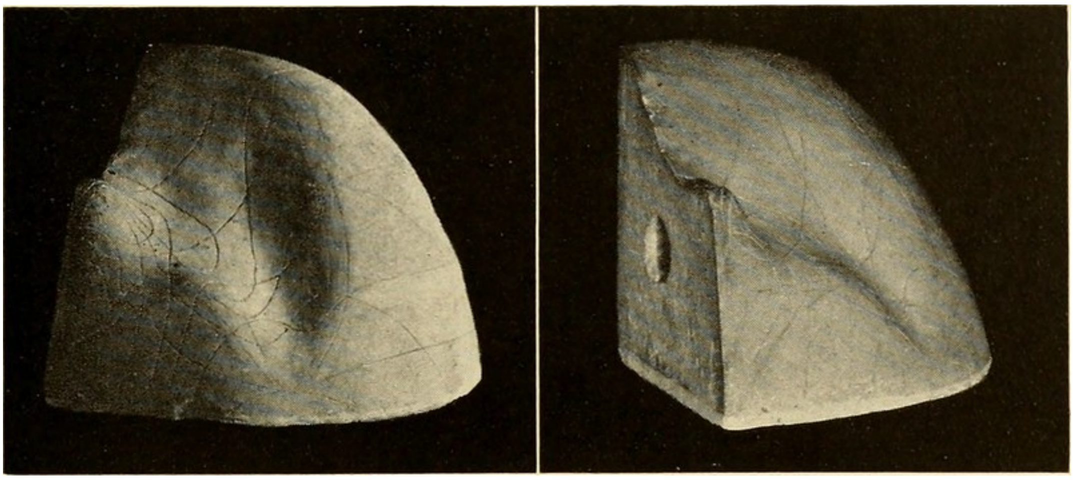


Figure 7: Image borrowed from F.G.Donnan[33]. Maxwell's thermodynamic surface

This subject is extensively developed at the early stage of the 1990s. In 1990, Daniel Thalmann claims that scientific visualisation can be regarded as a novel method of numerical simulation, which mainly focuses on geometry, animation, rendering and the related application on the natural science and medical aspect[34]. In 1991, Ed Ferguson defines the scientific visualisation as a methodology. He believes that this technique is a multidisciplinary methodology which utilises many domains that are independent and has a growing trend towards integrating with each other, including computer graphics, image processing, computer vision, signal processing and user interface development. The unique goal of scientific visualisation is to be a medium which connects the scientific calculation and scientific observation. Scientific visualisation appears for meeting the growing demand for processing the very active and dense data source[35]. In 1992, Brodlie claims that scientific visualisation focus on discovering and studying the data and information to obtain insight into them, which is the fundamental purpose of many scientific research studies[36]. In 1994, Clifford Pickover concluded that scientific visualisation applies computer graphics on scientific statistics for justifying hypothesis and interpreting the data comprehensively[37].

Computer animation uses computers to create moving images combining the idea of art, technique and science. Although 2D computer graphics are widely used due to its low bandwidth and fast real time rendering efficiency, 3D computer graphics is becoming more common for giving a global view of the whole structure of the target to be animated. This is also referred to as Computer Generated Imaging (CGI). Medical animation as an instruction tool for medical professionals or patients is one of the most commonly used application of computer animation.

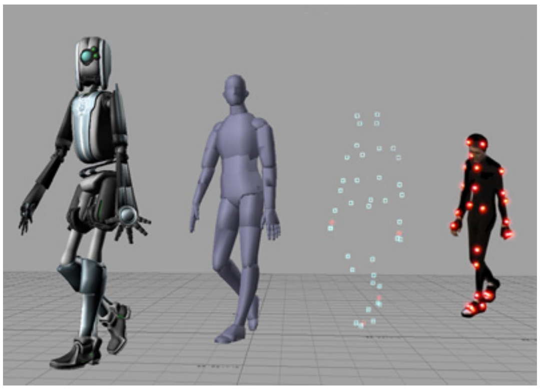


Figure 8: Image borrowed from Wikipedia[38]. An example of computer animation

When it comes to a particular system, by the use of the computer, computer simulation is a better strategy for scientific visualisation. Computer simulation attempts to simulate an abstract model with programs or network of computers. It is a useful part of mathematical modelling of many natural systems in physics, chemistry and biology. The simulation process helps to obtain insight into the operation of those systems. Besides the small amount of objects modelling, computer simulation allows the scale of events being simulated to be large. By using multiple supercomputers in the United States Department of Defence High-Performance Computing Modernisation Program, Jet Propulsion Laboratory achieved a computer simulation with a considerable scale[39].

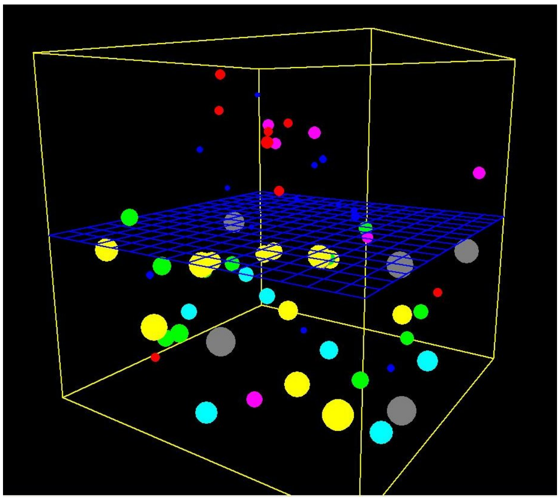


Figure 9: Image borrowed from Wikipedia[40]. Computer simulation of the process of osmosis

Animating spintronics devices would be an example of computer animation, as well as a computer simulation. The demonstration, of how the racetrack memory works including the change of domain walls, current electrodes and magnetic polar, can be categorised as computer animation work. At the computer simulation aspect, the presentation of the magnet to be written implies the various input pattern, which can be changed by the users from the scripting hierarchy. The whole devices which contain a large number of racetrack memory "unit"s could potentially have a large scale. However, in this implementation, the animation would concentration on the components and the working detail instead of the overall structure.

3 Methodologies

3.1 Implementation tools selection

There are several available currently existing tools which could be appropriate for this animating task, including an integrated development environment and programming languages. Some of the technique would be introduced, discussed and compared in this section. Considering the fact that the time cost of learning different visualisation technique, as well as the integration of the works, would be considerable, which could affect the progress of the whole project. Therefore, although all tools going to be introduced may have achieved animation or 3D model programming examples, only one would be selected as the main method for development.

3.1.1 Unity

Unity is a cross-platform game engine developed by Unity Technologies. Besides making games, this engine can be also used in many other domains such as film, architecture, engineering. Unity, which is a strong tool and has been used to develop many successful productions, allows users to create a visual experience in both 2D and 3D.[41] Since Unity is such a powerful interface, it takes time to learn its combination of the visual editor and sophisticated coding, which is complicated[42].

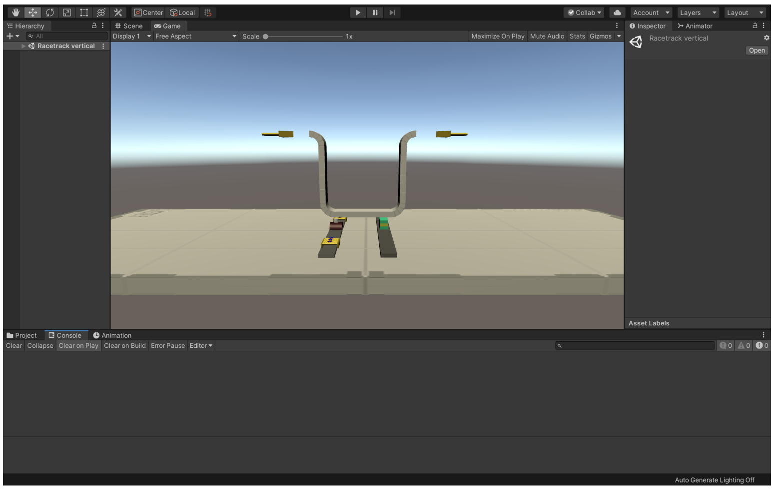


Figure 10: A screenshot of the Unity development interface

3.1.2 Blender

Blender is a free, corss-platform and open-source 3D computer graphics software toolkit for creating animated films, visual effects, interactive 3D applications and computer games. It contains a lot of features such as modelling, texturing, rendering and video editing. Some advanced users would make some python scripting to customise the application and write specialised tools by using Blender's API[43].

