UNIVERSIDAD COMPLUTENSE DE MADRID
FACULTAD DE BELLAS ARTES

TESIS DOCTORAL

Superar el límite de la pantalla: el futuro integrado del diseño industrial e innovación de la interfaz

Beyond the edge of display: the integrated future of indutrial design and interface innovation

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

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Directores

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Madrid

Universidad Complutense de Madrid
Facultad de Bellas Artes

Memoria presentada para optar al grado de doctor por
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MADRID, 2019

UNIVERSIDAD
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MADRID

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estudiante en el Programa de Doctorado Bellas Artes,
de la Facultad de Bellas Artes de la Universidad Complutense de Madrid, como autor/a de la tesis presentada para la obtención del título de Doctor y titulada:

Superar el límite de la pantalla: el futuro integrado del diseño industrial e innovación de la interfaz

Beyond the Edge of Display: the Integrated Future of Industrial Design and Interface Innovation

y dirigida por: Jaime Munarriz Ortiz
Miguel Angel Valero Espada
Miguel Oliveros Mediavilla

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Abstract

Part 1 Thesis Abstract

1.1 Thesis Abstract

"The creation of an integrated design system for both the industrial design and the user interface design for Consumer Digital Devices (CDDs)."

The goals of this thesis are to streamline the design process of CDDs for both their hardware and software, simplify the process of their conception, creation and production, motivate the design and interactive innovations for the next generation of CDDs.

Starting with the process of investigating the design history of CDDs, we noticed the increasing bi-directional influence between the graphical interface design and the industrial design of these products. We started to work on the hypothesis:

"A connection point between classical industrial design theories and modern innovations in the world of interface design can be found, and the future of CDD requires a universal design system for both its hardware and software."

In order to put our hypothesis into practice, it is important to clarify the generic and specific objectives.

The generic objectives of this thesis include:

- Explore the design achievements on CDDs beyond political economy limitations;
- Summarize the design value of CDDs;
- Revisit the design history of CDDs and analyze their design demands in the post-digital era;
- Bridge between user interface design and classical industrial design theories applied to CDD products.

The specific objectives of this thesis include:

- Research the history of graphical user interface design;
- Comprehend the relationship between hardware limitation and interface rendering;
- Study the application of classic industrial design theories on user interface;
- Summarize the influence of interface design trends on the industrial design of CDDs.

Focusing on the objectives of the thesis, we selected the suitable methodology for both the theoretical and the practical investigation:

- **Library search.** There is a huge amount of academical and practical work done in the history of industrial design and user interface design. By using the library search method, all of these investigation results could serve as an important theoretical basis for this thesis;

- **Transdisciplinarity.** During the investigation process, various academic areas are involved: industrial design, user interface design, industrial technology, software engineering, marketing, user behavior study, aesthetics, digital art, art theory and bio art. Transdisciplinarity helps us to have an integrated understanding of these academic materials, making all disciplines work towards a common aim;

- **Cross-sectional analysis.** In order to sort out the independent variables caused by usage scenarios and mass production limitations, we transversally analyzed CDDs that appeared in the market within the same timeframe regardless their form factor and interaction paradigm;

- **Comparative analysis.** As our object of study, CDDs are born with two contradictions caused by their consumer product nature: the contradiction between the latest design findings and the reality of mass production; the contradiction between the UX expectation of the product and the acceptance in general public. Using comparative analysis helps us to have a better understanding of the design choices and compromises of the CDDs in the market;

- **Mind mapping and graphical analysis.** In order to improve the visualization and legibility of the thesis, we used mind mapping and graphical analysis as part of our methodology used in the research development phase. A mind map and a logical research diagram inspired by algorithm graphs is included for each chapter of our research development;

- **Case study.** CDDs has a few decades of history in the consumer market. In this thesis, we included 4 case studies, each focusing on a specific theme:

  - Gaming consoles, focusing on the graphical computing power evolution;
  - Design evolution of input methods on CDDs;
  - Design evolution of output methods on CDDs;
  - Apple Inc.'s product design history since the 1980s;

- **Usage of dictionary of terms.** In the part 8 of the definition of this thesis, we provided a dictionary of terms, in order to improve the legibility and facilitate the comprehension of the thesis.

The results obtained from the investigation process include:

- A panoramic view of the user interface design history on CDDs;

- An in-depth understanding of graphical hardware evolution and the limit it set for interface rendering;

- A summary of the reapplication of classical industrial design theories on the user interface design of CDDs;

- A summary of the influences of user interface innovations that eventually benefits the industrial design of CDDs;

- As mentioned above, case studies from different perspectives of the design for CDDs;

- An exploration for the creation of a unified design system for CDDs based on the latest evolutions and revolutions of technology in the consumer digital market.

The following conclusions can be illustrated based on the research results:

- The market background and the evolution of content plays a key role on the design evolution of CDDs;
- As a type of consumer products facing limitations of mass production, the creation of CDDs has its own workflow and its unique design values;
- As the terminal of content consuming, CDDs evolve with and play a key part in the lifestyle of the post-digital era. They have a huge impact of the society of today;
- Integrating the design system for the industrial design and the user interface design of CDDs leads to products with better user experience and smoothes the learning curve of new devices for customers;
- With a unified design system, an intense bi-directional influence between industrial design theories and interface design innovations is happening in the process of the conception, creation and production of CDDs. This bi-directional influence takes the design for CDDs one step further, and has its impact on the social lifestyle in the post-digital era.

1.2 Resumen tesis (en español)

"La creación de un sistema de diseño integrado para el diseño industrial y el de la interfaz de usuario en dispositivos digitales de consumo (DDC)."

El fin de esta tesis es mejorar el proceso de diseño de DDC tanto para su hardware como para su software, simplificar el proceso de concepción, creación y producción, así como motivar el diseño y las innovaciones interactivas para la próxima generación de DDC.

Comenzando con un proceso de investigación que respete la historia del diseño de los DDC, notamos un incremento en la influencia bidireccional entre el diseño de interfaz gráfica y el diseño industrial de estos productos. Trabajamos sobre esta hipótesis:

"Se puede encontrar un punto de conexión entre las teorías clásicas de diseño industrial y las innovaciones modernas en el mundo del diseño de interfaz. El futuro de los DDC requiere un sistema de diseño unificado para ambos: hardware y software."

Para poner nuestra hipótesis en práctica, es importante aclarar los objetivos genéricos y específicos.

Los objetivos genéricos de esta tesis incluyen:

- Explorar los logros de diseño en DDC más allá de las limitaciones de la economía política;
- Resumir el valor de diseño de los DDC;
- Revisar la historia del diseño de los DDC y analizar sus demandas de diseño en la era post-digital;
- Conectar el diseño de la interfaz de usuario y las teorías clásicas del diseño industrial aplicadas a los productos DDC.

Los objetivos específicos de esta tesis incluyen:

- Investigar la historia del diseño de la interfaz gráfica de usuario;

- Comprender la relación entre la limitación de hardware y la renderización de la interfaz;
- Estudiar la aplicación de las teorías clásicas de diseño industrial en la interfaz de usuario;
- Resumir la influencia de las tendencias de diseño de interfaz en el diseño industrial de los DDC.

Centrándonos en los objetivos de la tesis, hemos seleccionado la metodología adecuada tanto para la investigación teórica como para la práctica:

- **Búsqueda en la biblioteca.** Existe una gran cantidad de proyectos académicos y prácticos realizados sobre la historia del diseño industrial y del diseño de la interfaz de usuario. Con la búsqueda en la biblioteca, todos estos resultados de investigación podrían servir como una base teórica importante para esta tesis;

- **Transdisciplinariedad.** Durante el proceso de la investigación, varias áreas académicas están involucradas: diseño industrial, diseño de interfaz de usuario, tecnología industrial, ingeniería de software, marketing, estudio de comportamiento del usuario, estética, arte digital, teoría del arte y arte biológico. La transdisciplinariedad nos ayuda a tener una comprensión integrada y transversal de estos materiales académicos;

- **Análisis transversal.** Para evaluar el diseño de los DDC superando los factores independientes causados por el escenario de uso o las limitaciones de la producción en masa, hicimos un análisis transversal sobre los DDC diseñados en el mismo período de tiempo, sin importar su factor de forma o paradigma de interacción;

- **Análisis comparativo.** Como nuestro objeto de estudio, los DDC nacieron con dos contradicciones causadas por su naturaleza de producto de consumo: la contradicción entre las innovaciones del diseño y la realidad de la producción en masa; la contradicción entre la expectativa de experiencia del usuario del producto y la aceptación en el público general. El uso del análisis comparativo nos ayuda a comprender las opciones de diseño y los compromisos de los DDC en el mercado;

- **Uso de mapa mental y análisis gráfico.** Para mejorar la visualización y la legibilidad de la tesis, utilizamos mapas mentales y análisis gráficos en la fase de desarrollo de la investigación. En cada capítulo de nuestro desarrollo de investigación presentamos un mapa mental y un diagrama lógico inspirado por gráficos de algoritmos;

- **Estudio de caso.** Los DDC tienen varias décadas de historia en el mercado de consumo. En esta tesis hemos incluido 4 estudios de caso, cada uno centrado en un tema específico:

  - Consolas de juegos, centrado en la evolución de la capacidad de la renderización gráfica;
  - Evolución de los métodos de input en los DDC;
  - Evolución de los métodos de output en los DDC;
  - La historia del diseño de productos de Apple a partir de la década de 1980;

- **Uso del diccionario de términos.** En la parte 8 de la definición de esta tesis, proporcionamos un diccionario de términos para mejorar la legibilidad y facilitar la comprensión de la tesis.

Los resultados obtenidos del proceso de investigación incluyen:

- Una visión panorámica de la historia del diseño de interfaz de usuario en los DDC;

- Una comprensión en profundidad de la evolución del hardware gráfico y su influencia para la renderización de la interfaz;

- Un resumen de la aplicación de las teorías clásicas del diseño industrial en el diseño de la interfaz de usuario para los DDC;

- Un resumen de las innovaciones de interfaz de usuario que han influenciado el diseño industrial de DDC;

- Estudios de casos desde diferentes perspectivas para el diseño de DDC;

- Exploración para la creación de un sistema de diseño unificado para los DDC basado en las últimas evoluciones y revoluciones de la tecnología aparecidas en el mercado de productos digitales para consumidores.

Hemos llegado a las siguientes conclusiones basándonos en los resultados de la investigación:

- El mercado y la evolución del formato de contenido juegan un papel clave en la evolución del diseño para los DDC;

- Como un tipo de productos para consumidores que se enfrentan a limitaciones de producción en gran cantidad, la creación de DDC tiene su propio flujo de trabajo y sus valores de diseño en particular;

- Como terminal de consumo de contenido, los DDC juegan un papel clave en el estilo de vida post-digital. Esta categoría de productos y su diseño tienen un gran impacto en la sociedad de hoy;

- Un sistema de diseño integrado para tanto el diseño industrial como el diseño de interfaz de usuario de los DDC nos dirige al nacimiento de una nueva generación de productos con una mejor experiencia de usuario y una curva de aprendizaje más suave para sus clientes;

- Con un sistema de diseño unificado nace una influencia bidireccional intensa entre las teorías de diseño industrial y las innovaciones en el diseño de interfaz en el proceso de concepción, creación y producción de los DDC. Esta influencia bidireccional traerá avances nuevos para el diseño de los DDC e impactará en el estilo de vida social post-digital.

1.3 Research Scheme

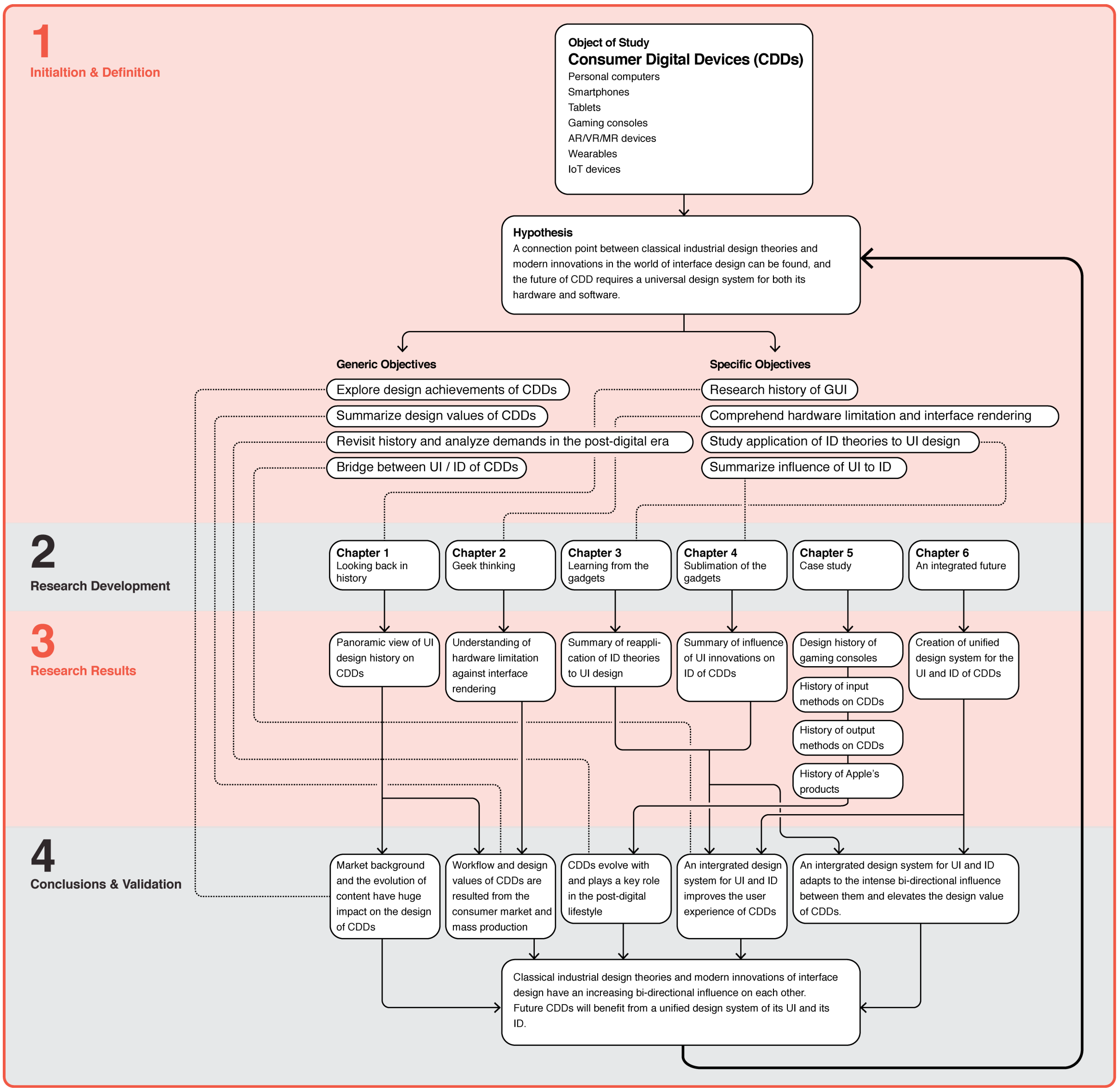

Figure 1 **Heda Weng**, (2019), *Research Scheme.* Courtesy of the author.

Part 2 Keywords

2.1 Keywords

Consumer Digital Devices (CDDs), User Interface Design, Industrial Design, Design Integration, Design System.

2.2 Palabras claves (en español)

Dispositivos digitales para consumidores (DDC), diseño de interfaz de usuario, diseño industrial, integración de diseño, sistema de diseño.