3.1.3 OpenGL

OpenGL(Open Graphics Library) is a cross-language, cross-platform Application Programming Interface (API) for rendering 2D and 3D graphics.The API is typically used to interact with a graphics processing unit inside the computer to accelerate the rendering speed in the hardware hierarchy[45].

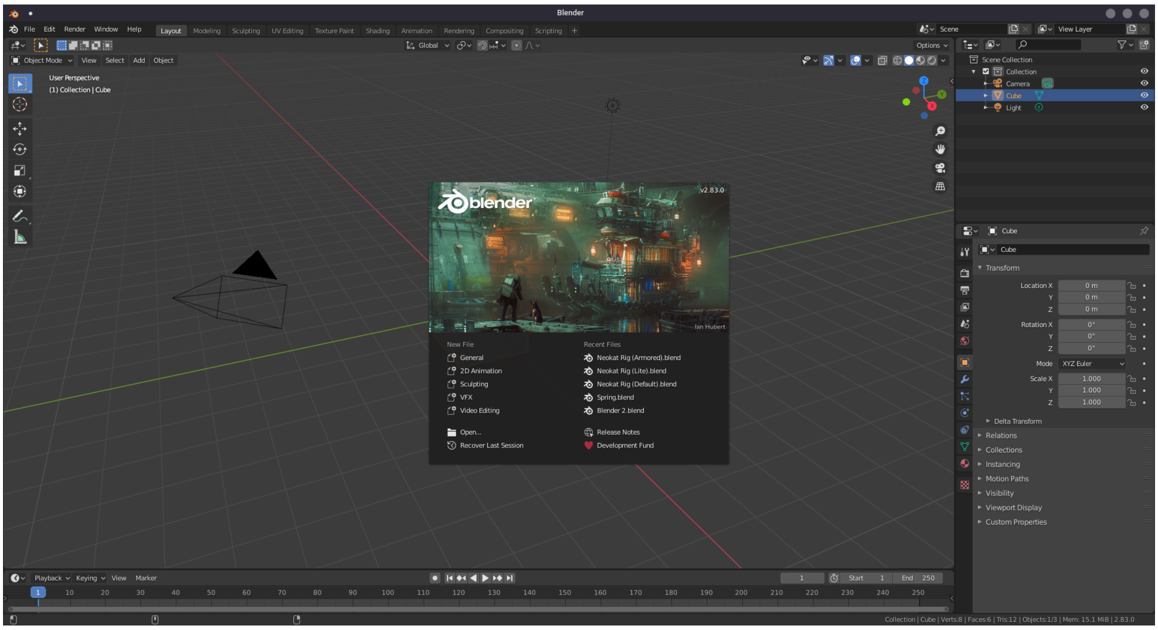


Figure 11: Image borrowed from Wikipedia[44]. The development interface of Blender 2.83

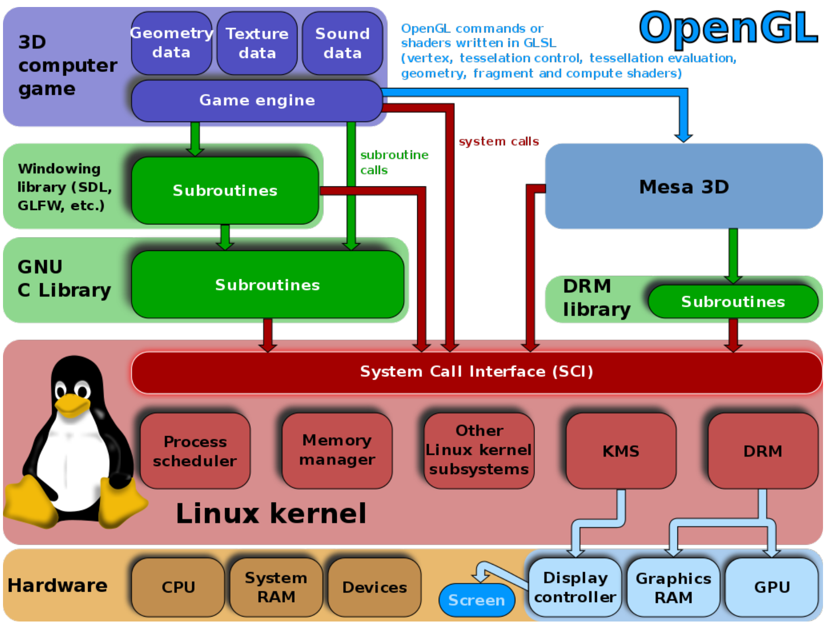


Figure 12: Image borrowed from Wikipedia[46]. The structure of OpenGL interacting with platforms

3.1.4 Comparison and selection

Blender is a program mainly for modelling, thus it could show a better modelling ability than other tools. However, creating applications or games in it is not the main purpose of this interface, which could have weaker animation support.

OpenGL, on the other hand, this API focus more on the lower hierarchy, which focuses on the basics like how to construct some specific visual effects. An example of it is the interface of Blender, which employs OpenGL to provide functionalities and user experience to the adopters. This API would be a good learning tool of understanding how the visual effects work, yet it is not ideal for the animation tasks which requires efficiency and flexibility.

Comparing to other current existing visualisation tools, Unity has an extremely productive visual workflow and a high degree of cross-platform support. The interface of this product is highly customisable so that the control of the variables during the testing phase would be simpler by modifying the value via the interface. Additionally, Unity is a game engine, which means that its purpose is to create games. This ensures the quality of the visualisation effects and the functionalities that could be involved in the project, where the functions can be modified or altered by programming using C# or JavaScript. The 3D animation support is relatively good as it has a robust graphic and audio quality.

Considering the demand for good convenience, usability and functionality, as well as the difference of the main scope of application, Unity is selected as the tool for animating racetrack memory.

3.2 Scientific visualisation based on physical principle

After acknowledging the concept as well as the overall structure of the racetrack memory, the strategy of animating this device would be relatively simple. The basic idea would be modelling, combining, scripting and animating.

Considering the modelling ability of Unity could be not satisfying enough, and the main purpose of this project is demonstrating the working process of spintronics devices, all models are designed as simple as possible so that they can be created by Unity basic interface.

Once the models are built, the combination work for models would be simply finished by referring to the valid models found from the paper and video during the researching phase. The existence of the grid in Unity provides more convenience for combining the models in a higher precision level.

Scripting and animating are mutually reinforcing. During the construction of the animation, the logicality behind the script should be modified anytime when the animation requires changes. This is because, in Unity, simple movements of objects can be achieved by using the basic interface, so scripting is required if a complicated change of states needs to be displayed in the animation.

Besides the basic construction of the model device, it is also important to find out a method to present details of the model, where some of these elements are invisible or unable to be observed. Presenting these hidden elements would provide a better learning experience for the general public. For example, the particle system inside the racetrack memory as magnetic particles, can not be directly displayed from the outlook of the device, then how should they be presented would be one of the problems to be focused during the implementation phase.

As mentioned in the challenge section, as a 3D model with an animation representing the working process of an actual device, the methods of presentation would be either in the form of video or an online interactive program. The corresponding advantages and disadvantages for each method would be discussed in the following sections and one of them would be eventually selected.

All the detail corresponding to the strategy would be illustrated more in the following implementation section.

4 Implementation of the spintronics animation

Initially, due to an inadequate understanding of the physical principle of the racetrack memory and the difference between the common hard-disk drive and spintronics devices, the inaccurate design of the racetrack memory model and the working process was implemented. The device was modified several times after more researches done. The inaccurate version would be compared with the implemented correct one in the reflection section.

4.1 Model Construction

According to the examples shown in the paper and video demonstrated found during the researching phase, model construction includes three main components - the magnet, the reading element and the writing element. Due to the limit capability to create models in Unity, the representation of all elements is represented in a simple way such as cubes, cuboids, arcs and cylinders.

As the main body of the device and carries the memory blocks, the structure of the magnet is intuitive, which contains four arcs and three cuboids. The magnet is not completely in a U shape as the data bits need to be passed through both the writing element and reading element, which requires a distance.