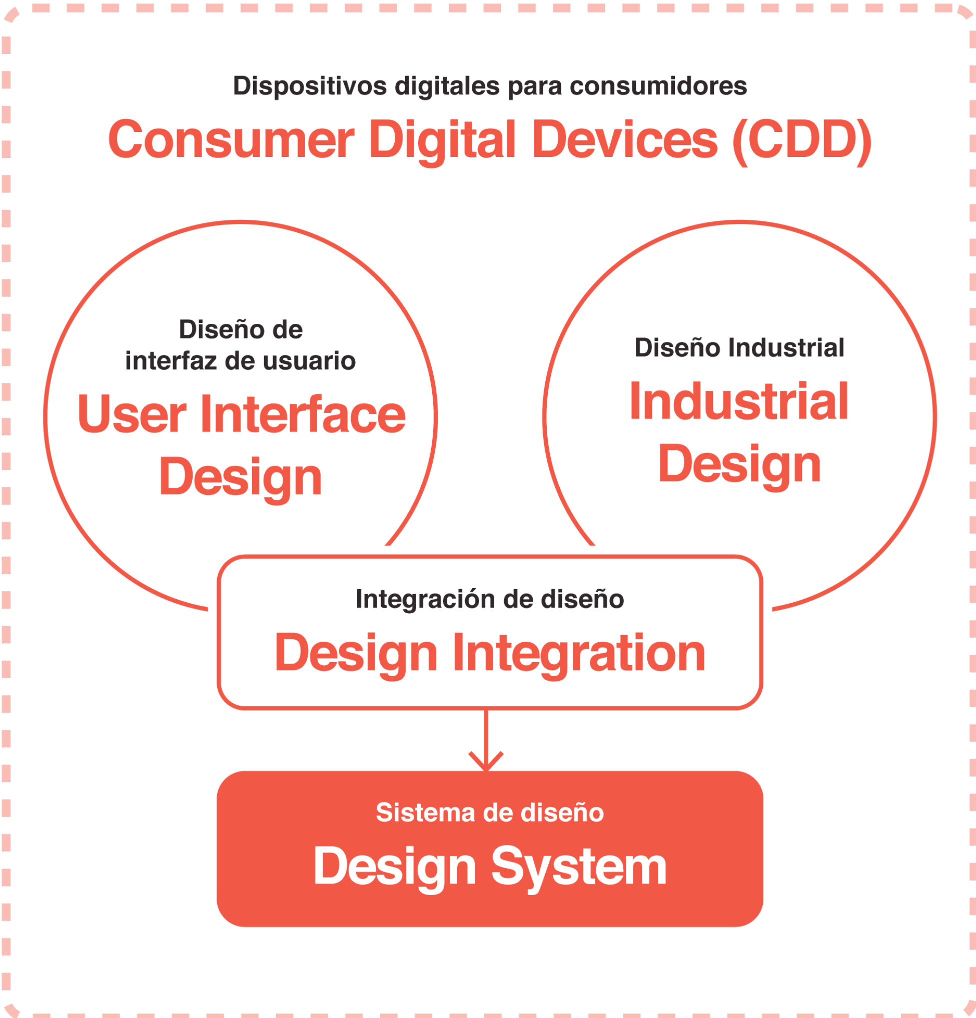

Figure 2 **Heda Weng**, (2019), *Keywords*. Courtesy of the author.

Definición y plan de investigación

Definition & Research Plan

Definition & Research Plan

Part 1 Introduction

1.1 General Introduction

Design is the fusion point of technology and humanity. As its name suggests, industrial design is born as a result of the development and evolution of technology and industry. The evolution of industrial design is heavily influenced by the development of technology and its social backgrounds.

The entry point of this research starts from the relationship between technology and society. Studying the history of industrial revolution, some theories with the intention to explain the impact of industrial technology on the society already surfaced as early as in the 19th century. During the 1920s, almost at the same time as the first capitalist crisis happened, the concept of "industrial design" took shape. Following the steps of the evolution of technology, industrial design has been developing its own theories ever since. With the birth of computers and digital devices, industrial design expanded from the construction of industrial products to the content that are displayed on the screens, creating one of its most significant branches, interface design. Today, under the umbrella of digital economy[1], the industry is seeing an exponential growth of content consumption; alongside, interface design developed its own innovations, which sometimes differs from classic industrial design theories[2].

This thesis studies the history of interface design, analyzes its evolution and investigates the connection between interface design innovations with hardware technology advancements. The thesis also analyzes the impact of classic industrial design theories on the interface design in Consumer Digital Devices (CDDs). Finally,

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[1] An economy based on digital computing technologies. Lately this term is especially referring to the economy that is conducting business through markets based on the Internet and World Wide Web.

[2] The theories for the process of design applied to products that are to be manufactured through techniques of mass production.

synthesizing these research results by establishing a bridge between recent interface innovations and classical industrial design theories, providing the possibility of the unification of theories for the design of both the hardware and the interface of CDDs, theoretically preparing the design for the next generation of digital products with advanced and enriched interactions.

1.2 Introducción General (en español)

El diseño es el punto de fusión entre lo tecnológico y lo humano. Como indica su nombre, el diseño industrial nació como resultado del desarrollo y la evolución de la tecnología y la industria. La evolución del diseño industrial está altamente influenciada por el desarrollo de la tecnología y sus antecedentes sociales.

El punto de partida de esta investigación es la relación entre tecnología y sociedad. Al estudiar la historia de la revolución industrial, en el siglo XIX ya surgieron algunas teorías con la intención de explicar el impacto de la tecnología en la sociedad. En la década de 1920, cuando se produjo la primera crisis capitalista, casi al mismo tiempo se formó el concepto de "diseño industrial". Siguiendo los pasos de la evolución de la tecnología, el diseño industrial ha estado desarrollando sus propias teorías desde entonces. Con el nacimiento de los ordenadores y los dispositivos digitales, el diseño industrial se expandió desde la construcción del hardware de los productos industriales hasta el contenido que se muestra en las pantallas, creando una de sus ramas más importantes, el diseño de interfaz. Hoy, bajo la economía digital, la industria está viendo el crecimiento exponencial del consumo de contenido; por lo tanto, el diseño de interfaz está desarrollando sus propias innovaciones, que a veces pueden ser bastante distintas en comparación a las teorías clásicas del diseño industrial.

Ésta tesis, que estudia la historia del diseño de interfaz, analiza su evolución e investiga las conexiones entre las innovaciones en diseño de interfaz con los avances de la tecnología de hardware, examinando a su vez el estado actual de los dispositivos digitales. La tesis analiza también el impacto de las teorías clásicas del diseño industrial sobre diseño de interfaz.

Sintetizando los resultados de investigación, la tesis establece un puente entre las recientes innovaciones de interfaz y las teorías clásicas del diseño industrial, ofreciendo la posibilidad de unificar las teorías del diseño de ambos, el hardware y la interfaz de dispositivos digitales para consumidores, poniendo como resultado las bases teóricas para el diseño de una próxima generación de productos digitales con interacciones multidimensionales y tecnologías más avanzadas.

1.3 Detailed Introduction

1.3.1 Technology, Society And Industrial Revolution

Technology in the Oxford Dictionaries

- *The application of scientific knowledge for practical purposes, especially in industry.*
- *Machinery and equipment developed from the application of scientific knowledge.*
- *The branch of knowledge dealing with engineering or applied sciences.*

The origin of the word “technology” in the English language could be traced back all the way to the 17th century, etymologically rooted in the Greek word “tekhnologia”, which means “systematic treatment”. Technology is practical and systematic, it is generally considered to be the application of science on society and people’s life.

Philosophers and economists have been studying the relationship between industrial technology and society since the 18th century. There has been a great quantity of philosophical speculations about the relationship between technology and society. With the first industrial revolution, when mass production products flooded into the consumer market, technology had its greatest impact on the society ever by the time. During the 19th century, systematic theories with the intention to explain the impact of technology on the society took shape, among them the most significant one was the technological determinism theory established by the American sociologist and economist Thorstein Veblen[3]. This theory assumes that “*a society's technology determines the development of its social structure and cultural values*” **(Kunz 2006, p.2)**; it seeks to show technical developments, media, or technology as a whole, as the key mover in history and social change.

[3] *Thorstein Bunde Veblen (1857 - 1929) was an American economist and sociologist who became famous as a witty critic of capitalism.*

As the American historian Merritt Roe Smith[4] assumed, technological determinism could be summarized as "*the belief in technology as a key governing force in society*" **(Smith 1994, p. 70)**. Of course, technology as a force brings a huge amount of benefits and advancements to the human world, but also leads to new questions to answer. The application of technology in the industrial revolution came with the aim to produce as much products as possible, in order to satisfy people's material needs by the time. Technology focuses on the increase of efficiency, but the demand of certain products within a society with certain population is limited.

As this conflict continues, in order to find a solution for the overproduction problem, industrial countries had to seek market for their products, which largely expanded the colonialism problem in the past. According to the United Nations list of Non-Self-Governing Territories, there are still different opinions about the political definition of today's dependent territories; however, with the independence of most ex-colonies, the past colonization system politically broke down during the 20th century. On the other hand, from the economic perspective the exportation of products and services is still the most common way for industrial countries to digest the excess production capacity. Politicians and economies still consider these behaviors as intents to control or influence other countries, especially former dependencies. However, on the other hand, overproduction also made globalization possible. Objectively, technology and industrial production did spread its own footsteps all over the world, completing a global production and supply chain, uplifting the overall life quality of the human race.

[4] *Merritt Roe Smith (1940 -) is an American historian. He is the Leverett and William Cutten Professor of the History of Technology at the Massachusetts Institute of Technology.*

1.3.2 Mass Production, Capitalist Crisis and the Birth of Industrial Design

Technology is granted the mission of the acceleration of the efficiency of the society, and it leads to an inevitable result of mass production as seen today. Beginning with the first industrial revolution in the 19th century, mass production eventually replaced the traditional handicraft industry, and we are seeing the impact of technology on the social development and the lifestyle of people growing in an exponential rate.

With the development of industrial technology, the human lifestyle saw its most rapid change ever. How do we understand this complicated relationship between technology and the society? Economists and philosophers have been discussing about it since the beginning of 20th century. During that time, the Frankfurt School[5] made a huge impact on social theory. These philosophers criticized both capitalism and consumerism. In their theories, the development of technology and industry made capitalist society “a rich society” or “an advanced industrial society”, as the working class no longer faces material shortage, it is not the main motivation of social revolutions as Karl Marx once predicted. In the meantime, it is believed that the definition of revolution nowadays is no longer the revolution of social structures, but the revolution of psychology or the structure of instinct of people. The instinct of human being is now limited with the industrial social culture, framing the liberal development of people.

If we trace back from the modern lifestyle to the industrial products involved in it, we could observe similar phenomenons. The application of industrial technology became an important factor on the improvement of people’s quality of life and the evolution of social culture: we are seeing more plentiful styles and categories of products than ever, yet the criticism about the devaluation of artistic value of the objects used in everyday life was also frequently appearing:

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[5] *A school of social theory and critical philosophy associated with the Institute for Social Research, at Goethe University Frankfurt.*

With the industry becoming increasingly efficient, the production workflow has become more standardized, and the products are becoming less unique.

Mass production led to an economic crisis in the early 20th century by overproduction: the supply of goods would grow beyond consumer demand, and so manufacturers turned to planned obsolescence[6] and advertising to increase consumer spending. Mass production led to an economic crisis in the early 20th century by overproduction, and this problem was most obvious in the automobile industry, as it was the “culprit” of all industries by that time: Henry Ford invented the concept of chained production and standardization, with largely improved the efficiency of car production. As a high value product, it was difficult to digest the excess capacity of the industry to colonies. The supply of goods would grow beyond consumer demand, and so manufacturers turned to planned obsolescence and advertising to increase consumer spending. That’s how consumerism was born: in 1924 when the automobile industry in the United States became saturated, General Motors head Alfred P. Sloan Jr. suggested annual model-year design changes to convince its consumers that a yearly unit replacement is necessary.

To convince the consumers that the new products are “revolutionary” and different from the old ones, the first thing came to people’s mind was to change the design and appearance of the products. Designers began to borrow the ideas from the Arts and Crafts movement in the 19th century, adapting them to industrial production, and that’s how Industrial Design was born. Heavily influenced by the Arts and Crafts movement[7] himself, the German architect Peter Behrens[8] is often considered as the first industrial designer in history.

Standing on the crossroad between technology and the liberal arts, industrial design becomes a modern study object which moderates the conflict between

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[6] *In industrial design and economics, is a policy of planning or designing a product with an artificially limited useful life, so that it becomes obsolete after a certain period of time.*

[7] *An international trend in the decorative and fine arts that began in Britain and flourished in Europe and America between about 1880 and 1920*

[8] *Peter Behrens (1868 - 1940) was a German architect and designer who was important to the modernist movement.*

mass production and people's aesthetic needs; it humanizes the stiff image of mass-produced products and provides an optimization on user experience. From a certain viewpoint, industrial design sticks art and technology together, then the market promotes them as commodities with an expiration date. However, an interesting phenomenon that could be observed is that consumerism is generally considered as the culprit of waste, however in the meantime industrial design became an important origin of innovation and diversity for the industry. As the American historian Melvin Kranzsberg[9] once said, "*Technology is neither good nor bad; nor is it neutral*" **(Kranzsberg, cited in Mims 2017)**, the way how technology changed people's lifestyle depends on how it is applied. Any object in existence is born with two-sidedness. In the case of technology applied on mass production, industrial design is the humanistic side of technology in the consumer market, its theories has become the concentrated expression of the aesthetic and philosophical value of consumer products.

[9] *Melvin Kranzberg (1917 - 1995) was an American historian. He was one of the founders of the Society for the History of Technology in the US and long-time editor of its journal Technology and Culture.*

1.3.3 Digital Economy And Graphical Interface Design

The evolution of industrial design keeps up the pace with the development of mass production and consumerism. With the rise of digital economies and creative industries in the 21st century, we are standing at a new turning point for consumer market. The representation of consumerism is no longer limited to the consumption of products; content and services are becoming an equally important part of modern lifestyle.

The digital mutation of the industry and society adds a new focus point to industrial design: a broader concept for the interface. Interface smoothes out the stiffness in the communication between consumer and device by adequately presenting the information. As the summation of the communication between a system and its user, the interface is not only physical but also visual and symbolic. The popularization of digital devices brought the interface beyond physical controls such as knobs, buttons and switches; digital interface is directly displayed on screens and controlled by general purpose input devices such as keyboard or mouse. With the invention of computers, user interface design branched off from industrial design while its main purpose expanded from the design of physical controls to the design of on-screen interaction between computing devices and their user. Since the early years of computer science (1950s and 1960s), the concept of digital user interface and "apps"[10] has been imagined and predicted, some of these studies were even focused on the use in the consumer market, which went beyond the scientific and industrial purposes of the creation of computers by the time. Some early explorations of interface could be observed in the works of Norbert Weiner[11]and Alan Turing[12] ; the Cybernetic Serendipity exhibition in 1968 at London already had an independent

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[10] Abbreviation for the word "applications". In modern media, this term generally refers to applications in mobile platforms, such as smartphones, tablets or watches.

[11] Norbert Wiener (1894 - 1964) was an American mathematician and philosopher. He is considered the originator of cybernetics, a formalization of the notion of feedback, with implications for engineering, systems control, computer science, biology, neuroscience, philosophy, and the organization of society.

[12] Alan Mathison Turing(1912 - 1954) was an English mathematician, computer scientist, logician, cryptanalyst, philosopher and theoretical biologist. He is the creator of the concepts of algorithm and computation with the Turing machine, which can be considered a model of a general-purpose computer.

part for computer art and some early interface design concepts. After the development of almost a century, the definition of interface design has been largely enriched; it became an indispensable part of modern industrial design and has developed a huge amount of its own theories.

Studying the history of interface design, a faster pace of evolution could be observed compared to industrial design in general. This mainly results from the fact that interface rendering has a tight relationship to the application of graphical and display technology. For a long time, a borderline between the physical world and the digital world could be observed. However, this phenomenon is changing during the last decade with the popularization of smartphones and mobile internet: with the evolution of display technology, pixels became indistinguishable under the observation of human eyes; the expansion of color gamut and High Dynamic Range (HDR)[13] technology made the colors of the digital world more vivid than ever; the recent exploration of OLED[14] and microLED[15] technologies provides the possibility of bendable and transparent displays, creating more possibilities for augmented reality (AR)[16], virtual reality (VR)[17], mixed reality (MR)[18] and wearable devices, elevating the importance of digital content consumption to the highest level in history. Meanwhile, the exploration of the concept of Internet of Things (IoT)[19] emancipates the interface from displays: these devices themselves generally do not include displays, we control them with various ways such as our voice, our touch and our gestures; when a display is needed, there is still the possibility of observing the status and controlling the

[13] *A dynamic range that is higher than the standard dynamic range. This term is generally used in describing the quality of digital audio or video.*

[14] *Organic light-emitting diode (OLED) is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current.*

[15] *An emerging flat panel display technology. microLED displays consist of arrays of microscopic LEDs forming the individual pixel elements.*

[16] *An interactive experience of a real-world environment where the objects that reside in the real-world are "augmented" by computer-generated perceptual information.*

[17] *An interactive computer-generated experience taking place within a simulated environment.*

[18] *The merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time.*

[19] *The extension of Internet connectivity into physical devices and everyday objects.*

device from the smartphone which stays in our pocket. The line between the physical world and digital world is blurring, as display is losing its rectangular form since its birth and the physical objects are becoming the interface itself.

Artists have long been imagining the type of interface that floats beyond the physical devices. Technological imaginary starts at the beginning of films. We could already observe some early hints of this kind of interface in the movie "Le Voyage dans la Lune" (A Trip to the Moon) created by the French director Georges Méliès[20] back in the year 1902. The imagination of digital interfaces further developed in successful science fiction movies such as Star Trek, Matrix and Minority Report, and now they all become the inspirations of the interface in the next generation of CDDs.

As designers and digital artists, we are standing at the point in history where we finally go beyond the edge of display: adapting to the removal of technological limits on the display, it could be observed that classical industrial design theories and characters are increasingly applied to the interface world; imagining a future with the disappearance of the line between physical world and digital world, it becomes necessary that industrial design absorbs and digests the fruit of interface design. Studying the recent technological achievements applied on Consumer Digital Devices (CCDs) and its impact on the design world, this thesis explores the possibility of the integrated future between classical industrial design theories and interface innovations.

[20] *Marie-Georges-Jean Méliès (1861 – 1938) was a French illusionist and film director who led many technical and narrative developments in the earliest days of cinema.*

Part 2 Object of Study

This thesis investigates the integration of classical industrial design theories and interface design innovations on Consumer Digital Devices. From the point of view of subject classification, interface design is the branch of industrial design that focuses on the human-computer interaction. As an outcome of the development of technology and economy, we need to take the historic and social background of both interface design and industrial design into consideration, select an adequate range for the object of study, and focus on the theoretical and practical relationship between them.

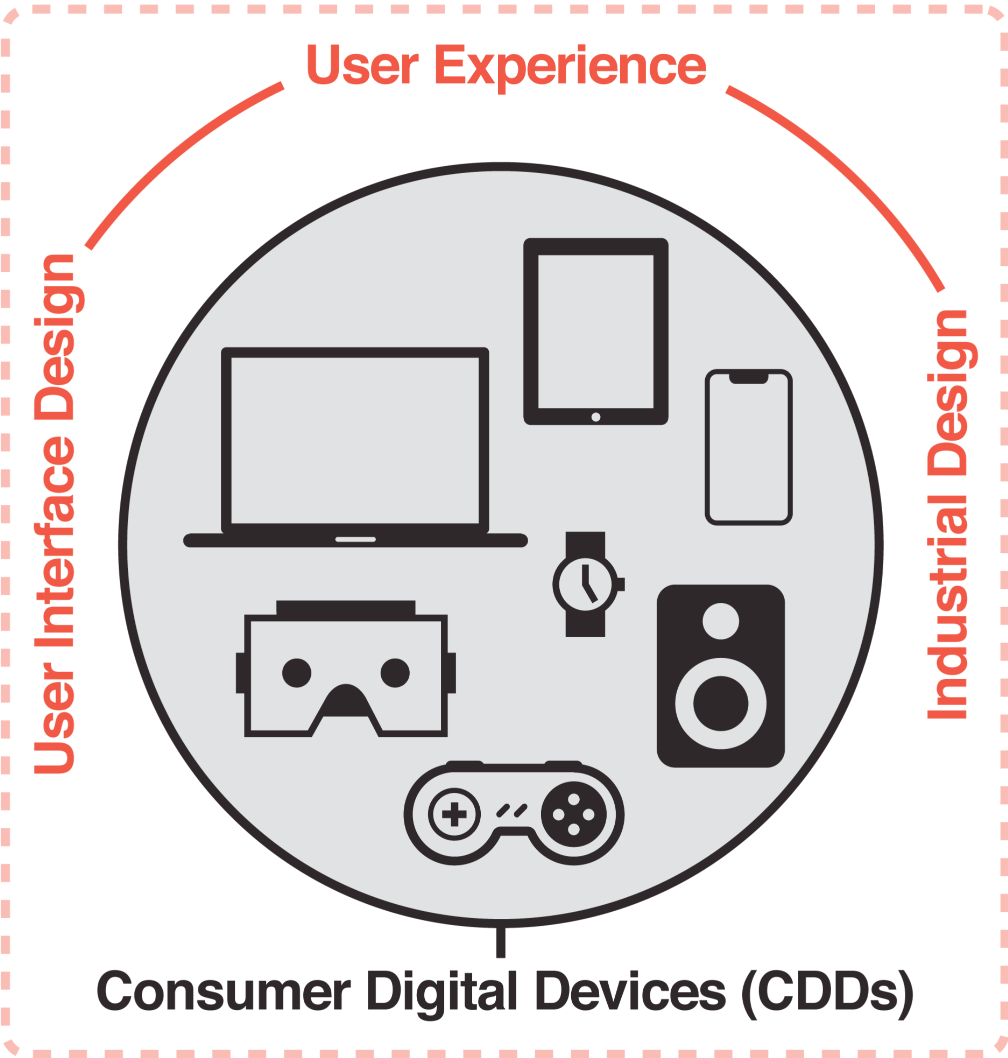

Figure 3 **Heda Weng**, (2019), *Object of Study*. Courtesy of the author.

2.1 Graphical User Interface (GUI) Design and Its History

In the family tree of industrial design studies, graphical interface design is a relatively new branch. For a better understanding of the relationship between interface design and its technological basis, we need a panoramic view of the history of interface. Since the birth of computers, there has been a few phases of the development for the generalized concept of “interface”: batch interface, command-line user interface, text-based user interface, and graphical user interface.

As this study roots in the field of fine arts, our thesis mainly focuses on graphical user interface.

The origin of graphical user interface could be traced all the way back to the 1950s, almost at the beginning of computers. In Norbert Weiner and Alan Turing’s early encounters, we could already observe their foresight and early concept of how people would interact with computers in the future. In the decade of 1960s, early prototypes of graphical user interface were already exhibited. In 1968, Douglas Engelbart[21] demonstrated NLS (the “oN-Line System”), the first prototype which already introduced the concept of mouse, pointers, hypertext, and multiple windows. During the 1970s, more investigation about GUI appeared all over the world of computing, among these research achievements, the most significant happened in the Xerox Palo Alto Research Center[22], where the WIMP (Windows, Icons, Mouse, Pointers) paradigm was first established, which would be the theoretical basis of GUI in the PC-era. After some commercial failures on early intents of GUI on personal

[21] *Douglas Carl Engelbart (1925 - 2013) was an American engineer and inventor, and an early computer and Internet pioneer. He is best known for his work on founding the field of human–computer interaction, particularly while at his Augmentation Research Center Lab in SRI International, which resulted in creation of the computer mouse, and the development of hypertext, networked computers, and precursors to graphical user interfaces.*

[22] *PARC (Palo Alto Research Center; formerly Xerox PARC) is a research and development company in Palo Alto, California with a distinguished reputation for its contributions to information technology and hardware systems.*

computers such as the Xerox Alto[23] and Apple Lisa[24], the first popularized personal computing device in the consumer market based on graphical user interface was born in 1984, the Apple Macintosh. During the next two decades which we call the PC-era today, the WIMP paradigm was largely unchanged, but the graphical user interface was advancing in a fast pace with the development of display technologies and the growth of computing power on these devices: colors were added, windows became resizable, a huge amount of details were added to the interface elements, such as gradients and shadows. In the decade of 1990s, some early intents of touch-based user interface also appeared on the market. With the beginning of 21st century, the world welcomed the post-PC era. A new generation of GUI comes with a new generation of Consumer Digital Devices represented by smartphones and tablets. Extra input methods such as the mouse and physical keyboard were removed, and displays began to occupy a larger part of the visible surface of these devices. In recent years, new categories of personal digital devices came out in the consumer market, such as augmented reality / virtual reality / mixed reality devices, wearable devices and internet of things devices. Each of these categories of devices explores a new field of interaction, and these devices are becoming even more intimate with people's everyday life; in the meantime we are still seeing constant adjustments on the interface of these products today. With the popularization of these devices, new paradigms of user interface are expected to be formed.

Viewing the history of GUI, there are some important conceptual relationships that should be taken into consideration:

- First of all, the development and advancements of display technologies and graphical computing power;
- Secondly, the birth of new generation of Consumer Digital Devices and the simplification of input method;

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[23] The first computer designed from its inception to support an operating system based on a graphical user interface (GUI), later using the desktop metaphor.

[24] Released in 1983. It is one of the first personal computers to offer a graphical user interface (GUI) in a machine aimed at individual business users.

- Thirdly, the expansion of usage scenarios, as computing devices with GUI are more and more deeply integrated in people's personal life.

2.2 The Industrial Design of Consumer Digital Devices (CDDs)

CDDs are the basis of the consumption of content and services in the digital industry. For a clearer definition, these devices have the following characteristics:

- **First of all, a digital device.** These devices fall in the generalized concept of computers. A CDD should have its own computing power and its technical basis.

- **Secondly, a device targeting the consumer market.** These devices provide ways for the consumption of digital content and services of various forms, including rich-texts, images, audio, video and other formats of information.

- **Thirdly, a device that integrates with graphical user interface.** As the main purpose of this thesis is focus on the relationship between industrial design and interface design, GUI is a decisive element. Also, it should be taken into account that a device integrated with GUI does not necessarily mean that a display is included: For example, the GUI of internet of things devices is possibly represented on smartphones as these devices are generally not equipped with displays.

With the definition mentioned above, during the research process, the study should focus on the industrial design of these categories of devices:

- Personal Computers;
- Smartphones;
- Tablets;
- Gaming consoles;
- AR (Augmented Reality), VR (Virtual Reality) and MR (Mixed Reality) devices;
- Ultraportable and Wearable devices, such as smart watches;
- Internet of things devices, such as smart speakers (with physical and voice interface) and smart displays.

2.3 The Overall User Experience (UX) of Consumer Digital Devices (CDDs)

In this thesis, both the GUI design and the industrial design of CDDs are studied. To us designers, these are two design branches; meanwhile for consumers, people purchase these products as a whole: an average consumer would not evaluate the software and the hardware of a product separately.

Users perceive the material part and the immaterial part of CDDs as a whole piece. The design quality of both hardware and software results in the overall UX of CDDs. The interface of these products generally uses metaphors from the physical world; in the meantime, in recent years, the hardware design of these products are moving forward on simplicity to better match their interface design.

As the industry is moving forward, the digital world is blending with the physical world on these products. On the interface side, following the rules of the physical world would reduce the learning curve of the new features on the platform. On the hardware side, making the product as simple as possible would make the physical object almost “disappear”, reducing the distance between the content of the screen and the content of the environment. From this aspect, providing a seamless and emerging UX is the ultimate goal of the design of these product. As a result, it is necessary to set user experience as another object of study for this thesis.

Part 3 General and Specific Objectives

3.1 General Objectives

3.1.1 Exploring Design Achievements on Consumer Digital Devices (CDDs) Beyond Political Economy Limitations

As industrial design is born with the rise of mass production and consumerism, its political economic attributes should be taken into consideration. In the meantime, with the intention of discovering the design achievements in an aesthetic way, it is necessary to study the political economics[25] background of the devices but also to look beyond these limitations.

It is part of our investigation process to cherry pick the design advancements of CDDs from the practical compromises caused by mass production and market limitations. Important political economics theories should be studied for this objective, including theories like technological determinism and consumerism. For the same reason, the technological and social background of CDDs should also be taken into consideration, a better understanding of related theories such as the Moore's law[26], the Gresham's law[27], and the product lifecycle[28] is also necessary.

The design of CDDs is born with compromises, as the success of such products requires the mitigation of difficulties in mass production, the economic analysis of the input-output ratio and the acceptance of new ways of interactions from the general public. However, as a category of products with one of the most extensive range of audience, CDDs is a huge stage for designers to introduce

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[25] The study of production and trade and their relations with law, custom and government.

[26] The observation that the number of transistors in a dense integrated circuit doubles about every two years. The observation is named after Gordon Moore, the co-founder of Intel.

[27] A monetary principle stating that "bad money drives out good". Applied to the market of consumer products, it can be interpreted as products with fair prices and covers the essential functionalities would occupy the majority of marketshare.

[28] The process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products.

their innovations to the general public. For a better research on the design achievements on CDDs, it is important to analyze the political economic factors on these products and to broaden the vision beyond these limitations.

3.1.2 Summarizing the Design Value of Consumer Digital Devices (CDDs)

As products targeting the consumer market, CDDs are complex, they include an integration of technological considerations, marketing considerations and design considerations. For a better summary of the design value of both the interface and the industrial design of these products, an aesthetic viewpoint is adequate and reasonable.

Zhu Guangqian[29], an important aesthetician and philosopher in modern Chinese art history made a summary that, 3 kinds of attitudes should be taken into consideration: *the scientific attitude, the practical attitude, and the aesthetic attitude*. **(Zhu, cited in Shim 2008, p.27)**

Specifically in the field of CDDs, the consideration of the 3 attitudes could also be established:

- **The scientific attitude** represents the physical and technological basis of a Consumer Digital Device. This material foundation is considered the cause of design compromises in some situations, but most importantly, it defines what the device is.
- **The practical attitude**, which could be translated to the important principle associated with 20th-century modernist architecture and industrial design, "form follows function". This attitude defines why and for whom the device is designed.
- **The aesthetic attitude** represents the style and design language on a product; it would include the personal taste and experience of a designer, also maintaining the overall image for the device in the market. It defines how the device looks like, and more profoundly, what is the abstract concept of this product, and how it would impact on the society.

[29] Zhu Guangqian (1897 - 1986) was one of the founder of the study of aesthetics in 20th-century China.

Combining with the limitations mentioned above in 3.1.1, these attitudes help us to distinguish the design characters of a device come from the compromises caused by mass production and public acceptance and the design characters mainly driven by the industrial designer's subjective initiation.

As Steve Jobs once said, "*It is technology married with liberal arts, married with the humanities that yields us the results that makes our heart sing*." **(Jobs, cited in Apple 2011, 1:08:30)** Consumers' aesthetic and functional needs motivates the design of devices, the higher standard of design requires the mitigation of compromises, and this mitigation requires the evolution of hardware technology. A properly designed CDD represents the balance between the aesthetic evolution and the hardware technology evolution. With the viewpoint of the three attitudes, this thesis intends to analyze the CDDs with a balance of their technological aspect and their aesthetic aspect, ultimately trying to achieve the goal of summarizing the design value of these devices.

3.1.3 Revisiting the Design History for Consumer Digital Devices (CDDs) and Analyzing Their Design Demands in the Post-digital Era

As devices facing a broader public, CDDs' design generally corresponds to the specific trend of how people consume content in each era. Revisiting the design history for CDDs could help us while trying to analyze the content consuming behavior of people in the post-digital era[30] hence coming up with key design requirements for the next generation of devices.

The history of CDDs began with the rise of the 3rd Industrial Evolution[31]. In the beginning of Industry 3.0, computers and automation were introduced as a way to improve the efficiency of industrial production, eventually expanding their appearance in the professional and consumer market. Viewing the market of today, each CDD has its own "computer" inside, and each generation of these devices appears with a more intimate involvement in people's everyday life. The evolution of industrial and computing technology made the miniaturization of computers possible, which served as the technological basis of each generation of CDDs. On the other hand, from a consumer's point of view, the evolution of these devices made content and information easier to access and faster to digest.

Revisiting the history of CDDs during the Industry 3.0 era, there are two most obvious trends:

- **First of all, the miniaturization of devices mitigated the time/ space limitation of data consuming.**

  In the era of PC and the introduction of internet, people need to be always at their desk, and sometimes even have to download content while they have internet access, store them on storage medias like floppies, CDs, and hard drives, then consume the content on their own devices. In the era of smart phones and tablets, people have these devices in their pockets and consume

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[30] *The era of the rise of an attitude that is more concerned with being human, than with being digital.*

[31] *The shift from mechanical and analogue electronic technology to digital electronics which began anywhere from the late 1950s to the late 1970s with the adoption and proliferation of digital computers and digital record keeping.*

information from the internet whenever and wherever as long as cellular connection is available. With the introduction of wearable devices, data consuming begin to adopt a proactive character: instead of taking their devices out, people would receive push notifications on their wearable devices, and decide if they would like to get more details.