The construction of the reading element is fairly simple, as it is a cube in an overall view. To present the layers with different material, cuboids with various colours can be made and then combine them. In the designed blueprint the green cuboids represent the ferromagnetic layers and the yellow one stands for the insulating layer.

The design of the writing element is the most difficult part. According to the currently existing model, the appearance of this component is simple, however, it is infeasible by just creating 3D objects to present the change of state such as the colour changed due to the change of the electrode as shown in the video sample. Therefore, at the early stage, the writing element is built with only a writing probe with a circular arc beneath it. The development of the changing feature would be explored further in the scripting phase.

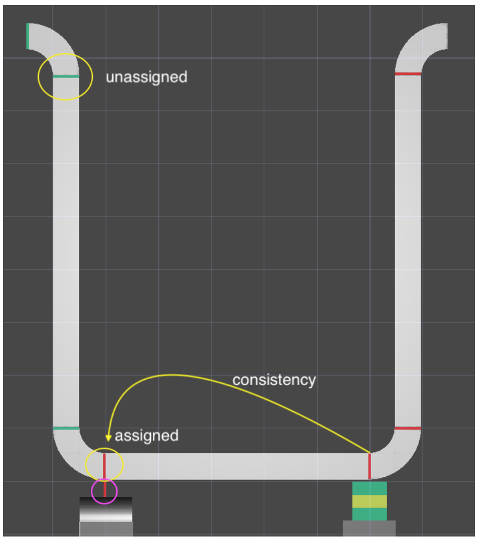


Figure 13: The initial design of racetrack memory

In order to obtain a better understanding of the racetrack memory, according to Figure 5 (B), a horizontal version is also designed and constructed. Two different versions of the model, with a similar structure of writing and reading elements, would potentially lead to a different topology while constructing a racetrack storage array. As indicated in 5 (E), the vertical version of racetrack memory "unit"s are used for forming the array, which implies that the horizontal one can also be used for the same purpose. According to the different spatial requirement, the flexibility of combinations of the racetrack memory "unit"s may be helpful for providing array devices with various shapes. The discussion concerning the array demonstration would be mentioned more in the future work section, as the main task for this project is to demonstrate the basic functionalities of the racetrack memory, whereas the array concept would be a more ambitious idea for the further development.

4.2 Hidden elements representation

In an overall perspective, some detail or physical elements cannot be analysis by just looking at the device, as in reality, they are not observable. To make the animation easier to be understood by users, those invisible details are supposed to present by auxiliary elements.

One of the most important hidden features would be the change of the domain walls in the magnet, wherein the real device, there would not be a change of colour whenever the memory block passes the writing probe. Therefore the change of colour, as well as the initial colour patterns which are already in the magnet are designed for demonstrating purpose. The moving memory blocks inside the track, which carry the auxiliary colours, are also a representation of the hidden element. The magnetic regions inside the magnet move from one side to the other due to the electric pulses provided from outside. Since the magnetic field varying inside the magnet is invisible and the velocity, acceleration and the size of each region are undetermined, the movement of the domain walls is displayed in an ideal condition.

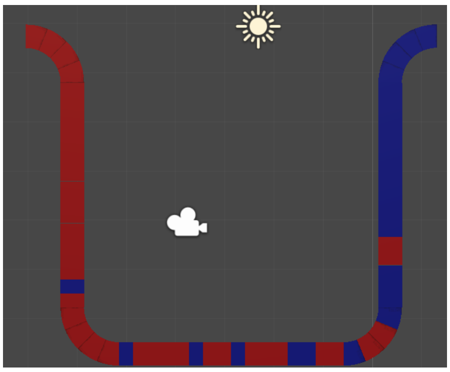


Figure 14: The complete design for the magnet as well as the domain walls inside

Another main hidden feature that is presented is the directions of the magnetic field as well as the current in the writing element. In physics, the direction of the current and the direction of the magnetic field shows the influence on each other under different conditions. In racetrack memory, the variation of electrodes causes the change of the spin torque, hence the movement of the domain walls inside the track. A similar phenomenon also happens in the writing element. With the current provided from either outside or coils tightened on the nanowire, the change of the magnetic field would directly affect the writing probe, so that the passing domain walls in the main track can be magnetised. Therefore, to present better ease for users to understand the working process, the electrode which leads to the direction of the current is presented as arrows, with the same colour as the magnetic field for consistency.

(a) Positive current with red arrows

(b) Negative current with blue arrows

Figure 15: Arrows representation for the electrodes

The only auxiliary representation of the actual magnetic field is presented inside the writing element since the other kinds of variation are already presented in other methods like the change of the colours for representing the states of domain walls.

In physics, there are a lot of methods to display the existence of the magnetic field. For example, by placing iron filings in a magnetic field, under the influence of the magnetic force, the powder would form a pattern consisted of lines, corresponding to the "field lines", which is an auxiliary name for presenting the magnetic field structure.

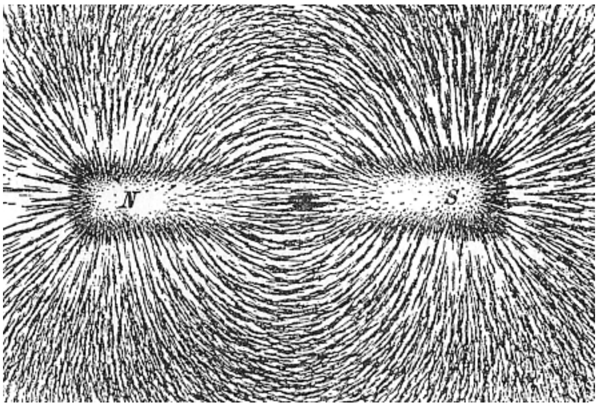
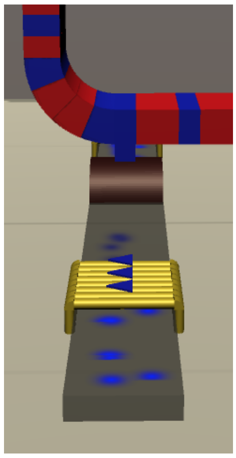


Figure 16: Image borrowed from Wikipedia[47]. The magnetic field is presented by iron filling sprinkled on paper placed above a magnet

A similar idea can be used in racetrack memory, to present the flowing property of the magnetic field, particle systems are applied inside the writing element, where beneath the writing probe the magnetic particles are flowing from one side to the other or the other way round in the track depending on the current through the coil. Like the experiment for presenting the actual magnetic field with the "field lines", the particles are the auxiliary items for presenting the change of the magnetic field inside the writing element.

(a) Red particle system due to the positive current



(b) Blue particle system due to the negative current

Figure 17: Particle system representation for the flowing magnetic fields

Besides the auxiliary elements inside the device, the electric pulses from outside are simply represented by arrows as well, as the direction of the electric pulse has a directive influence on the moving direction of the domain walls inside the magnetic track. With rightward arrow presented at the left side of the magnet, the domain walls move from the left to the right, which also firstly pass the writing element, achieving read after write. On the contrary, the leftward arrow at the right side of the magnet would eventually lead to writing after reading. However, considering the demonstrating purpose and the fact that the principle of the storage device is what needs to be concentrated on, the risk of instruction hazard, where the data dependency possibly occurs due to the out-of-order instructions, is neglected.

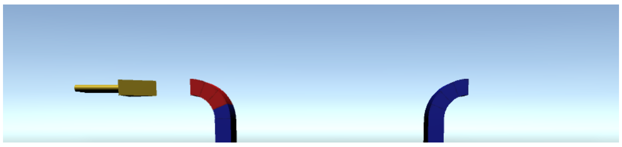


Figure 18: Current pulse from the left side

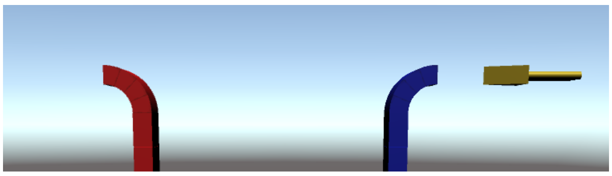


Figure 19: Current pulse from the right side

4.3 Functionality design

Once the construction of the model is finished, a reasonable algorithm should be designed, which allows the functionality of each component to be presented accurately, hence the whole spintronics animation can be appropriately displayed. The vital idea of the magnetisation between the magnet and the writing probe is the consistency of the electrode as well as the polar. Since the representation of the magnetisation is by changing the colour of the divided memory blocks, the origin of these serial changing processes would be the starting point of the algorithm, which is the current provided through the writing element.