- **Secondly, portable digital devices with single purpose getting replaced with general computing platforms as soon as technology permits the size decrease of the latter.**

  In the PC era, there were various categories of digital devices with single purpose that could be considered as "accessories" of personal computers, as updates of their content generally depends on the connection to the PC. Examples of these devices includes iPods, digital cameras and ebooks. Nowadays, we see these device categories gradually disappearing with the enrichment of the functionalities of smartphones. Same thing is happening with wearable devices: as soon as the smart watches are getting independent LTE connection, the market of workout health sensors and ultraportable music players is being quickly encroached.

As mentioned above, there are two main factor of the evolution of CDDs that could be summarized: the format of content consuming and the evolution of hardware technology. Combining these two factors with the era we are living in right now, we see two important transitions:

- **Firstly, the transition from Industry 3.0 to Industry 4.0.**

  The term of Industry 4.0[32] is introduced in the world of manufacturing technologies to describe the current trend of automation and data exchange in mass production. Industry 4.0 fosters what has been called a "smart factory". Within modular structured smart factories, cyber-physical systems monitor physical processes, creating a virtual copy of the physical world and making decentralized decisions.

[32] *A name given to the current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems, the Internet of things, cloud computing and cognitive computing.*

This industrial transition corresponds to the trend of Internet of Things in the consumer market. Up to now, CDDs generally include a “computer” of its own, serving as a central hub to control the user’s digital accessories, similar to the situation in history when PC serves as the central hub for MP3 players and digital camera. Industry 4.0 in mass production would push Internet of Things forward, gaining internet access for more digital accessories in the consumer market, such as smart home devices, speakers, car mounted displays and televisions. Once these devices get the access to Internet independently, they would move forward a single step to gain their own computing power and make decentralized decision to provide proactive content for their consumer. The time and place of data consuming would see its further extension as we see the increase of the disruption of the type of connections between a certain type of digital content and a certain type of digital devices.

- **Secondly, the transition from digital media to moist media.**

Roy Ascott[33] used the term “moist media”[34] to describe the emergent confluence in media art of (wet) biological processes and (dry) computational systems. Moist media was his imagination of how the future of media would be in the post-digital era. It describes how art would be created and distributed: representing a multiplicity of media, configured and manipulated in an infinite number of ways by distributed authorship, publication, and distribution. **(Ascott 2000, p.4)**

The multiplicity of media implies the emancipation of content consuming in a certain format, creating the possibility to adapt digital information to an extensive range of devices, separating content from its hardware basis.

In conclusion, revisiting the history of CDDs’ design, we could achieve a better comprehension of how digital content is unchaining from physical devices, and

[33] *Roy Ascott (1934 -) is a British artist, who works with cybernetics and telematics, on an art which is technoetic, focusing on the impact of digital and telecommunications networks on consciousness.*

[34] *In response to developments in new media art around the turn of the millennium, the term moist media was coined by Roy Ascott to signal the emergent confluence in media art of (wet) biological processes and (dry) computational systems*

further analyze the demands of data consuming in the post-digital era. The borderline between digital content and physical object would become much more blurry, giving birth to a unified design system for both worlds.

3.1.4 Bridging Between User Interface Design And Classical Industrial Design Theories

The most important general objective of this thesis is to compare and sum up the achievements on both the industrial design and the interface design of CDDs.

In a typical process of industrial design, the designer needs to find the adequate material according to the functionality, taking advantage of the character of this material and finding the adequate processing technique.

Similar to the physical materials used in the world of industrial design, graphical user interface design uses “digital materials”, namely, interface elements in the digital world. The characters of these “digital materials” normally varies according to the limitations of the display technology and graphical power on the current device.

With the discovery and experiments of new materials, the display technology industry has been revolutionizing in a fast pace during the last few decades; under Moore’s law, the processing and graphical power on digital devices in the consumer market has been growing geometrically, which means new digital materials are also being created. With the rapid development of display technologies, intents of revisiting classical industrial design theories in interface design workflows have become increasingly frequent.

Industrial design defines the physical part of the device, interface design defines the digital part of the device. Bridging between user interface design and classical industrial design theories as a general objective of the thesis would create the opportunity of summarizing a more unified design theory, as the borderline between the physical (material) part and the digital (immaterial) part of the devices is becoming blurry.

3.2 Specific Objectives

3.2.1 Researching the History of Graphical User Interface (GUI) Design

As a research area branched from industrial design, GUI design has been revolutionizing in a fast pace during its seven decades of history.

Researching the history of GUI design helps us to understand the aesthetic and technological factors that have been contributing to its evolution.

- **The aesthetic factor: GUI design frequently gets its inspiration from cases of traditional graphic design and visual communication.** GUI design is standing on the shoulder of the past research achievements of graphical design. As an example, we can easily relate the visual style of the icon grids in modern mobile operating systems to the ideas of the square icons with rounded corners designed by Lance Wyman[35] for the 1968 Olympic Games in Mexico City. The International Typographic Style (Swiss Style)[36] originated in the 1920s has been a major influence behind the recent wave of "flat" design language represented by the redesign of iOS 7 and Google's Material Design.

- **The technological factor: Computing devices are considered as the material basis for graphical user interface.** Studying the history of the material basis of CDDs helps us to distinguish the legacy standards and tools preserved in the workflow of modern day GUI design. The level of hardware technology defines the peak that interface rendering could reach in a certain era. As an intention to keep backward compatibility, traces of legacy graphic standards designed for inferior devices could be found easily in modern systems. Here's an example that we experience everyday without noticing:

[35] *Lance Wyman (1937 - present) is an American graphic designer. He is known for his work under Pedro Ramirez Vazquez, design concept and direction, in developing applications of the Mexico 68 logo in Ramirez Vázquez's personal office in Mexico City.*

[36] *A graphic design style that emerged in Russia, the Netherlands, and Germany in the 1920s and was developed by designers in Switzerland during the 1950s. As a part of the modernist movement, it emphasizes cleanness, readability, and objectivity.*

The 216 “web safe colors”[37] widely used in modern CSS originated from the end of the 90s, when CRT displays with limited color gamut[38] were the mainstream monitors for the PCs.

Researching the history helps us to comprehend the impact and inspiration from related academic areas on GUI design of CDDs.

[37] *In the mid-90s, many displays were only capable of displaying 256 colors. A color table of 216 colors was created with the intent to show the same colors on webpages across displays.*

[38] *In color reproduction, including computer graphics and photography, the gamut, or color gamut, is a certain complete subset of colors.*

3.2.2 Comprehension on the Relationship Between Hardware Limitations And Interface Rendering

As mentioned in 3.2.1, the limit of hardware power contributes as an influence factor to interface rendering along the history of user interface design.

There are many well known examples of this relationship: the pixels in GUI elements were always distinguishable to users until the day that "Retina Display"[39] - the first ultra-high pixel density display was revealed; in some earlier versions of PC operating systems such as the Windows XP, when user intends to move something on the screen with mouse, a rectangular - instead of the actual interface element - was rendered to indicate this movement... Certainly, these facts of lack of details on the interface were results of compromises between the original design concepts and the actual computing power that a CDD could provide.

In order to gain a better comprehending on the relationship between hardware limitations and interface rendering, not only the GUI languages that have been released alongside the CDDs in the market need to be researched. It is also necessary to compare the design concepts and patents from the manufacturers with the actual products, in order to find out the compromises due to the limited hardware power.

[39] *Retina display is a brand name used by Apple for its series of displays that have a higher pixel density than traditional displays.*

3.2.3 Studying the Application of Classic Industrial Design Theories on User Interface

As the hardware power grows in an exponential way under the umbrella of Moore's Law, the precision of graphical rendering for GUI elements and their animations has become a recent design focus on CDDs.

Designers came up with many great ideas of how GUI interface elements could be pshycoligically more related to real-life object, in order to take advantage of the extra graphical power to make the interface more user friendly.

At the beginning of this trend, the interface improvements were focusing on the imitation of physical materials. Skeuomorphism[40] was the main character of this era. In a typical software product during the decade of 2000s, we could observe a wide usage of textures in interface rendering, such as the "frosted glass" in Windows Vista, the "brushed metal" in Mac OS X 10.3 "Panther", and the "linen" of the early versions of iOS. This trend quickly caused inconsistency, logical confusion and waste of resource on CDDs. These interface elements only "looks like" real life materials instead of "behave" like physical products, as they were designed under the guide of GUI design theories.

In order to restore simplicity, the "flat" revolution quickly overtook the space of skeuomorphism in the interface of CDDs. The vision of GUI designers expanded to the achievements of industrial design theories. For example, instead of using simple rounded corners, the icons on the phones are now rendered with curvature continuity[41], a concept widely applied in the design of physical products; instead of using illustrations, some interface elements are directly rendered in 3D softwares, which are widely used in industrial design. These applications of industrial design theories improves the coherency between the virtual interface and the physical device, making them "behave similarly".

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[40] *Skeuomorphism is a design style that praises the usage of derivative objects that retain nonfunctional ornamental design cues (attributes) from structures that were inherent to the original.*

[41] *In industrial design, this refers to the calculations that process the transition between straight lines and curves in order to visually smooth out the change of curvature.*

Looking into the future, with AR, VR and MR technologies, the border between the display and the physical device will become more and more blurry in the user's perspective. The application of industrial design theories on GUI will be further expanded, eventually unifying the design languages of both worlds.

3.2.4 Summarizing the Influence of Interface Design Trends on the Industrial Design of Consumer Digital Devices (CDDs)

In addition to the influence of industrial design theories on interface design, GUI design trends also has an impact on the physical devices.

Looking beyond the pixels and frame rate, conceptually GUI design seems more "idealistic" for designers: there are less engineering limitations on the distribution of elements, no seams are needed in order to attach the virtual materials... On the way of improving the coherence between the software and the hardware of CDDs, industrial designers sometimes simulate digital materials in their design.

Researching the most recent and advanced CDDs in the market, there is a phenomenon that manufactures getting obsessed with "seamless" unibody designs. At the beginning of this trend, industrial designers intend to reduce the physical parts of the assembly in order to make the device look like a single piece of material. Nowadays, this trend has evolved to the next level: conceptually, industrial designers are achieving a certain level of dematerialization to CDDs, upgrading the aesthetic level of the design of these products. A great example would be the "Jet Black" color of the iPhone 7. The assembly is mainly made of glass and aluminum, however, with the special process of polishing and anodization, the aluminum part of the device loses its metal feel and gets fully integrated with the glass display. Conceptually, this new trend of industrial design is floating above the physical character of the materials, making the imaginary of the device more abstract. This is clearly influenced by the enthusiasm of "flat" and simplicity under the current trend of interface design.

Summarizing the influence of interface design trends on the industrial design of CDDs makes the design of the whole device (including its software part and hardware part) conceptually more coherent, elevates the imaginary of the physical product, and potentially adds more aesthetic value to these products in the consumer market.

Part 4 Hypothesis

This thesis intends to answer a question: What will be the relationship between interface design and industrial design in the next generation of Consumer Digital Devices (CDDs)?

We have the hypothesis of this thesis:

A connection point between classical industrial design theories and modern innovations in the world of interface design can be found, and the future of CDD requires a universal design system for both its hardware and software.

Consumer Digital Devices were born with the mission to facilitate the obtention and usage of content for personal use. As personal devices, they came with the characteristics of media. In order to further improve the efficiency and accessibility of these devices, the design of both their hardware and their software should take the presentation of information as the centerpiece, as the design for both parts are serving the same target. As a result, creating a unified system for user interface design and industrial design for Consumer Digital Devices would further improve the integrity and coherence of these devices, theoretically preparing design studies for the next generation of devices like wearables, Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) devices, adapting to the world when information is freed from a certain form of device serving as its carrier.

In order to achieve a unified theory of user interface design and industrial design and an integrated future for the design of CDDs, it is important to take various factors into consideration:

- **First of all, investigate the pace of current hardware technology in the area and analyze the industry trends.** Liberating the information from a certain type of device is not equal to the elimination of devices. The integration of user interface design and industrial design of CDDs does not mean the former is more important than the latter. As the substance basis for the presentation of information, although we are facing less technological limitations, it's important to have the horizon of technology in mind, and summarize the possible controlling factors for the industrial design of CDDs in the next decade.

- **Secondly, from the history of user interface design, summarize the gains and losses of past attempts of bringing the visual styles or industrial design theories to the interface world.** Although there has not been a unified theory system for the integration, attempts to apply physical disciplines to the world with the displays are getting increasingly frequent in the consumer market. From the pseudo-3D interface rendering in the video games in the 1980s, the first intents of the introduction of perspective rendering in generic personal computing platforms in the 1990s, the introduction of z-axis rendering in the early 2000s to the swing phenomenon between skeuomorphism and flat design trends in the last decade, these acts taught us designers some precious lessons. As some of these attempts made to the consumer market and were introduced to the generic public, it could serve as an important experimental evidence for the integration of user interface design system and industrial design system on CDDs.

- **Thirdly, going beyond consumer devices that has been released in the market, and investigate the most recent theoretical and conceptual advancements on the design of CDDs.** As a result of mass production, objects in the consumer market come with compromises and limitations from the current industry level. However, designers would prepare the concepts and prototypes of new generations of devices, which also serves as a great motivation for the advancements of industrial technologies. As a thesis facing the future of design in the consumer market, it is very important to search not only the patent catalog of the industry leaders like Apple and Google, but also the recent theoretical and practical achievements on industrial design and user interface design in universities and important design agencies. This research process provides a panoramic view of the current directions that the industry is working on, and we could select one or more of these directions as the standpoints of this thesis.

Part 5 Status of the Subject of Study

5.1 Status of Subject

5.1.1 Status of Industrial Design on Consumer Digital Devices (CDDs)

Since the beginning of personal computers, the form factor of CDDs has always been revolutionizing. Each form factor of a category of CDDs corresponds to an established paradigm of interaction, for example:

- The WIMP (windows, icons, menus, pointer) paradigm defined the personal computer category;
- The touch screen interaction paradigm defined the smartphone category;
- The touch-stylus interaction paradigm defined the tablet for productivity category.

We are standing at an important turning point for the industrial design of Consumer Digital Devices as new paradigms of interaction are emerging:

- Smartphones have become an essential part of personal and professional life in the modern society, and the competition of both the hardware market and the software market have entered the homogenization phase. In a market mainly depending on the update decisions of current users, consumers have higher expectations on product design. As a result of its physical characters, the most perceivable image of a smartphone is its display. Internal and external consistency would significantly enhance the sense of the design quality of a smartphone. In recent years, the market sees a growing trend of higher screen-to-body ratio.

- With the emerging AR (Augmented Reality), VR (Virtual Reality) and MR (Mixed Reality) display technologies, the interface is no longer limited within a certain "display area" whose edge is clearly acknowledgeable by an average consumer.

- CDDs are manufactured with more sensors than ever. At the beginning of personal computers, the machine is depending on the commands that come from the inputs devices such as the keyboard and the mouse. As of now, a device as small as a smart watch get several microphones, a touch screen, an ambient light sensor, a gyroscope, a heart rate sensor, etc. These devices are getting much more powerful but physically smaller. CDDs are getting into the most intimate relationship ever with customers in their everyday life. Interface interactions are no longer limited to the display area as we see other types of output methods in the market of CDDs, such as sounds, vibrations and haptic feedbacks.

With all of the new characters of the CDD market mentioned above, taking the technology advancements into account, it’s becoming very clear that the design of CDDs is standing at the point of entering a brand new “holographic" era. Interface is becoming more and more “physical”, merging into the reality world, making the edge between the display and the physical body of digital devices less significant with every generation of devices, eventually merging the industrial design and the interface design of CDDs.

5.1.2 Status of Graphical User Interface (GUI) Design Studies on Consumer Digital Devices (CDDs)

The first commercially successful CDD with graphical interface was the original Macintosh (sometimes referred to as Macintosh 128k) in 1984. However, user interface design has a much longer history than that. Early computer research undertaken by Norbert Werner and Alan Turing already looked into concepts and definitions of the idea of graphical user interface. For computing devices, interface design dates back even further. The mechanical controls interaction on the very first mechanical and programmable computing machine (the Analytical Engine) made by Ada Lovelace[42] and Charles Babbage[43] marks the beginning of human-computer interaction. Throughout the decades-long design history of computers, physical controls are gradually getting replaced with graphical interface as computing devices are getting more compact. In the meantime, GUI took inspirations from physical objects to smooth out its learning curve.