Due to the speciality of Unity, objects created through the interface can be appended with scripts, which enables the target objects to possess the desired features and functionalities.

According to the physical principle behind the racetrack memory, the change of state of the device is designed in sequential logic. A background input system is firstly implemented, which can convert the text input values into a sequence of binary digits. Then according to the binary pattern, each digit would be treated as a signal, which would be retrieved by the current coil object sets. The coils then would display the red or blue arrows, standing for the 0 or 1 signal respectively. The magnetic field generated by the electrical coils would then present the same property as the coils, flowing from one side to the other depending on the current. The writing probe then would detect the same signal from the generated magnetic field, which is represented by the particle system, so that it can be altered into the same state just like particle system as well as the coils. Hence the passing blocks are changed according to the signal transferred from the writing probe, and at the end achieves the magnetisation effect visually.

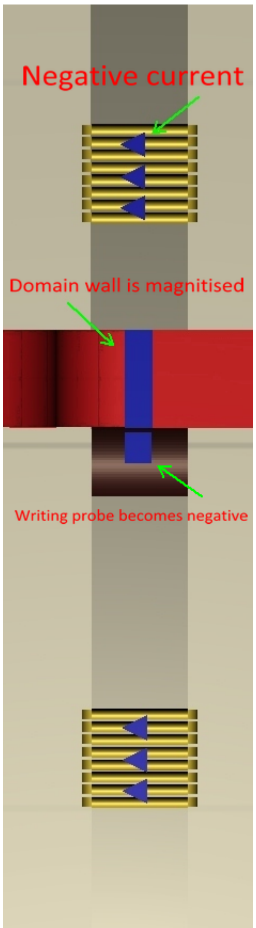
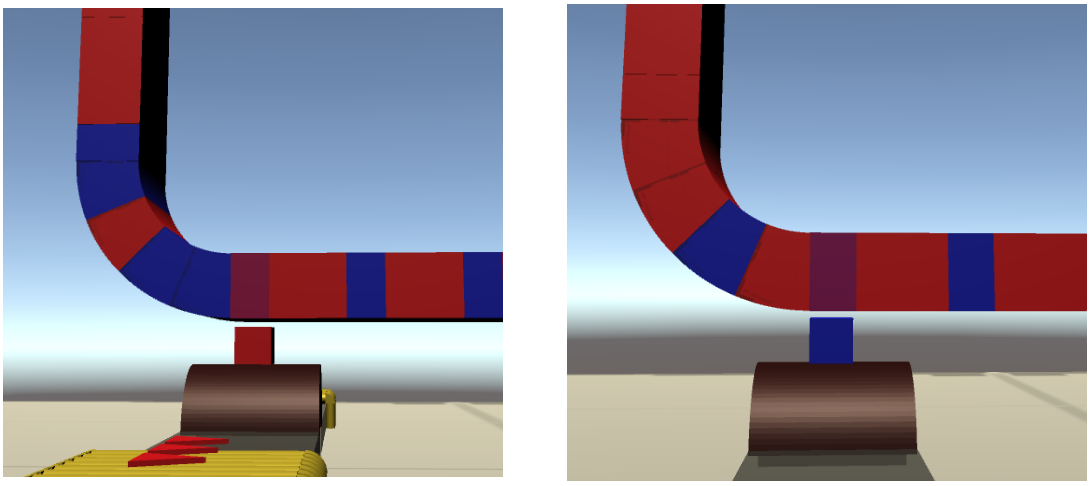


Figure 20: Top view from the racetrack memory indicating the consistency of the signals throughout the device

The essential significance of the writing element is magnetisation. Although the magnetisation effect from the writing probe on the passing domain walls is not instant, the period of the process is too short to be observed. The presentation of this magnetisation process is another auxiliary idea in the animation. With the help of colour interpolation, the passing memory blocks over the writing probe would be gradually changing colour, where the period of each magnetisation is extended long enough to be observed clearly.



(a) Process of magnetisation under positive electrode

(b) Process of magnetisation under negative electrode

Figure 21: Magnetisation under different electrode conditions

4.4 Animating design

To visually achieve the movement of the domain walls, which is the actual animating part, it is important to thoroughly understand the connection between each memory block.

According to the racetrack memory physical principle, the current pulses drive the memory blocks to move along the magnet. This idea needs to be reconsidered during the developing phase. In the programming aspect, each memory block instead needs to record the state of the previous one so that the data or information carried in a block can be passed from one to another. However, as indicated in Figure 21, the blocks passing through the writing element need to be checked whether the signal contained inside the block has the same polarity as the probe. The value would be changed if the condition is not met, or otherwise, leave it as it used to be. This magnetisation process interrupts the original memory passing chain and updates passing rules for the rest of the blocks, as they need to rerecord the one passing through the writing probe. The interruption and updating process occurs whenever the magnetisation happens.

By using the collection data structure, an array which records the state for each block is constructed. This allows the management of all memory blocks to be methodical and clear. The concept would be processing the propagation of the domain walls from the perspective of objects to the perspective of an array data structure, which is an idea of reduction of dimensionality. The array would firstly index all the blocks, and whenever a magnetisation process occurs, the array would update the value of the changing blocks at the corresponding position. Then for each propagation, the blocks are assigning colours by referring to the values inside the array correspondingly.

Apart from the domain walls animating problem, other elements of the device would be relatively simple, as the function of moving objects in an indicated direction can be provided by the Unity interface. This includes the electric pulses on both side of the magnet, where the arrows moving from one side to the other stands for the continuous electric pulse input; also, the flowing particle system standing for the generated magnetic field inside the writing track can be applied with the same function.

4.5 User experience

As an animation with teaching purpose, besides the basic requirement where the working process of the racetrack and the principle of the spintronics needs to correctly and presented, it also needs to possess some demonstration properties to improve the user experience.

In default, due to the camera setting in Unity, the perspective of watching the device is a stationary point. Although the pose of the camera can be adjusted in the interface, it cannot be changed when during the playing mode. Thus a dynamic camera viewpoint is needed which can be moving around to a specific viewpoint, as well as the change of orientation and position.

To improve, for the default playing mode, the view is no more static, instead, the self-position rotation function is implemented, that the camera rotates around the device so that the racetrack can be observed in 360 degrees. A dynamical camera control function is also implemented, where users can exploit the mouse and keyboard to control the view of the camera. To be more specific, the mouse allows users to control the orientation and the keyboard allows users to control the camera to move forward, backward, leftward and rightward. This enables some specific part of the device to be observed more specifically such as the writing probe under the magnet.

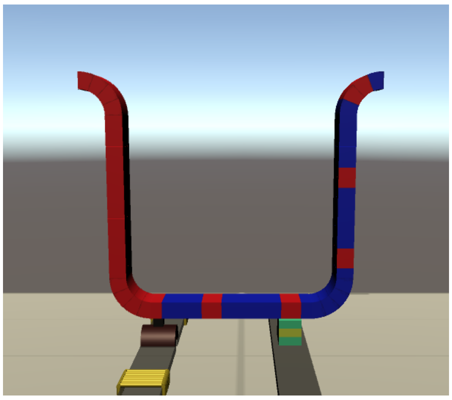
In addition, an extra keyboard control function is applied to the current pulses elements, that during the playing mode, users can press keys to alter the direction of the electric pulses so that the domain walls can be moving in two opposite directions. The effect can be referred to the presentation in Figure 18 and 19. The function would be also demonstrated in the final presentation of the project.