Another interesting fact is that since the early experiments of GUI in the 1960s, interface design has always been this "independent kingdom" in the world of industrial design in general. This is mostly the result of limited graphical hardware power and immature display technologies. In the meantime, the theoretic field of interface design is moving forward in a fast pace, following the hardware advancements of CDDs under the Moore's law.

The physical world is continuous, the digital world has intervals. As Neal Stephenson[44] described in his book "In the Beginning... Was the Command Line", computers with GUI actually continue to perform the same sequential process that he did through the telegraph from his school to send software instructions to the central computer: "*the processing model and sequential commands was never*

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[42] *Augusta Ada King, Countess of Lovelace (1815 - 1852) was an English mathematician and writer, chiefly known for her work on Charles Babbage's proposed mechanical general-purpose computer, the Analytical Engine.*

[43] *Charles Babbage(1791 - 1871) was an English polymath. He originated the concept of a digital programmable computer.*

[44] *Neal Town Stephenson (1959 -) is an American writer known for his works of speculative fiction. His novels have been categorized as science fiction, historical fiction, cyberpunk, postcyberpunk, and baroque.*

changed" **(Stephenson 1999, p. 25)**. Since the birth of computers, the intervals of the digital world is rooted in the fundamental of how do silicone-based computing devices work. However, with sufficient accuracy and frequency, the intervals of user interface rendering can get quite unnoticeable under human sensory. Display technology and graphic power of CDDs in the current market has finally reached to this point that the smoothness of an interface becomes comparable with the movements of physical objects. Having a display of 120Hz refresh rate is no longer a dream that seems so far away.

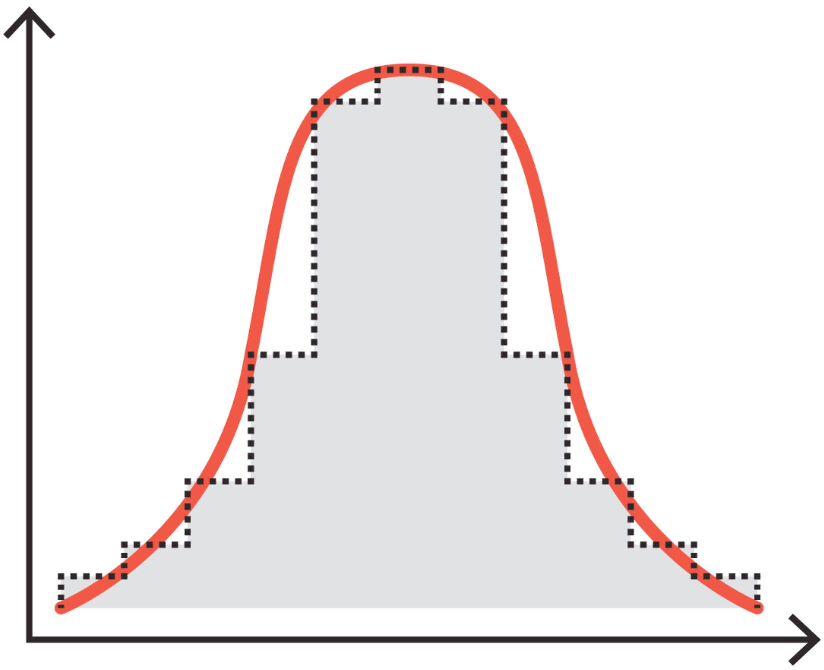


Figure 4 **Heda Weng**, (2019), *Physical World Is Continuous, Digital World Has Intervals*. Courtesy of the author.

In recent years, CDDs have become a huge impact factor in people's lifestyle. People are obtaining a wide range of content with these devices, in the meantime, the devices are getting more and more wearable. This leads to a fact that user interface design projects for CDDs are limited by smaller screens but larger information scale.

As we are facing these new challenges, revisiting the design history of CDDs and the evolution of the content that they present would help improve the quality of interface design on these devices.

5.2 Motivations for Topic Selection

Personally speaking, my academic background is complex: when I was studying a Bachelor's Degree of Industrial Design in Zhejiang University at the Department of Design, which was part of the School of Computer Science. Professionally, I have both the experience working as an interface designer and a software developer.

As a designer with both the experience on the hardware and software of CDDs, in the past few years I encountered some theoretical limitations on the design system in both areas. Professionally and academically I did my own exploration and learned from different materials and projects. One way to resolve the limits of user interface design problems was to learn from the broader world of industrial design. In the software design and development field, some new tools and guidelines were developed and released by the market leaders such as Apple and Google. Analyzing these materials, I frequently find the inspiration of classic industrial design theories.

Under communication with my tutors, we came up with our research plan. In order to further extend our explorations on both user interface design and industrial design, we selected the topic for my PhD research.

In this thesis, we are focusing on CDDs, including PCs, smartphones, tablets, wearables, VR/AR/MR devices and internet of things devices with interface. As commodities of mass production facing the general public, this type of devices is a central representation of the industrial and academical results of various areas: industrial design, user interface design, interaction design, hardware engineering, marketing, user behavior study... We are focusing on the design part of this topic, but also including the influences of the other academic areas.

In order to achieve a balanced structure, materiales from both the industrial aspect and the academical aspect on the user interface design and industrial design of CDDs were researched as the theoretical basis of this thesis.

Part 6 Methodology

In order to adapt to different types of resources in related research areas, various research methods have been used during the process of conception and creation of this thesis, The research methods of this thesis include:

- Library Search;
- Transdisciplinarity;
- Cross-sectional Analysis;
- Comparative Analysis;
- Mind Mapping and Graphical Analysis;
- Case Study;
- Usage of Dictionary of Terms.

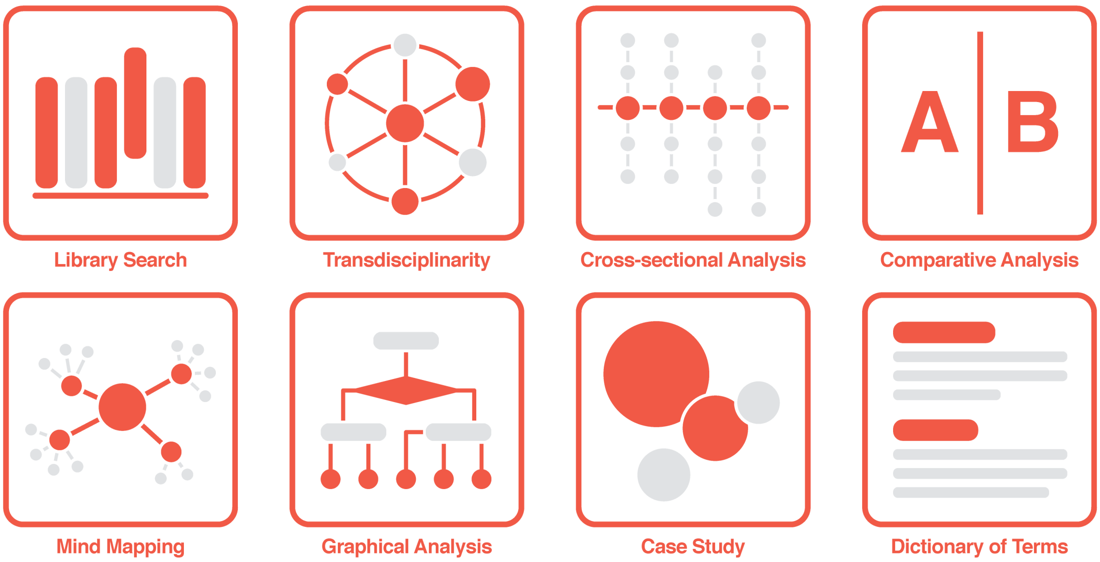
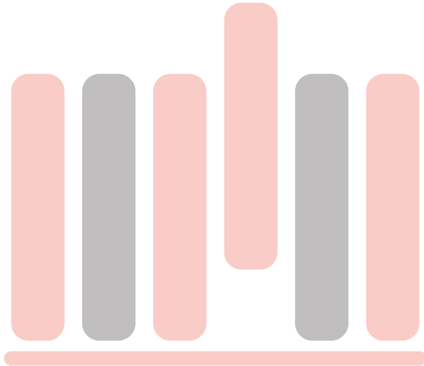


Figure 5 **Heda Weng**, (2019), *Methodology*. Courtesy of the author.

6.1 Library Search

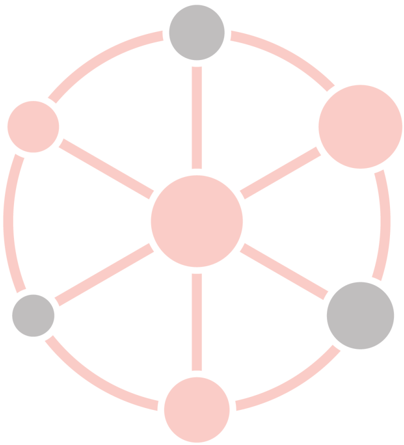


Industrial design was born at the beginning of 20th century and became one of the most important theoretical branch in the academic world of design. Since the early prototypes of graphical interface for personal computers, user interface design also has a history of almost 70 years.

There are a huge amount of academical and practical work for both industrial design and user interface design. Library search is an important method to get familiar with the history of both worlds.

Materials that should be considered as source for library search include books, design catalogs, academic works with related research field, design patents of products and prototypes by device manufacturers in the history of CDDs.

6.2 Transdisciplinarity



CDDs is related to the research result of multiple academic areas, including industrial design, user interface design, industrial technology, software engineering, marketing, user behavior study, aesthetics, digital art, art theory and bio art. As parts of the theoretical basis for the design and manufacture of CDDs, these academical areas complement each other during the whole process of conception, creation and production.

This thesis is focusing on the design of CDDs, however, according to the industrial properties of these devices, all of the academic areas mentioned above serve as limitation factor in practice. Transdisciplinarity is an important research method of this thesis, as the research on these related areas would help explaining the compromises and special characters on past and current products. All of the academic areas mentioned above have their impact on different steps of the conception, creation, production and consumption of CDDs.

It is also important to have a knowledge on the current trends and advancements of these related academic areas for a profound analysis about which of the recent design research results would be applied to mass production on CDDs in the near future, while others are staying at the conceptual phase for further development in long term.

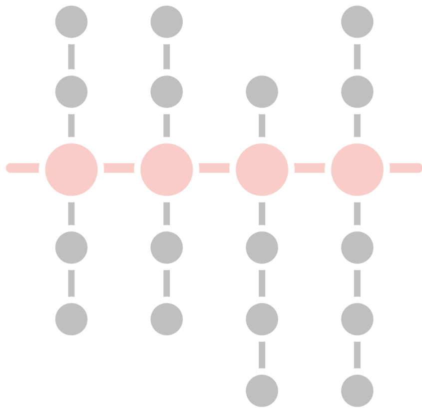
On the other hand, user interface design and industrial design for hardware have always been related academic areas, but each has developed its own theories for the specific needs for practical use. With the intention of creating a unified design system for both worlds, this thesis takes transdisciplinarity as its point of departure.

6.3 Cross-sectional Analysis

As devices for consumption of content and services in the digital industry, various types of CDDs with different form factors and interaction paradigms were created in order to adapt to different usage scenarios. As mentioned in the definition of our object of study, these form factors include:

- Personal Computers;
- Smartphones;
- Tablets;
- Gaming consoles;
- AR (Augmented Reality), VR (Virtual Reality) and MR (Mixed Reality) devices;
- Ultraportable and Wearable devices, such as smart watches;
- Internet of things devices, such as smart speakers and smart displays.

To achieve an integrated vision of the design value of different types of CDDs, it is necessary for us to transversally analyze them in order to sort out the independent variables caused by usage scenarios and mass production limitations. Cross-sectional analysis (or transversal study) is our methodology to horizontally compare the design of different types of CDDs that appeared in the market within the same timeframe regardless their form factor and interaction paradigm.



6.4 Comparative Analysis

As mass production commodities facing the general public, beginning with their conception to their production, CDDs are mainly facing two contradictions: **The contradiction between the latest design findings and the reality of mass production; the contradiction between the UX expectation of the product and the acceptance in general public.**

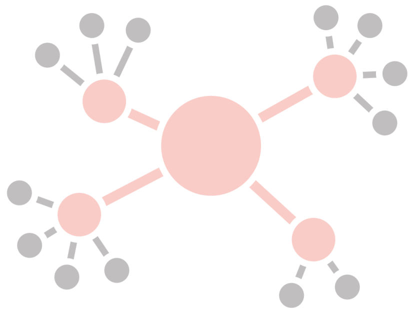
Based on transdisciplinarity and library search, the resources for further research could be enriched. Within a healthy frame of study, the analytic link on the chain of research has a huge importance. To better utilize the two contradictions mentioned above as entry points for the summarization of the research resources, comparative analysis becomes an important study method for this thesis:

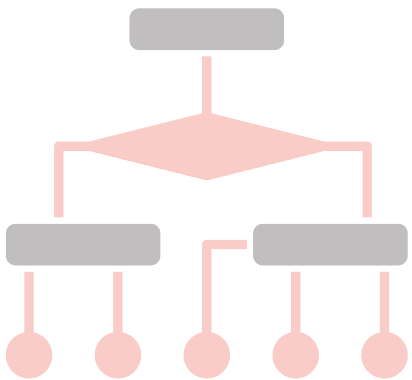
- **For the understanding of the contradiction between design theories and the compromises made for mass production needs**, it is necessary to compare the original concepts, design patents and prototypes with the final products pushed to the market. With this comparison, we could sort out the compromises on the design CDDs for the efficiency of mass production, and try to combine them with the latest advancements on industrial technologies and to find solutions in the design of the next generation of products.

- **For the understanding of the contradiction between UX expectations and the design acceptance in the consumer market**, we should focus on the evolution of each type of CDDs, compare their generations, find the appearance and reappearance of design characters and functionalities, analyze the learning curve of these experiences, combine them with the studies on user behavior, and finally summarize the lessons learned about the adaption of design on CDDs facing the general public.

6.5 Mind Mapping and Graphical Analysis

As we widely used research methods such as transdisciplinarity, cross-sectional analysis and comparative analysis to direct our study both horizontally and vertically, a logical network is weaved to direct the development of our research. In order to improve the visualization and legibility of the thesis, we included mind mapping and graphical analysis as part of our methodology used in the research development phase.





For each chapter of the research development part of this thesis, we included a mind map to express the logical development of our practical research. Additionally, in order to visually present our research results of each chapter, we used the graphical analysis method to connect our sequence of thoughts and practical materials in a logical diagram visualization. This visualization is inspired by the algorithm graphs commonly used in computer science and digital studies.

6.6 Case Study

An important part of the materials for this research are actual devices in the consumer market. Case study is a typical method to analyze the evolution of the study objects.

To have a panoramic vision of the study area, 4 case studies were selected with different starting points and aspects:

- **Case study on gaming consoles.** As devices focusing on entertainment, the market has a higher expectation about the graphic power on gaming consoles. In the history of hardware engineering, gaming consoles served as the pioneer of the application of many graphical rendering methods in the consumer market. As a result, user interface innovations would be experimented on the advanced hardware foundation of gaming consoles and then making their adaption to more generic computing platforms.

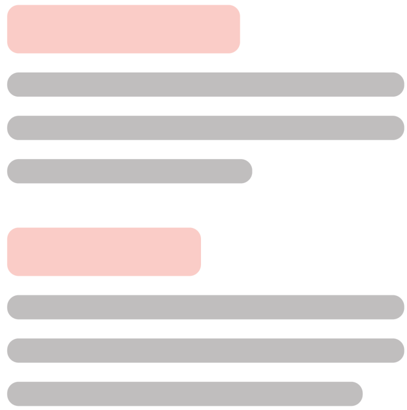
- **A case study on the evolution of input methods and another one on the evolution of output methods in Computer-Human Interaction.** Interaction is multi-directional. The interaction between human beings and digital devices includes both the process of digital devices executing the commands by it user and the procedure of the user comprehending the information presented by the devices. In order to have an understanding of computer-human interaction in depth, it is important to study both the evolution of input methods and output. The evolution of input methods of user interface indicates the evolution of user behavior and the whole process of how CDDs became increasingly more humanized; the evolution of output methods of user interface indicates the evolution of which type of content served as the main purpose of each generation of devices and how digital content is presented on them. Combining both of them provides us a better vision on the combined evolution of technological-design advancements and content consuming behaviors in the consumer market.

- **Case study on the products of Apple Inc. since early 1980s.** The first time that GUI made a great impact in the consumer market began with the Macintosh in 1984. As one of the few companies that manufactures both the hardware and software of CDDs and still surviving since the 1980s, Apple Inc. remains as one of the market leaders of these products. Analyzing the design evolution of Apple would provide a continuous history of design evolution of CDDs since their first appearance facing the public.

6.7 Usage of Dictionary of Terms

As mentioned above, the achievements of different academic areas are applied to the whole process of conception, creation, production and consumption of CDDs.

Since a broad range of materials are involved in the research process, it is important to provide a dictionary of terms to improve the legibility and facilitate the comprehension of the thesis.



The dictionary of terms includes the explanation of the keywords and important concepts involved in the research process, which are sorted out in 3 parts:

- **General terms.**
- **Important concepts on the user interface design of CDDs.**
- **Important concepts on the industrial design of CDDs.**

This dictionary of terms is attached in the Part 8 of the introduction of this thesis.

Part 7 Summary of the Process

In my previous study for the Master's Degree in Design, I researched the possibility of interface design and data visualization in 3D with Virtual Reality devices. During that process, I realized that a huge amount of classic industrial design theories learned previously contributed to my study. This doctoral thesis is a follow-up and sublimation of the previous experiences with a broader territory for its application and also a higher theoretical level.

During the academic year 2014 - 2015, I started my journey of this PhD program based on some research results of the final project of my Master's Degree. The data visualization that project was implemented on Oculus Rift, a VR device. Since VR devices were considered as an extension of gaming terminals by that time, we came up with the first title of this thesis: "Interface and new technologies for the design of video games". While studying the history of video game interface design, we observed this interesting phenomenon: many graphical interface elements and their rendering technology started with video games later entered the mainstream consumer market as essential parts of the user interface on consumer devices. With a higher demand of graphical power from the consumer market, interface elements in video games have been playing a key role in the conception of components for graphical user interface in broader platforms such as operating systems.

As an expansion from the research results of my first year, we started to study the history of GUI design in personal computing products. Similar to what I did with the video games interfaces, we summarized a timeline of the evolution of GUI on personal computers. Comparing both timelines, this phenomenon could be observed: for a long time in history, with better hardware power focused on graphic rendering, video game terminals pioneered different kinds of interface rendering technologies which were later applied in the personal computing platforms targeting consumer market. However, a significant change could be discovered when we are moving to the recent years of the timeline: with the digital economies in the recent years, personal computing devices are no longer just professional gadgets, they are now integrated much more intimately to people's everyday life, serving as a consumption device. The most popular gaming terminal is no longer an independent device;

smartphones, which are generally considered as personal computing devices, carry most of the popular video games of today. Gaming terminals could be considered personal computing devices at the same time, and vice versa. Looking into related books, articles and publications, we found a more exact definition for the concept: Consumer Digital Devices (CDDs).

During the academic year 2016 - 2017, we shifted the focus of my research onto the history of CDDs in general. Both the evolution of user interface and industrial design of CDDs are involved in my research. One of the most important materials from these evolutions is the development of display technologies. Studying the history of CDDs, we observed a change in their paradigms based on the evolution of input methods. During this process, the screen occupies more and more proportion of the visible surface of CDDs, eventually, the major input method is integrated into the screen, and touch-based devices became the mainstream. The display serves as both an input and an output method of some devices; it essentially became the most recognizable part of some CDDs, such as smartphones and tablets. With the popularization of AR, VR, MR and wearable devices, the displays are gaining even more importance: the viewing angle of their displays is almost the same size as the devices themselves, conceptually, the displays almost equal the summation of every functionality in these devices. Another interesting fact is that the GUI of CDDs are increasingly gaining details on physical indications. In this process, some principles of classical industrial design for physical products are being applied directly on graphical interface elements on the screen.

In the fourth year of the program, we intend to sum up all of the results of previous research, connecting the body of work with the economical and political background of its time, trying to make a conclusion and reaching as a result to a higher theoretical level. After discussing with my tutor and directors, the title of the thesis has been modified to “Beyond the Edge of Display: the Integrated Future of Industrial Design and Interface Innovation”. This new title describes more adequately the whole research process, also indicates a clearer theoretical concept. Some materials of the early research process in the first two years of my PhD program are summarized into case studies; in the meantime, all of the content of this thesis has been placed under a new frame of study focusing on the bi-directional influence between the user interface innovations and the industrial design theories on CDDs. The research also extended to the social and economical impact of the design of CDDs, connecting the object of study to a broader background.

The academic year of 2018 - 2019 is the year of summarization. Collecting all of the results during the research process, we made some further adjustments on the structure and the content of the thesis, in order to improve its readability.

Part 8 Dictionary of Terms and Important Concepts

In order to provide a better comprehension of the thesis, this part includes a dictionary of terms which explains some important concepts in the research area of the thesis. These terms are divided in 3 sections:

- **General terms.**
- **Important concepts on the user interface design of CDDs.**
- **Important concepts on the industrial design of CDDs.**

8.1 General Terms

- **Design System**. A design system is an overarching scheme that provides the guidance of visual and interaction rules, design logic and architectural structure for a design project. For large scale projects of either user interface design or industrial design, creating a design system is normally an early step in the workflow. The purpose of establishing a design system is to guide the design execution with consistency and reusability.

- **Horizontal and Vertical Integration**. In the product development and mass production process of Consumer Digital Devices (CDDs), depending on the business model of manufacturers, both horizontal and vertical integration could happen. With horizontal integration, manufacturers of CDDs intend to diversify their products and services to offer. The design of different product lines / services of the same manufacturer usually take inspiration from each other in this horizontal integration model, creating a series of products and services under the guidance of related design systems. On the other hand, with vertical integration, manufacturers of CDDs take more control on certain product lines and focus on the in-house production of more components and technologies in the supply chain. As our research focus on the design system integration for both the user interface design and the industrial design of CDDs, when researching topics of mass production, horizontal integration is the adequate model to analyze.

8.2 Important Concepts on the User Interface Design of Consumer Digital Devices

- **Interface**. In the world of programming and telecommunication, a broader definition of interface would be the protocol that permits the communication between two entities. Specific to CDDs, the interface is the summation of the communication between a device and its user. In order to discuss the design of both the physical body and the digital content on CDDs, the definition of user interface design in this thesis refers to the design of digital interface.

- **Interaction Flow**. In the workflow of user interface design, in order to mitigate the limitations of static screens, designers use interaction flow to describe the steps of users' interaction in realizing the proposed functionality of the product. Interaction flow is normally represented by a circuit graph, indicating the triggers, interaction rules, feedbacks, interaction loops and interface element modes.

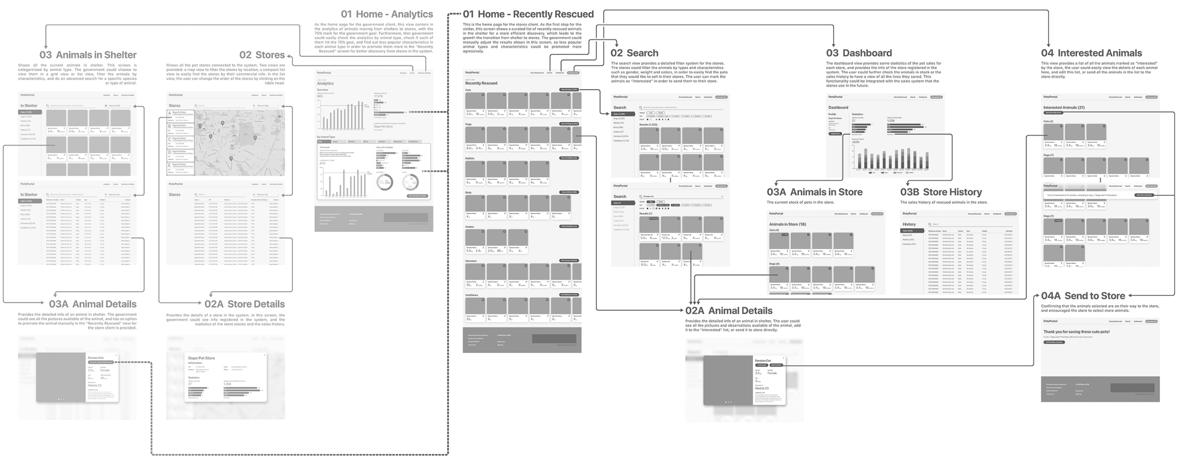


Figure 6 **Heda Weng**, (2019), *A Circuit Graph with Wireframes Indicating an Interaction Flow*. Courtesy of the author.

- **Digital Materials**. Design follows the cognitive laws of human being. In the digital world, interface uses metaphors simulating the physical rules of the real work for a better adaption to user habits. The elements used in an interface are based on digital materials, in comparison with the concept of physical materials used in industrial design.

- **Physical Feedbacks**. Feedback bridges the digital world with the physical world, it provides a signal to human senses. Visual feedback is the most important way of feedbacks in interface design, however other physical feedbacks like sound feedbacks and haptic feedbacks should also be taken account of in the interface studies, as they are also corresponding to different kinds of human senses and are becoming more and more important given the fact that digital devices are having a more intimate relationship with human beings nowadays.

- **Intervals**. In comparison with the continuous physical world, the rendering of digital devices is based on the calculation of hardware. With the working principle of computing devices based on silicone, it's very important to take intervals into account in a typical workflow of interface design.

- **Holographic Interaction**. This is an interesting concept which is commonly seen in artworks reflecting the imagination about human interface in the future, when the dependence on a certain physical component for the realization of interface interactions is highly reduced. Back to reality, the interface design AR, VR and MR devices appearing in the market in recent years are greatly inspired by these artworks. The introduction of the "holographic interaction" concept would help us illustrate the possible advancements in the next decade with the continuous blurring of the edge dividing the digital interface from the physical design of a device as of now.

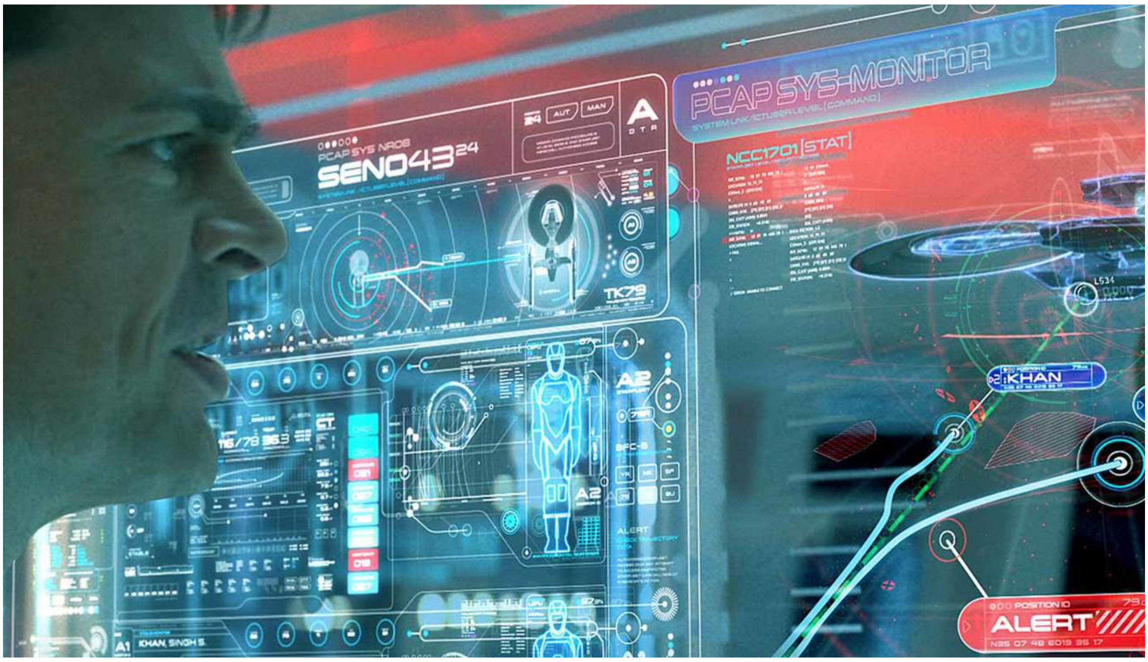


Figure 7 **Rudy Vessup**, (2013), *Holographic Interface Imagined in the Movie "Star Trek"* [ONLINE]. Available at: http://www.rudyvessup.com/star-trek-2-holographic-glass-ui [Accessed 12 February 2017].

8.3 Important Concepts on the Industrial Design of Consumer Digital Devices

- **Internal and External Consistency**. This term is used to describe the correlation between the industrial design of CDD's outer casing and the distribution of its internal components. Understanding the concept of internal and external consistency is part of the process of the comprehension of the industrial design compromises facing the challenges pf mass production.

Figure 8 **iFixit**, (2017), *iPhone X's Rear Camera Design Is Consistent with Its Internal* [ONLINE]. Available at: https://www.ifixit.com/Teardown/iPhone+X+Teardown/98975 [Accessed 15 February 2018].

- **Curvature Continuity**. In the transition from a flat to a curved surface, a typical traditional rounded corner would cause an abrupt change in the curvature. In industrial design, in order to achieve a smooth curve transition with user-friendly look and feel, higher-degree equations are used to calculate the curve. A curve or surface can be described as having G*n* continuity, *n* being the increasing measure of smoothness. The most commonly used continuity in industrial design are G2 continuity (commonly known as "curvature continuity" which measures position, direction, and radius of curvature at the ends of the curves) and G3 continuity (in additional to the factors measured in G2, planar acceleration is also considered).

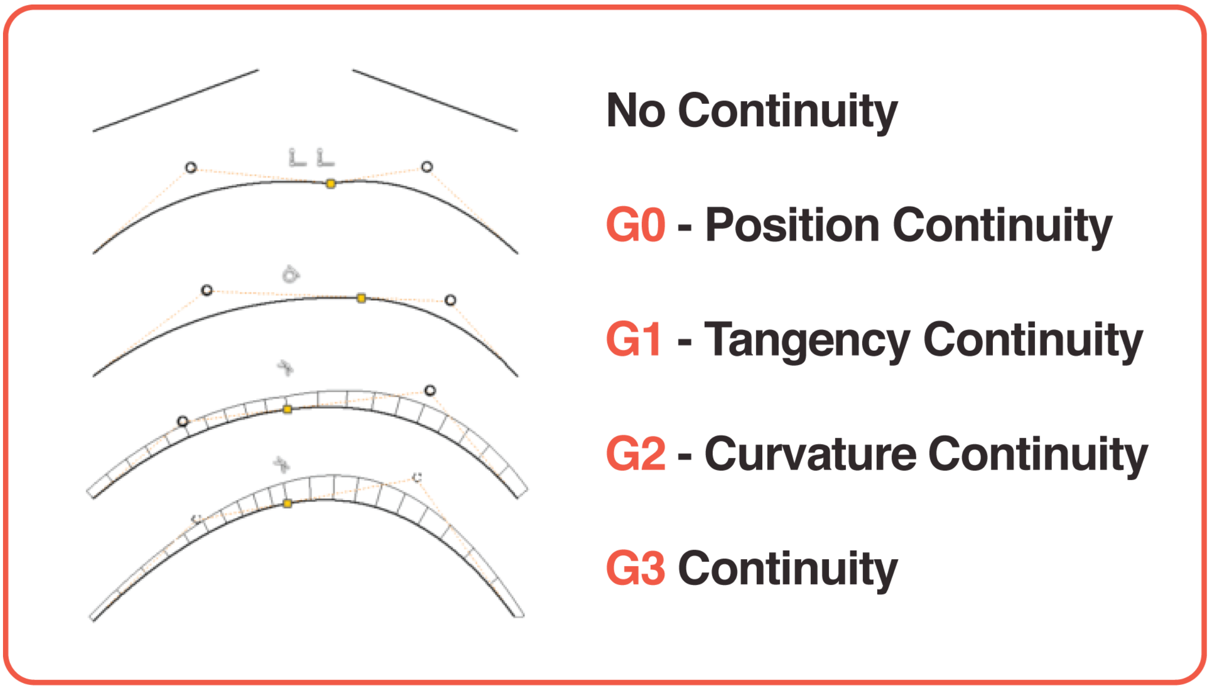


Figure 9 **Heda Weng**, (2019), *G0, G1, G2 and G3 Continuity in Industrial Design*. Courtesy of the author.