5 Evaluation

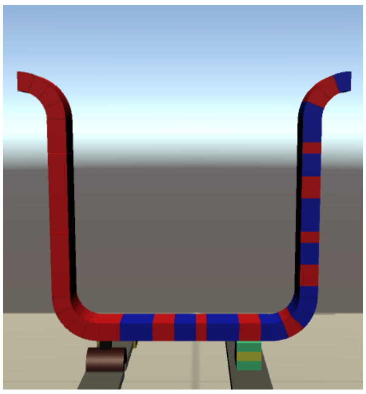
5.1 Basic function testing

Although the animation was supposed to be displayed to obtain responses, the device itself can be tested beforehand with different input values to check the correctness of the functionalities. According to the learnt principle, the input pattern would need to be converted into a numerical string and then be translated into a binary string. Hence the binary would be matched to the electrodes to change the polarities of the magnetic field inside. In the racetrack memory device, the magnet which carries memory blocks are designed with 64 blocks, and since the writing element start magnetising the device at a specific position (roughly 23rd block), the pattern of the magnet with at least 4 characters can be observed, which are 32 binary bits in total. Before the changing position, all blocks are randomly initialised with 0 or 1 to improve the realism of the memory because, in real devices, the memory would be containing some values unless the device is brand new. When the passing block has the same value as the writing probe, the value remains and else it is altered.

Apart from checking the correctness of the encoding of the input values, it is rather intuitive to observe the different pattern according to the appearance of the magnet on the racetrack memory when different values are used for testing. To make the pattern reflected on the magnet different enough to observe, several the input values are tested, where some of the inputs are only numerical strings and others are characters strings. Although all inputs are eventually encoded into 8 bits binary string and be presented as red or blue blocks, the combination of the pattern shown can to some extent verify the correct functionality of the device.



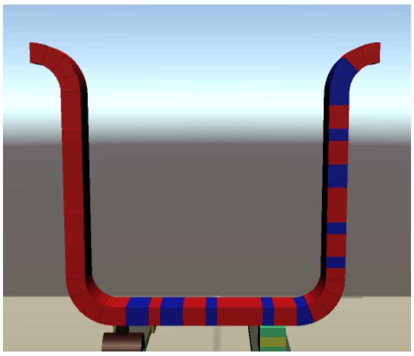
(a) Input value: 00000000



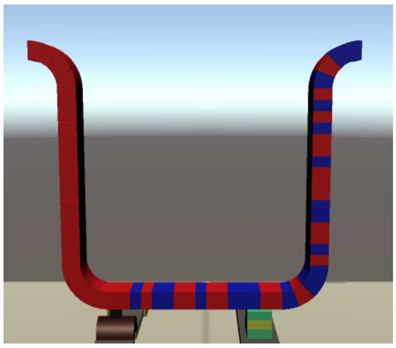
(b) Input value: 11111111

Figure 22: Numerical strings input values

The vertical version of the racetrack memory was used for testing the input pattern, as the visual effect can be illustrated more obviously. Under the tests with long and repetitive numerical strings, the output patterns of the racetrack memory are repetitive and simple, that every 8 bit the combination of the positive blocks and negative blocks are the same because each digit in the string is encoded individually and has the same encoded result. On the other hand, if the testing input values change to words, the output pattern reflected on the magnet would have a completely different appearance from that of the numerical ones, because as a characters string, characters in a word would be encoded respectively and the corresponding 8 bits result would be irregular unless the word has same characters inside.



(a) Input value: good



(b) Input value: nice

Figure 23: Characters strings input values

5.2 2D vs 3D

The designed animation was compared with the referred models mentioned in the referable valid model section, where the comparison focuses on the correctness, accuracy and visual experience aspects.

With the testing results in the previous section, including the similar moving pattern with the one in IBM's video, it can be asserted that the model in the implemented animation is working correctly and accurately if the input values are no longer than 4 characters.

As for the visual experience aspect, even though the racetrack memory device in the implemented animation referred to several currently existing models from either posted video or academical papers, the 3D presentation of the concept is more advanced than those reference examples. As mentioned before, an animation with teaching purposes would provide the adopters with a better learning experience. Compare with IBM's research video, the racetrack memory animation not only visualises a profound physical phenomenon in an intuitive way but also guides the adopters to observe components with a closer perspective. In the animation video, the indicating arrows which explain the roles of the components, the enlarged scenes, the dubs and subtitles all improved the visual and learning experience, as shown in Figure 24. As for IBM's video, only the 2D model is displayed and it is difficult to understand the working process of the device because the video was not intended to teach but demonstrating a new concept of computer data storage.

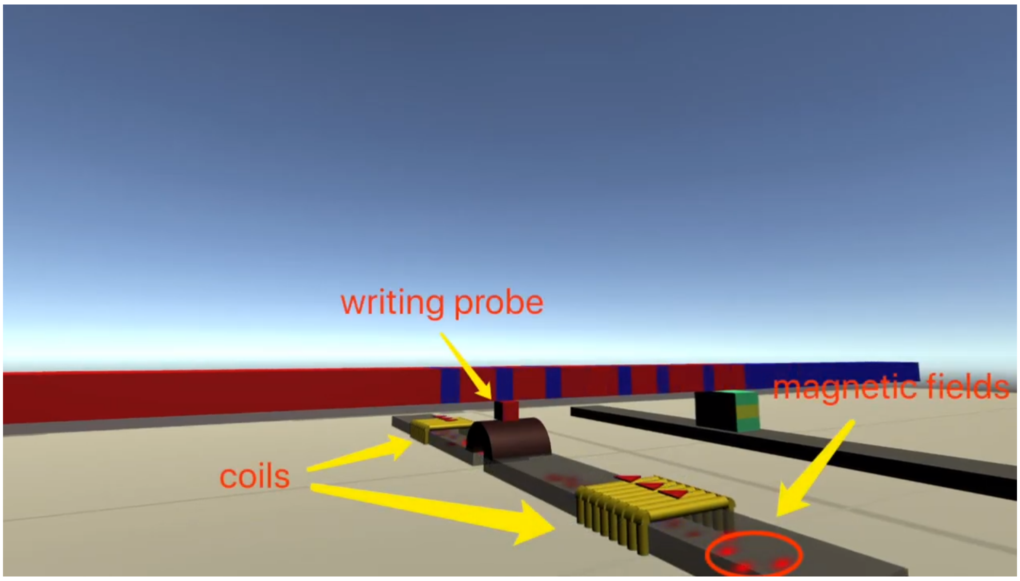


Figure 24: Screenshot from the animation video. This is the horizontal version of the racetrack memory device. Indicating arrows on the detail of the components makes the concept easier to be understood.

The implemented animation would be listed in the appendix.

5.3 Collecting and categorising subjective responses

As mentioned, it is challenging to find a proper method for the evaluation as the scientific visualisation needs responses of users who have experienced the animation, which could be subjective and hard to be categorised.

A video was made with several designed scenes which allows the adopters to observe some details of components from the racetrack memory device such as magnet domain walls, the writing components and the reading components. To improve the acceptance of the video, subtitles, dub and background music are applied. The designed scenes would guide users to obtain a better route to learn knowledge about the spintronics as well as the racetrack memory device, including the detail of each component.

The implementation of the video hence can be useful and helpful for the evaluation as users can directly provide their responses after watching the video. To make the response more objective and easier to be categorised, a questionnaire was designed.

The questionnaire aims for collecting responses from adopters who have watched the animation video. Considering the adopters could be from various realms, that not all of them are professional at computer science or physics or both, the questions designed in the questionnaire need to be a simple form and easy to answer. Besides the form of the questionnaire, the answers are designed to be collected as a quantifiable result, that most of the answers for the questions can be selected by scale from 1 to 5. The collected results then can be categorised and displayed via a statistical graph such as a pie chart. The designing logic for the questionnaire firstly considered the background of the surveyed because the related knowledge of either physics or computer science could help the adopters easier to understand the principle of the racetrack memory. The questions then are designed based on the quality of the animation and retrieve the responses from the adopters after watching the video. Questions like to what extent can people understand the working process of the device can be answered with the help of the linear scale, where 1 stands for the lowest extent - that people cannot understand the video at all; and 5 stands for the highest extent - that people can understand the video completely. Besides the content of the device in the video, as the project also aims for providing a proper learning experience, the questionnaire also asks to what extent the animation possibly inspired the general public to have the interest to explore more content in the science field. Finally, as the perspective from the general public towards the animation could be various and the project itself is not perfect, the last question of the questionnaire is the suggestions to modify or improve the quality of the project or the animation.

5.4 Result analysis

The animation is published online, as well as the designed questionnaire. Up to the evaluation stages, there are 12 adopters in total watched the video and finished the survey. The result for each question is listed as a figure, where some of the answers are shown in the form of the pie charts and others are in the form of the bar charts.