- **Redundancy**. In engineering and industrial design, the internal of products is usually designed with reserved extra space or duplicated components with the intention of increasing the reliability of the system. This methodology is called redundancy. Understanding the concept of redundancy helps us to understand the fact that in order to pursue both product stability and high yield rate in mass production, packing components with the latest technology in flagship CDDs is a very challenging engineering and industrial design task.

Desarrollo de la investigación

Research Development

Research Development

In order to put our investigation into practice, we evaluated our objectives and made our development correspondingly.

Our practical research includes 6 parts, each corresponds to one of the chapters in our thesis:

- **Chapter 1. Looking Back in History: the Evolution of User Interface Design on Consumer Digital Devices**. Beginning with the early concepts of GUI long before digital devices' entrance to the consumer market and ending with the interface design of the latest categories of CDDs such as AR, VR, MR and IoT devices, we made a review of the UI design evolution on CDDs.
- **Chapter 2. Geek Thinking: the Reconciliation Between Hardware Limitations and Interface Rendering**. In this chapter, we took the user interface evolution history obtained from Chapter 1 and made a comparative analysis with the evolution of graphical hardware in order to enhance our understanding of interface rendering corresponding to its technical background.
- **Chapter 3. Learning from the Gadgets: the Reapplication of Classic Industrial Design Theories on the User Interface of Consumer Digital Devices**. In this chapter, we analyzed and summarized the practical examples of the usage of classic industrial design theories in the user interface of CDDs.
- **Chapter 4. Sublimation of the Gadgets: the Influences of User Interface Innovations on Industrial Design Theories**. In this chapter, we explored user interface design's visual and conceptual influences on the industrial design of CDDs.
- **Chapter 5. Case Study**. In order to look into the research results of the first 4 chapters from different perspectives, we made the following case studies in order to expand our understanding of the relationship between the user interface and industrial design of CDDs in depth:

- **The design history of gaming consoles**. As the most graphical-progressive category of CDDs, gaming consoles serve as a pioneer of interface rendering technologies;
- **The history of input methods on CDDs**. In this case study, we focused on users' active interaction with their devices by analyzing the input methods of CDDs' interaction paradigms.
- **The history of output methods on CDDs**. In this part, we focused on users' passive interaction with their devices by analyzing the output methods of CDDs' interaction paradigms.
- **History of the design of Apple Inc.'s products**. As one of the pioneers that pushed graphical user interface into consumer market and one of the few manufacturers that survived both the PC-era and the Smartphone-era, Apple has one of the most complete product line and design history of CDDs. We explored Apple's design history focusing on its evolution.

- **Chapter 6. An Integrated Future: the Great Unity of User Interface and Hardware Design**. In this chapter, we further analyzed the research results from the previous chapters and made our exploration of a unified design system for both the hardware and the interface design of CDDs, focusing on the latest evolution of media consumption and the categories of digital devices that just started to explore their possibilities in the consumer market.

Material from many different academic areas are used as the basis of our research. Above the research methods such as transdisciplinarity, cross-sectional analysis and comparative analysis, in order to improve the readability and the clarity of the thesis, the chapters in the research development part are presented with mind mapping and graphical analysis.

The chapters in research development share the same structure:

- **Introduction and mind map**. Every chapter begins with an introduction indicating the structure and purpose of the corresponding practical research part. The introduction is accompanied with a mind map to present the logical development of the research.

- **Research diagram**. As the main body of each chapter, the research process is visualized graphically. Each chapter develops around a logical research diagram that organizes the materials according to their logical context.
- **Summary**. At the end of each chapter, as a conclusion of the corresponding part of research development, a summary of the research results is also presented. These research results are further analyzed and validated in the conclusion phase.

1837
Analytical Engine
Charles Babbage & Ada Lovelace

1936
Automatic Computing Engine (ACE)
Alan Turing

1968
oN-Line System (NLS)
Douglas Engelbart

1973
Xerox Alto
Xerox PARC

1984
Macintosh
Apple

1995
Windows 95
Microsoft

2007
iPhone
Apple

2010
iPad
Apple

Chapter 1

Looking Back in History

The Evolution of User Interface Design on Consumer Digital Devices

“

We had a human/computer interface a hundred years before we had computers… simply grafting them on to the already-existing technologies for translating letters into bits and vice versa: teletypes and punch card machines.

(Stephenson 1999, p. 5)

”

Chapter 1 Looking Back in History

The Evolution of User Interface Design on Consumer Digital Devices

1.1 Introduction and Mind Map

1.1.1 Introduction

In a generalized definition, the term of "interface" refers to any "*shared boundary across which two or more separate components of a computer system exchange information*". **(Hookway 2014)** In our research, we are focusing on the concept of "user interface" in a narrower sense: a user interface is a shared boundary across the human sensory and a computing device.

The history of computing device dates all the way back to *the "Analytical Engine" made by Charles Babbage and Ada Lovelace*. **(Graham-Cumming 2010)** At the beginning of computing devices, the input and output components were not the objects that we are familiar with nowadays: there was no displays, no keyboards and mice. However, users were able to interact and interchange information with these machines. To understand the evolution and formation of the mature user interface paradigms that we see on our CDDs everyday, in this chapter, we are traveling back in history and looking for the roots of the user interface itself.

An expansive and in-depth review of the history of user interface design on CDDs serves as a solid foundation of our practical research. In this chapter, we are looking back in the long history of user interface design on computing devices. The research materials are evaluated from 4 perspectives:

- **Historic timeline**. An evident way for the analysis of CDDs' interface design evolution is to place all materials in the same timeline. Based on this historic timeline, we will be able to further analyze the evolution of design trends and interface rendering techniques in CDDs. Time serves as the main line of this chapter's content, correspondingly, we made Chapter 1's research diagram chronological.

- **Device categories and usage scenarios**. As the summation of different types of devices for media consumption, CDDs could be subdivided in different categories according to their usage scenario. These usage scenarios are always flowing with people's social lifestyle and media consumption demands, motivating the mergence, fission and mutation of CDD categories.

- **Interaction paradigm**. The hardware and technological foundation leads to the invention of input and output methods of CDDs. Once a combination of certain input and output methods gets stabilized to form a certain category of CDDs, an interaction paradigm is established. Studying the interaction paradigm of CDDs help us understanding user interface's adaptation to the input and output hardware of CDDs throughout their history.

- **Media consumption format**. Media consumption on CDDs are realized through the storage and delivering of information. Generalizing the time background, usage scenarios and interaction paradigms of CDDs leads to a summary of media formats presented in these devices, which helps us to comprehend of the relationship between user interface and content.

1.1.2 Mind Map

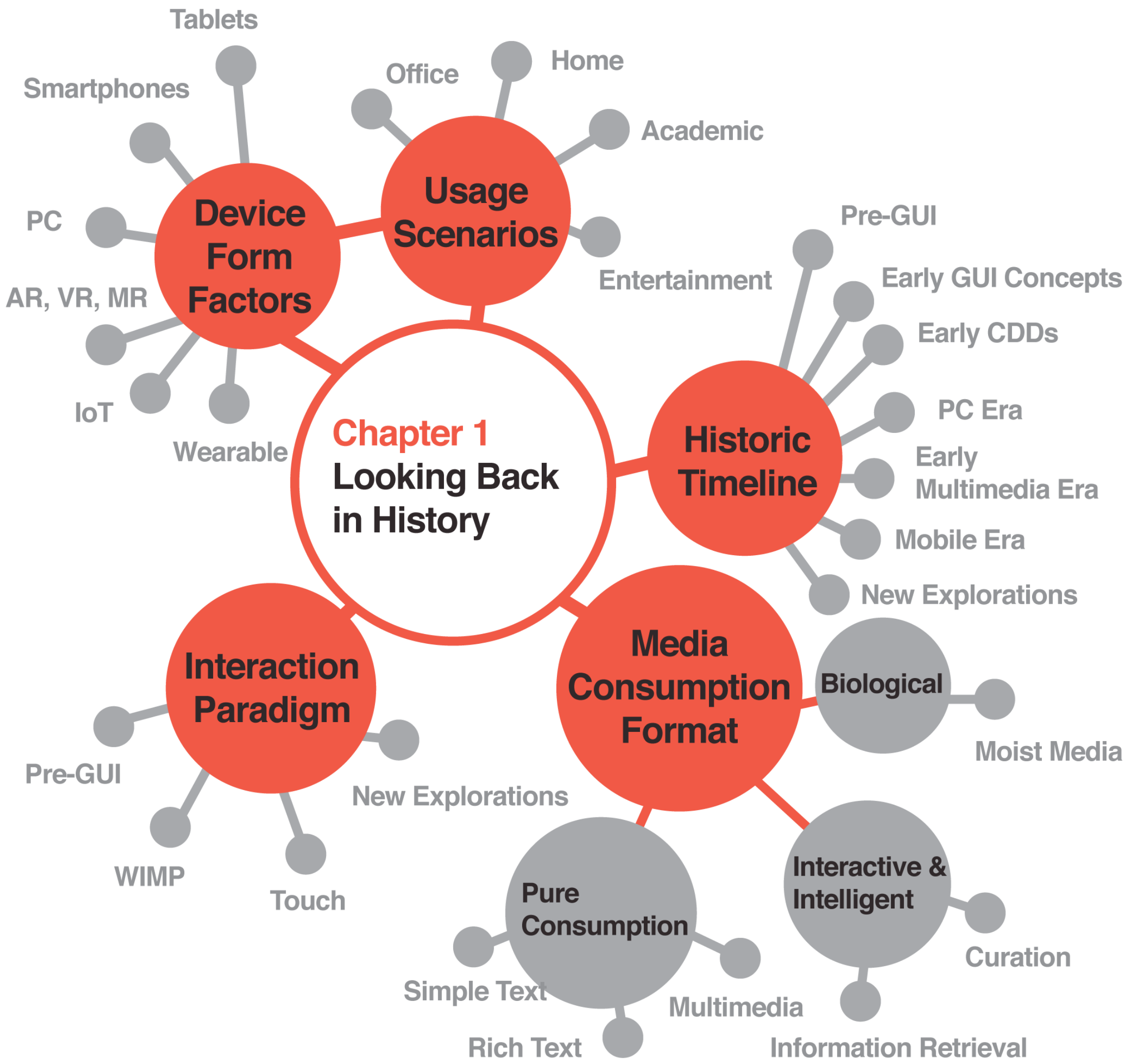


Figure 10 **Heda Weng**, (2019), *Mind Map of Chapter 1*. Courtesy of the author.

1.2 Research Diagram

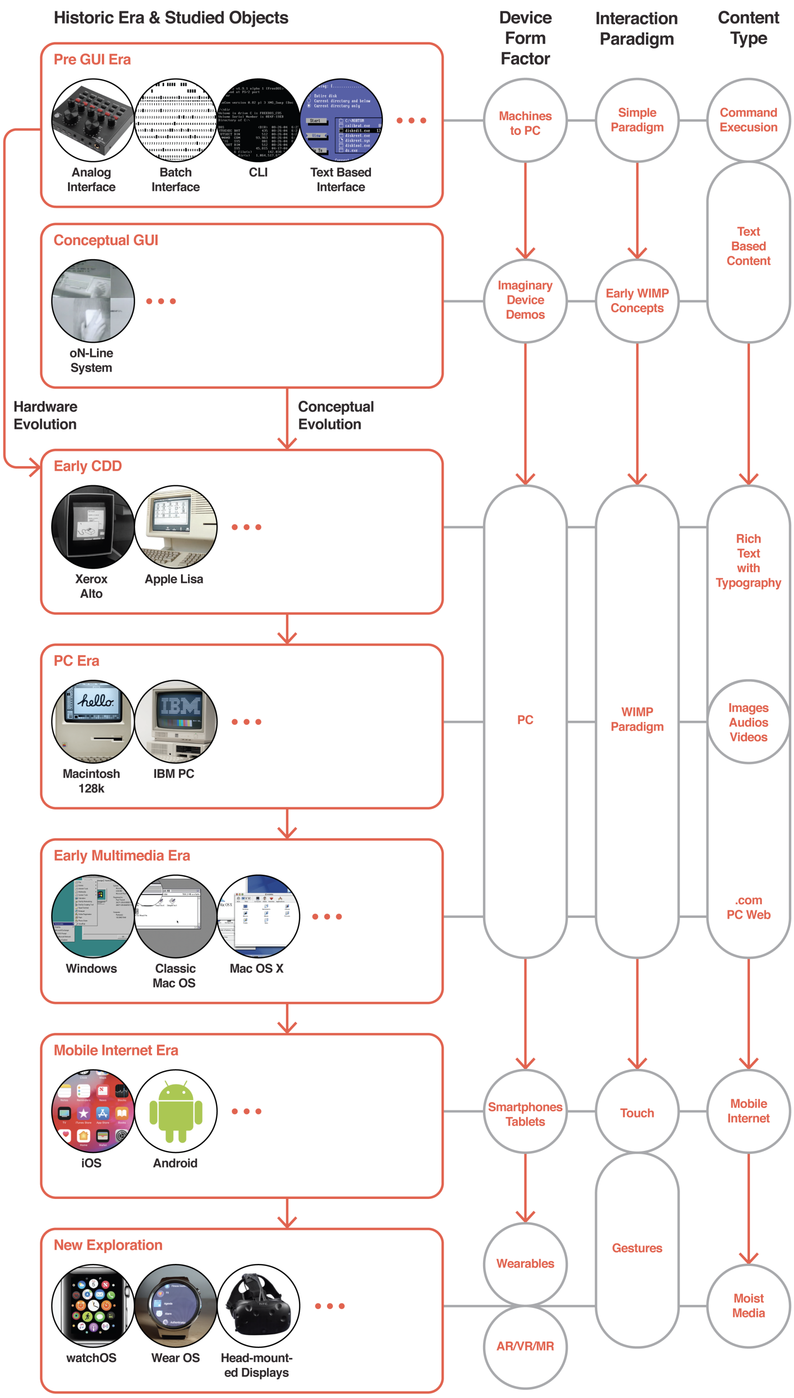


Figure 11 **Heda Weng**, (2019), *Research Diagram of Chapter 1*. Courtesy of the author.

1.3 Summary of Research Results

With the research of this chapter, we were able to review the interface design history of CDDs and obtained a panoramic view of interface design evolution since the conceptual beginning of this product category.

In order to analyze the evolution of design trends and interface rendering techniques, we ordered the research materials in a historic timeline, and analyzed these materials from different perspectives: device form factor, usage scenario, interaction paradigm and media consumption characteristics.

With the historic timeline analysis, according to the visual style evolution and the theoretical development of user interface design, we were able to summarize the eras of user interface development on CDDs:

- **The pre-GUI era**. Before graphical user interface (GUI) were technologically possible on personal computers, computing devices had several dominant types of user interface: analog and mechanical interface[45], batch interface[46], command-line

Figure 12 **Tokopedia**, (2017), *Analog Interface in a Sound Card* [ONLINE]. Available at: https://www.tokopedia.com/wirashoponline/mixer-sound-card-external-soundcard-audio-live-microphone-asmr-v8 [Accessed 05 March 2018].

[45] *The type of interface that is purely based on physical controls, such as buttons, analog knobs and switches.*

[46] *The input methods of this type of interface are generally punched cards or equivalent media like paper tapes, while the output method is normally line printers to these media.*

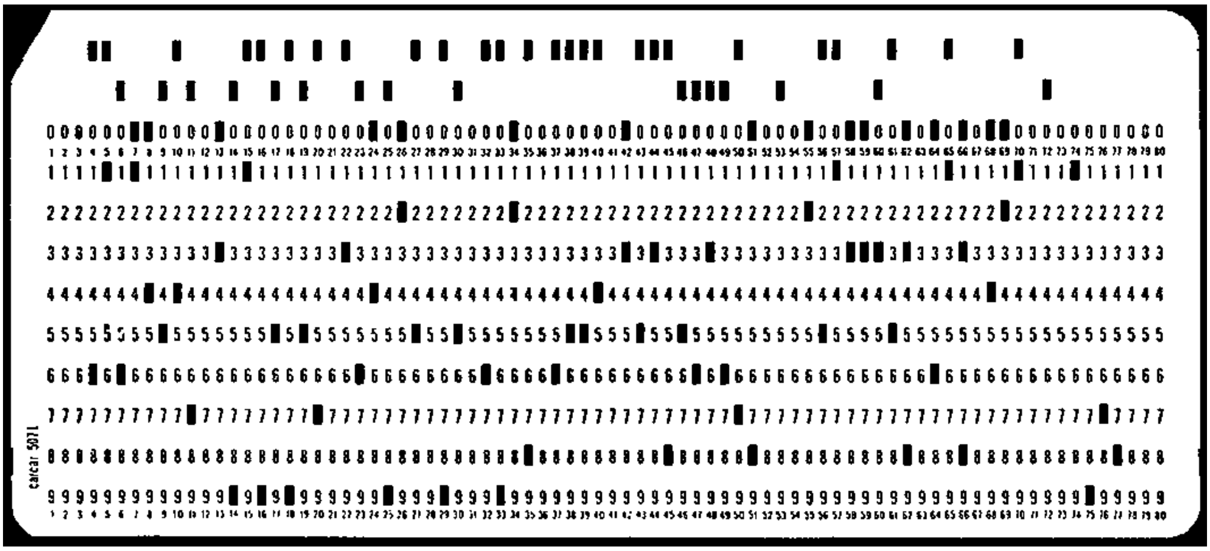


Figure 13 **Lydia Kats**, (2015), *A Punch Card Used for Batch Computing* [ONLINE]. Available at: http://llkats.github.io/osbridge-2015-slides/ [Accessed 09 September 2016].