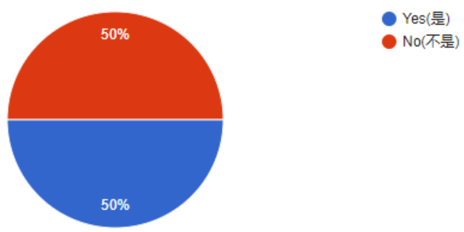


Figure 25: Results of question - "Do you have good background knowledge of physics?"

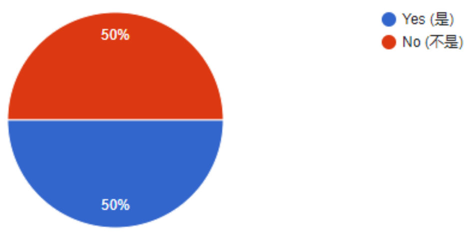


Figure 26: Results of question - "Do you have good background knowledge of computer science?"

In order to obtain relatively objective responses for statistical analysis, the questionnaires were distributed to different groups of people, that some of the tested have the background knowledge of physics; some of them have the background knowledge of computer science; some tested have knowledge at both realms and some tested have neither of them. As shown in Figure 24 and Figure 25, the tested people satisfied the expected standard, that 50% of them are good at physics and 50% of them are not. As for the same question for computer science, the result is the same as that of the physics one.

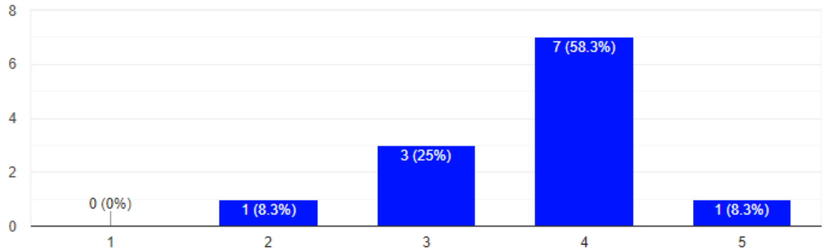


Figure 27: Results of question - "To what extent do you understand what is going on in the animation?"

Then it comes to the main question that if the animation can express the idea of the racetrack memory clearly. The answers are moderated, as the number of the tested who can understand the animation completely and can hardly understand the animation covers 8.3% respectively. According to the diagram, it presented a left-skewed normal distribution, that 58.3% of the tested claims that they can understand the animation well, which is level 4 in the linear scale. 25% of the tested claim that they can only understand part of the knowledge that the animation tried to deliver.

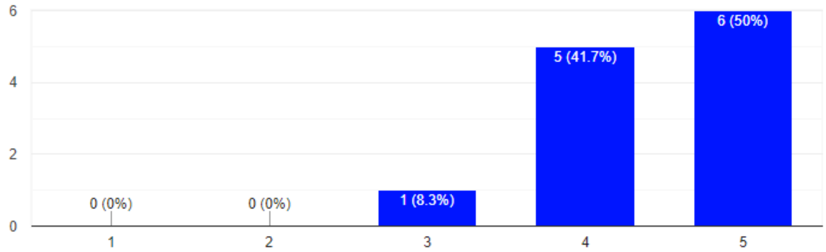


Figure 28: Results of question - "To what extent do you agree with the correctness and accuracy of the animation in the physics and computer science aspects?"

The result of the question regarding the correctness and accuracy is interesting as the responses from the tested tend to be praising the presentation of the animation. 50% of the tested agree that the animation perfectly demonstrated the principle of the racetrack memory demonstration, in both the correctness and accuracy aspects. 41.7% of them agree that the animation presented the working process of the device in good quality. Only 8.3% think that the animation is presented in moderate quality.

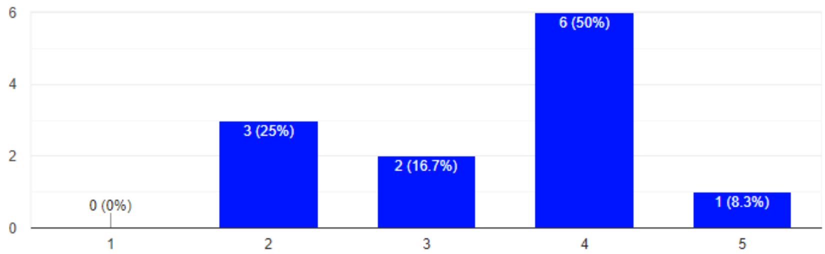
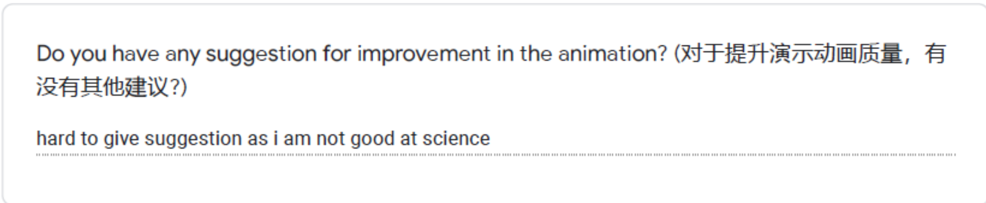


Figure 29: Results of question - "Affected by the animation, to what extent would you be interested in learning more knowledge in the science domain?"

The responses about the question - to what extent the users are inspired to have interested in learning more knowledge in science - are various. Although the greatest proportion of the answers is that they have relatively great interests in learning more scientific knowledge, which covers 50%, the second-largest proportion is that they barely have interests in learning, which covers 25%.

The figures show the responses from the tested in a statistical perspective, whereas the reason for the distribution of the all above is difficult to analyse without the actual text responses. The last question of the questionnaire, which asks for the suggestions or comments regarding the animation, provides clues and information for the reason for the above result.

The received comments and suggestions are various, that some of them understand the animation very well who give objective and useful suggestions at the end; whilst some of the tested who can hardly understand the animation cannot give very helpful replies. The extent of understanding of the video would affect how would the tested answer the rest questions during the survey, for example, if a person who cannot understand what is going on in the video, then the comment from him/her on whether or not the animation is presented accurately and correctly would not be objective, as they do not know how to answer but give a random response. As a result, the tested would all give very positive responses for the accuracy and correctness provided from the animation, that the tested who understand the video would agree with the quality of the video and others would assume the video was presented in a correct way. Some responses like "I could not give any suggestion as I am not good at science" helps justify the analysis, as shown in Figure 29.


Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

hard to give suggestion as i am not good at science

Figure 30: One of the comments from the questionnaire

A similar analysis can also be applied to the question regarding if interests are inspired by the video, where responses for the question are more realistic. The concept of the racetrack memory, including a profound exploration of electronics and magnetism, is too confusing for beginners, thus there are many tested replying that they were not inspired with great interests.

For those who understand the video well, the suggestions from them were insightful and also inspired the ideas for the future works on the spintronics realm. Some tested claim that the animation would be more interesting and a better understanding of the device would be achieved if the racetrack memory can be shown as a "unit" that works in an industrial array, which indicates a great direction for the further development. Some tested gave suggestions focusing on the content of the video, that the usage and functionality can be better understood if the racetrack memory can be applied to the current application or industrial device. There are some similar suggestions like the watching experience would be improved if this innovative device can be compared with some currently existing computational data storage, including the requirement of a better illustration of the spintronics phenomenon happens inside the nanowire.

The designed questionnaire as well as the included suggestions would be all listed in the appendix.

6 Reflection

6.1 Model modification

It is necessary to compare the current design of the racetrack memory device with the previous one (indicated in Figure 13), as the structures between them are very similar, whilst the data updating and the movement of the domain walls are different in a concept level. To reach the teaching purpose for the animation, although the incorrect version is not displayed, it is meaningful to discuss it in this reflection section so that misconception could be avoided.

Previously, the design of the racetrack device was inaccurate as the memory blocks propagate in the magnet in the form of the empty data bits, instead of domain walls, which are consecutive poly-crystalline structure. Transferring bits via a track and alter the values inside them is similar to the idea of the hard disk drive, also known as HDD[3]. Difference between the racetrack memory and HDD would be the use of the reading element and the form of the memory passing inside the track. In racetrack memory, there are already information or data recorded in the memory blocks inside the magnet and the movement of the domain walls are the consequences of spin-transfer torque, whilst in HDD, blocks are propagated with empty value and the movement of those empty bits are not caused by the electric pulses nor effects of spintronics phenomenon. Also, as mentioned in the background section, the traditional data storage device access the memory by moving the mechanical components whilst in the racetrack memory, components are all static, and the memory bits gets moved or altered under the effect of electronics or magnetism.

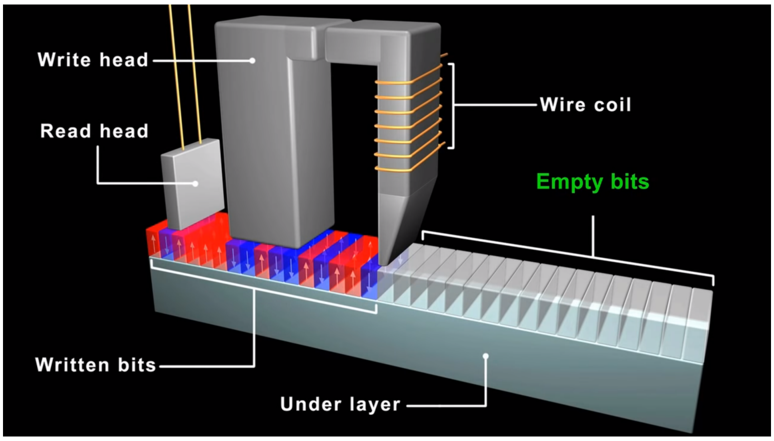


Figure 31: Screenshot from YouTube video - Magnetism: Data Storage(the link is listed in the footnote). The concept model of Hard Drive Disk

6.2 Project completeness

Initially, at the designing stage, the animation was expected to provide a stunning effect including ideas such as a fluent change of scenes or high-quality modelling and rendering effect. Since Unity and C#, as well as the spintronics related physics knowledge, are all completely new fields to me, as a computer science student. Learning all these new knowledge even took a relatively longer period than the actual programming stage. The process of the implementation of the incorrect version also

[3]YouTube video Magnetism: Data Storage - https://www.youtube.com/watch?v=f3BNHhfTsvk&list=PLpzuiHec3gNAe7YrtAMALi_8MJtyCrNd8&index=42&t=0s

consumed some time, yet which is also a good learning process to obtain a better understanding on the racetrack memory device.

At the end of the development, the basic demonstration of the working process of the racetrack memory device is finished. Some additional auxiliary elements are applied to the animation to improve the watching experience for the adopters who are new to this domain. A demonstration video with several enlarged scenes, background music, subtitles and dub has been made and has been uploaded on the internet. However, due to the limited time, extra features are not implemented and these will be discussed in the future work chapter.

6.3 Limitation of the project

Although the animation is good for demonstrating processes that are difficult to be observed under an ideal experimental environment, this is also a weakness for it because, in reality, it is hard to achieve an experimental setting that any other unrelated factors such as environmental magnetic field are excluded. Also, the flexibility feature of the animation requires it to be modified whenever there are changes in the real device, which is another consumption to the time and computational resource.

The model itself inside the animation also has an inevitable problem, that the flexibility of the number of memory blocks is limited. In the implemented device, there are 64 blocks in total inside the magnet, although the number can be changed to larger or smaller, the size of the device, including the writing probe in the writing component, need to be changed to fit the variation. This limitation, therefore, would be difficult to deal with some extreme cases, for example, if there is a test input value which contains more than 8 characters, the converted binary pattern would exceed 64 bits. The number exceeds the storage of the magnet, so when those bits which have passed the device, they are unable to be observed again, even by reverting the direction of the current pulses. After all, the animation aims for demonstrating the spintronics principle, thus the size of the device, as well as the number of blocks and the fact that the animation can only show limit storage size, was not devoted too much time for solving.

On the other hand, since the goal of this project is to animate a device based on a physical phenomenon, all information contained in the animation would be designed according to the properties that the device possesses. In other words, the limitation of the actual device would be the limitation of the actual device in reality. For example, the distribution of the domain walls inside the magnet theoretically exists whilst they could not be perfectly equally divided. However, in the animation model, even the currently existing referable valid models from other scholars paper, these magnetic memory blocks are assumed to be equally distributed. This is because the possible inaccuracy is too subtle to be observed and there is no reason for identifying it if the animation is only designed for teaching purpose, thus these details are neglected.

In addition, in the computational data storage domain, racetrack memory, as an application of spintronics, is still in development, which means the device is not exploited in any current industrial computer devices. Therefore, a complete perspective of the racetrack memory is currently not able to be demonstrated, and hence the animation only shows the concept model of it instead of the actual computer devices. What is more, if the final racetrack memory device comes out and the exploited principle is different from the implemented animation, the video could be outdated and discarded.

6.4 Improvement based on the current features

Despite the completeness of the project, due to the limit of time, there are some specific features that can be improved for the current version of the animation.

However, it is necessary to point out that some of the improvements of the features could be helpful for boosting user experience, whilst they would not change the main functionalities of the animation. Although the following features would be discussed, the most essential task is to achieve the animation with correct physical principles. Therefore, these supplementary are discarded during the actual implementing phase considering the time problem.

All the improvement considerations came up after the implementation of the project, where some of them came from self-evaluation and some others were from the suggestions of friends, teachers and people surveyed.

6.4.1 Presentation of domain walls

In the current version, the movement of the domain walls inside the magnet track moves one block per second, whilst in reality or ideally, the movement of these blocks should be more fluent or say, more natural. This is because the movement pattern inside the magnet is designed as 1 Frame Per Second (FPS). The human visual system can process 10 to 12 images per second and perceive them individually[48], thus in a usual video, the FPS of objects should be displayed in at least 12 so that for the human being it can be perceived as motion. For the racetrack memory case, the initial consideration was to clearly show the process of the movement of the domain walls as well as the magnetisation process of the passing blocks via the writing element. The motion was designed to be slow because in reality the magnetisation process is too fast and lots of details inside the device are invisible. A better solution to the motion problem would be separating the moving phase and the magnetisation phase, that the velocity of the moving memory blocks inside the magnet would be increased if there is no necessary magnetisation, otherwise, whenever a different signal occurs, all blocks would stop and wait until the magnetisation process is finished. This idea may require a new logicality which could change the whole structure of the algorithm behind the device.

6.4.2 Camera views

The camera view would automatically rotate around the device unless other viewings controlling keys are pressed. The feature is reasonable as a demonstrating tool. However, although the interaction functions are designed, it is hard to perceive them by watching the animation. In order to pursue a better visual experience in the animation aspect, a better idea would be designing a particular route for the camera so that besides rotating around the device for a short period, it can automatically move to other specific components such as the writing element to obtain a closer observation. With this idea, the demonstration would be more fluent and it could provide a better visual experience to users.

6.4.3 Modelling, rendering and lighting

As mentioned before, the modelling capability of Unity is limited, in the animation, the whole device was constructed in a simple way, which is combinations of objects. Unity also possess the ability to adapt a predefined object from other development platforms, for example, Blender is good at modelling and rendering, the constructed object can be exported and imported into Unity for further development. By exploiting items from this kind of platform, details of the components of the racetrack memory, such as the electric magnetic coil on the writing element, can be depicted as more aesthetic.

On the other hand, rendering the model appropriately would also increase the visual experience for users. For example, assigning the magnet and the coils with metallic material rendering increases the realism of presenting the device.

In addition, the lighting feature of Unity makes the demonstration more vivid, as the angle and intensity of the light would change the view depending on the position and orientation of the camera, which is the actual perspective for users. In the playing mode, with the rotation of the camera, the device would be shown in a bright and dark effect, that the camera is at the same side and the opposite side to the lighting source respectively. The bright side would show all the colours and rendering materials involved whilst the dark side would lead to a complete black visual effect for the scene. A good design of the distribution of the light needs to be considered so that the model should be demonstrated clearly.

6.5 Website presentation

There are many methods for presenting this project online. As a demonstration method, the video can guide users to learn or closely observe some particular aspects like reading or writing elements. It is simple and effective to improve the visual experience by adding subtitles and background music in the video. The video was eventually selected, however, some features of the project itself maybe not completely experienced by users such as user interaction functions, which is not directly shown in the video. In addition, the input value for the racetrack memory can be altered through the script, so that the demonstration of different input pattern can be shown, whilst in the video, only one type of input string was displayed. The process of making the video was difficult, as the content included needs a proper consideration so that with the help of subtitles and demonstration of the device, adopters can understand the idea of the racetrack memory device. It is also challenging to delivery a relatively complete knowledge about the device in a short time as the video aims to provide a good visual experience as well as a learning experience which requires the content to be straightforward and easy to understand.

Another considered method would be uploading the whole project on a website so that the features of interaction functions and the input values aspects can be utilised. Users can try the program with different values for the input pattern and control the position of the camera to obtain different perspectives from the designed video. This idea may require proper use of some web programming language or API, for example, the program originally changes the input pattern through the script, which is not directly managed by users, and if the program is demonstrated with interactive functions, the change of values for the input pattern should also be available, that an input frame may be required and the retrieved values need to be transferred to the script for changing the states of the device.

However, this method of presentation would require users to have a proper understanding of these domains, because, without guidance from video, it could be difficult for the general public to appropriately observe the detail of the device to understand the main ideas of spintronics. On the other hand, it requires more user experience for this online version, because aspects like how to change the input values and how to alter the position of the camera would all have influences on the users when they are using the program. Therefore, an appropriate instruction should be designed for this form of presentation.

7 Future Work

As an innovative technique, racetrack memory is still in development, which means that the utilities and working process remain in a theoretical stage. Despite the current features of the animation, more ideas can be used to achieve a higher level for the presentation, but most of them would not directly be related to CGI technique. Some of them require more profound research in the physics domain and others need some explorations on designing aspects.

7.1 Observable working detail inside the reading element

From the currently implemented animation, the reading element is statically located beneath the magnet, where the process of the reading element retrieving magnetic polarities and converting into computational signals is not shown in detail. Unlike the writing element, which by applying auxiliary elements such as particle systems can visualise the working detail in a simple presentation, the reactions happening inside the reading element are more complicated and cannot be simply represented by the auxiliary elements. Instead, it is better to create another new scene to present the process because the magnetic field, the movement of electrons, as well as magnetic particles, should be presented in a larger scale and it is difficult to contain all of these in a small space.

As mentioned, the physical principle inside the reading element requires more complete and deeper research on spintronics, where the knowledge included would be difficult to learn and understand, hence more time would be needed.

7.2 Display the model in an industrial level

As mentioned before, in animation the racetrack device, either the vertical version or the horizontal version, can be regarded as a "unit". Inside a real computer storage device, this unit would not work alone, in other words, it would be integrated with a large number of the same units, which conforms a big array, as indicated in Figure 5 (E). The integration theoretically allows the racetrack memory device to work in high efficiency and be able to propagate large amounts of data or information.

It is possible to animate the above idea using CGI technique if an industrial level demonstration is required. The scene firstly needs to be modified into a larger scale which concatenates the "unit"s in a proper structure and order. However, the large scale demonstration could lead to confusion to users that the working detail of each unit could be not observed concretely. Therefore, a tradeoff between the detail and the whole structure demonstration needs to be found.

Additionally, a new algorithm for propagating the data signals through the integrated system needs to be reconsidered as the capability of the track undertaking the number of memory blocks occurs a massive change. In case that the amount of data is very large and the order of them has less importance, the method of retrieving data could even be altered into key-value matching algorithm such as hashmap. In the matching algorithm, the key would be the position or order of the specified memory block, and the value stores the signal contained by the memory block. In this way, the computational cost for demonstrating the working flow of the array would decrease, hence improving the efficiency of the animation so that higher FPS can be provided to improve the visual experience.

7.3 Collections of the spintronics animation

For the computer storage domain, since spintronics includes various types of devices, animating one of them may not involve enough information for the general public to learn. It is good to come up with ideas which aim for better user experience and the effectiveness of learning spintronics. To reach a further and more intact demonstration, a kind of collection program can be designed, that all animations of the different types of devices based on spintronics can be contained in it. A Graphical User Interface (GUI) can also be designed to make the program easier to be used by people, including elements like tags to choose which spintronics device to be displayed. For example, when the program is executed, the GUI initially shows a list of devices and when a user is interested in a device such as a racetrack memory or MRAM from the list, by pressing the tag in the GUI then the animation for the devices can be displayed. Besides the list of animation, when a specific device is demonstrated, the program with some variable controlling elements such as drag bars would allow users to try various variables such as the intensity of the current through the racetrack memory and observe the difference of the device works under different conditions.

7.4 A skyrmion racetrack memory

Racetrack memory, as an undeveloped type of computer storage technique, to be a more specific concept should be a skyrmion racetrack memory. Racetrack memory even though is believed as a new type of memory storage method, which shows potentials to surpass the performance than the current method of computer data storage devices, it is still far away from being actually implemented due to the existence of the skyrmions. In particle theory, the skyrmion is a topologically stable field configuration of a certain class of non-linear sigma models. This was originally proposed as a model of the nucleon by Tony Skyrme in 1962[49]. The skyrmions, in theory, would be the actual carriers of memory segments in the racetrack memory device design. The skyrmions can be manipulated under the effect of spin current generated within the ferromagnet or by the spin-Hall effect arising from a non-magnetic heavy metal under-layer[50].

However, the skyrmions, that the racetrack memory is relying on, also become the barrier for the racetrack memory to be implemented. Andrew Kent, a professor of physics from New York University, claims that the small skyrmions are not stable in common environments unless they are in very specific material environments. Therefore, the current most important mission is to find out the ideal materials that can undertake the skyrmions, as well as under which situation can they be created[29].

The current implemented video is inspired by the structure of the traditional hard-disk drive, combining with the idea of spintronics and the reference from IBM's design. If the related problems on the skyrmions are resolved, the racetrack memory device then could be different from the current implemented video, as in the animation there is no related information or knowledge introduced about skyrmions. Hence a new design for a skyrmions racetrack memory device is required, including the reconsideration of the structure of the device, auxiliary presentation of skyrmions and the related moving pattern of the skyrmions. Although both the former and latter would present the essential principle of spintronics, the latter involves more professional physical knowledge, which requires the video to possess a better design and presentation to provide a good learning experience for the general public.

8 Conclusion

Nowadays the computer science realm expects more memory storage devices with high storage efficiency while keeping the size of the device the same or even smaller. Spintronics is an innovative realm that still needs more exploration as this technology has great potential that could meet the increasing demand for computer memory storage. Animating the racetrack memory would only be one of the applications of the spintronics technique, whilst the racetrack memory is still in development and only the concept can be shown. Another reason that becomes a barrier to this form of data storage is the unstable control of skyrmions, as mentioned in the previous section.

Similar to other types of memory storage techniques, despite the improvement of the data storage efficiency problem and the size reduction problem, spintronics needs to further boost these advantages, as these are always the main aspects that the current computer data storage realm focuses on. Besides that, the use of electricity and magnetism would be an extra problem for constructing the devices based on spintronics. The future work section might not have discussed the full potential directions of the spintronics as many products could be developed in various field based on this technique.

9 Appendix

9.1 Appendix - A

The demonstration racetrack memory video: http://bit.do/rm_animation or
https://www.youtube.com/watch?v=vaW9Zqd1vdk.
The feedback questionnaire for the racetrack memory video: http://bit.do/rm_animation_survey or
https://docs.google.com/forms/d/e/1FAIpQLSdhX_3R7FXVPArLINAEK1UdLnB7bqV2VYNc7fU3gVhQLncUYQ/viewform.

9.2 Appendix - B

Suggestions and comments for the last question of the questionnaire are listed below:

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

Would be more interesting if the animation show where this race track memory unit is located in the full memory system

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

Expect deatil of reading element

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

Expect adding animation character; hard to understand without introduction

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

the concept can be used in real world applicaiton, which could make it easier to be understood

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

describe what is this concept can be applied into so that users can understand them better

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

no

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

hard to give suggestion as i am not good at science

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

This demo dubbing is so magical

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

maybe change the background to make the experience better

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

try to compare with the current technique and point out what is it good at

Do you have any suggestion for improvement in the animation? (对于提升演示动画质量，有没有其他建议?)

it will be better if the author can show the differences between the mechanical moving parts bass HDs and the racetrack; the difference between the traditional solid state memory such as Flash,PROM, etc. and the racetrack, which is critical to show how to represent bits and how to write and read those bits by illustrating the spintronic inside the nanowire

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