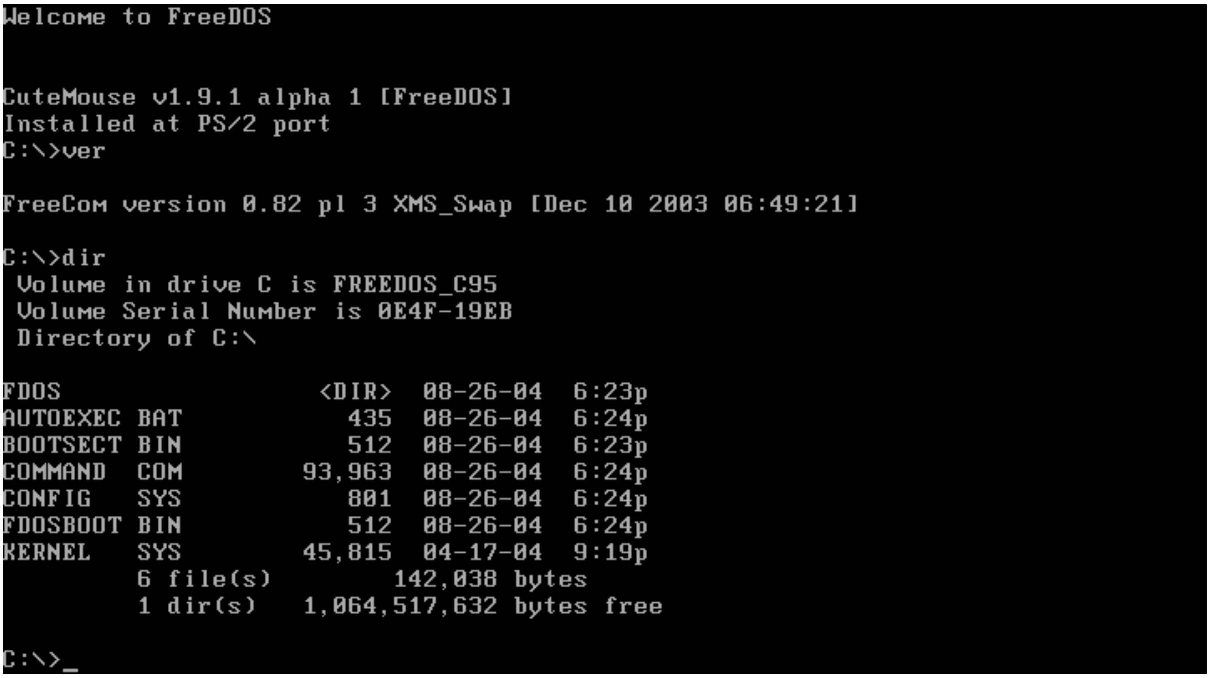


Figure 14 **Jim Hall**, (2018), *Command Line Interface in the FreeDOS Terminal* [ONLINE]. Available at: https://opensource.com/article/18/4/gentle-introduction-freedos [Accessed 12 January 2019].

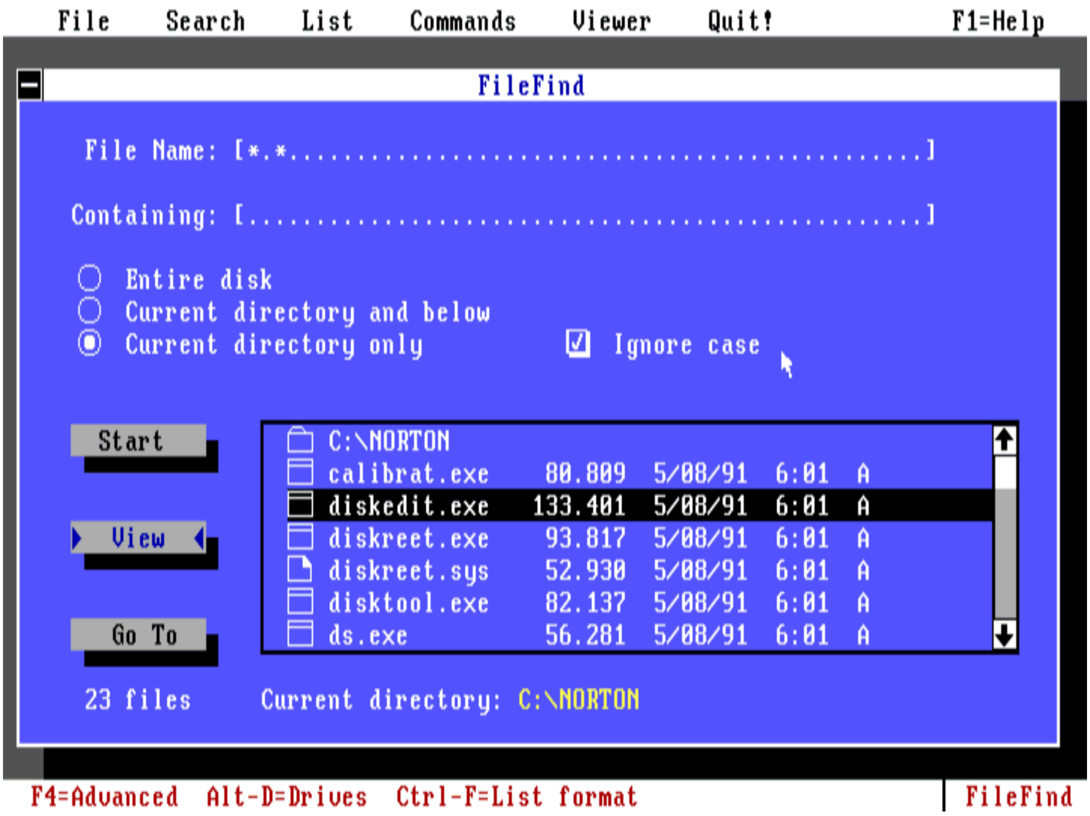


Figure 15 **Wikipedia**, (2008), *Text-based User Interface Introduced the Concept of Menus in Desktop* [ONLINE]. Available at: https://en.wikipedia.org/wiki/History_of_the_graphical_user_interface#mediaviewer/File:Norton_Utilities_6.01_UI.png [Accessed 12 January 2019].

user interface (CLI)[47] and text-based user interface[48]. These interface types are the early expressions of how human being interact with computers; they serve as an important source for the inspiration of GUI concepts.

- **The era of conceptual explorations of GUI**. GUI is a natural result of user interface evolution. It marks the priority transition from maximum utility of computing power to the adaptation of human intuition in human-computer interaction. The oN-Line System (NLS) presented by Douglas Engelbart became a landmark computer demonstration of its time, it was even retrospectively referred to as "*the mother of all demos*". **(Bardini, 2000)** The NLS demonstrated the possibilities of many GUI elements that we are familiar with, such as video conferencing, multiple windows and mouse cursors. The conceptual explorations of GUI encouraged the human-centered cogitation of user interface designs and theoretically prepared GUI's applications in the PCs in the decades of 1970s and 1980s.

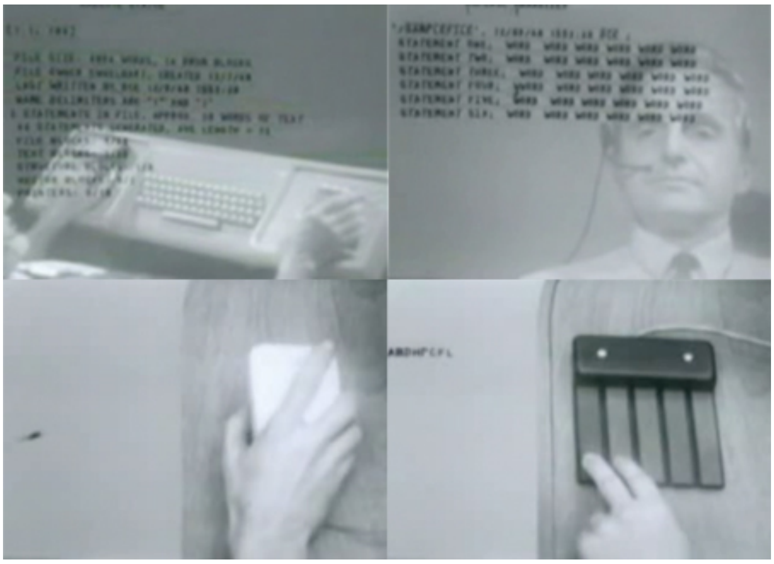


Figure 16 **HCI**, (2007), *NLS Demo by Douglas Engelbart* [ONLINE]. Available at: https://hci.typepad.com/hci/2007/04/douglas_engelba.html [Accessed 08 July 2017].

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[47] Also known as command-line user interface, console user interface and character user interface (CUI), is a means of interacting with a computer program where the user (or client) issues commands to the program in the form of successive lines of text (command lines).

[48] Before the introduction of GUI into personal computers, a pulldown menu system at the top of the screen, a status bar at the bottom, shortcut keys that stay the same for all common functionality were introduced to improve the usability of CLI, forming the text-based user interface.

- **The emergence era of GUI on early generations of CDDs**. At the beginning of 1970s, researchers at Xerox Palo Alto Research Center developed the WIMP (Windows, Icons, Menus, Pointers) paradigm, and the first working prototype with GUI, the Xerox Alto, came out in 1973. Early CDDs with GUI in the market such as the Xerox Star and Apple Lisa commercially failed due to the high cost, limited computing power and poor performance. These early CDD products put GUI and the WIMP paradigm into practice and developed the concept of "what you see is what you get (WYSIWYG)", marking the introduction of graphic design concepts such as typography and visual hierarchy into personal computing. The interface advancements of early generations of CDDs built the foundation for the commercial breakthrough of these devices in the publication industry.

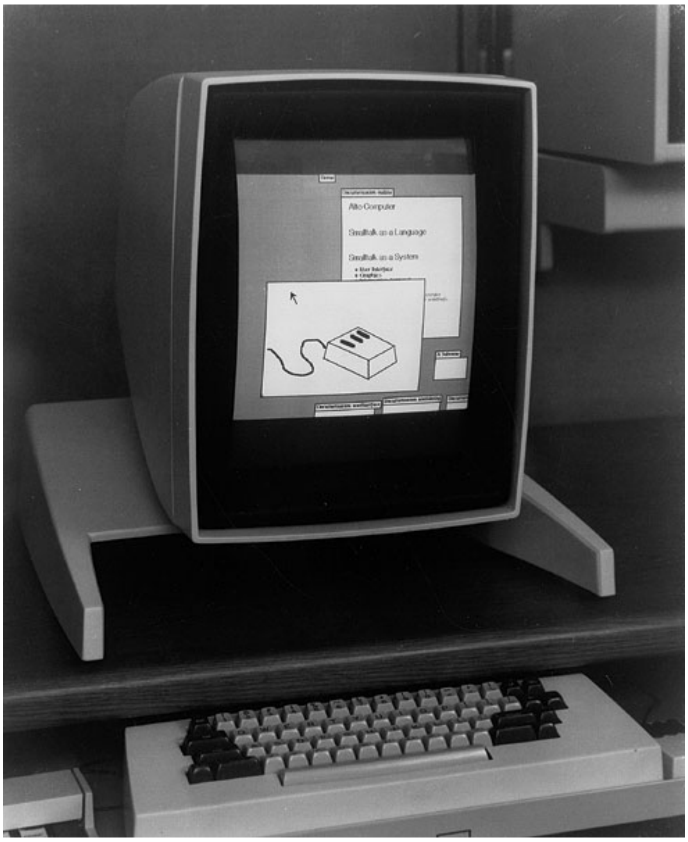

Figure 17 **Toastytech**, (2003), *Xerox Alto* [ONLINE]. Available at: http://toastytech.com/guis/alto3.html [Accessed 17 July 2016].

Figure 18 **Wikipedia**, (2008), *The Introduction of Typography in the First Version of Mac OS* [ONLINE]. Available at: https://en.wikipedia.org/wiki/Computer_font#/media/File:Original_Mac_fonts.png [Accessed 16 March 2015].

- **The PC era**. The first commercially successful CDD was the Apple Macintosh in 1984. As the dominant category of CDD during the decades of 1980s and the 1990s, personal computers with the WIMP paradigm started their success in the publication industry and gradually got introduced into offices and homes. With the development of display hardware in this era, personal computers were able to display a richer color gamut. The user interface of the PC era visually enriched the WIMP paradigms with the introduction of metaphors such as borders, shadows and rounded corners. In the 1990s, with the introduction of the Multimedia PC (MPC)[49] standard, personal computers are no longer only productivity gadgets in the office as their usage expanded to entertainment. The PC era marks the first evolution of media consumption in CDDs. In addition to text and shapes, CDDs of this era gained the ability to present images, audios and videos.

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[49] A recommended configuration for a personal computer (PC) with a CD-ROM drive introduced in 1991.

Figure 19 Ben Lovejoy, (2014), *The Macintosh 128k* [ONLINE]. Available at: https://9to5mac.com/2014/01/24/falling-in-love-with-the-macintosh-128k-back-in-1984/ *[Accessed 30 March 2017].*

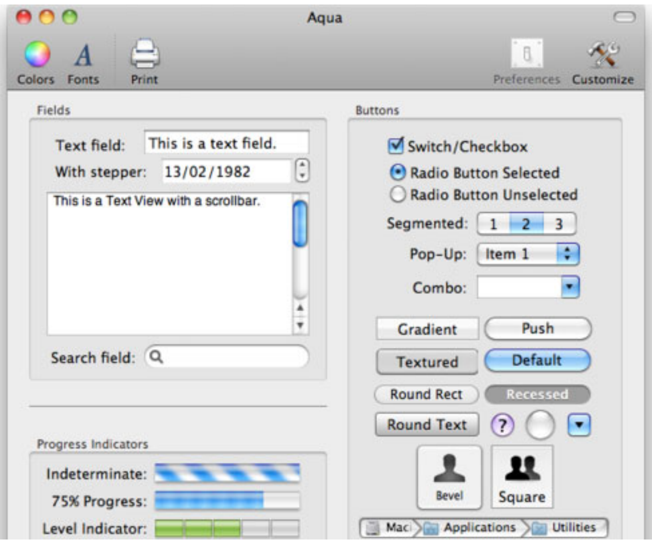

Figure 20 **Damien Scott**, (2011), *Mac OS X's Aqua Interface Language with Acrylic Components* [ONLINE]. Available at: https://www.complex.com/pop-culture/2011/03/the-10-most-innovative-features-introduced-in-mac-os-x/ [Accessed 25 February 2018].

- **Early multimedia era: the .com bubble and the prosperity of skeuomorphic interface**. With the evolution of computing power under Moore's law, the available hardware capacity for interface rendering saw its growth in an exponential way. As a continuation of the human-centered cogitation since the beginning of GUI, user interface elements on CDDs towards the end of the 1990s and the beginning of the 2000s took the imitation of real-life objects to an exaggerating level. The domination of skeuomorphism in the user interface design of CDDs moved well beyond the initial usage of metaphors with the intention of creating a user-friendly learning curve, and started to show the limits of this concept: the visual noisiness affected the quality of information presentation. In the meantime, internet showed its social impact with the .com bubble. As the main entrance to the internet for most people, PCs continue to dominate the CDD market in this era as the content of user's other digital devices rely on the synchronization with their PC. The media consumption on CDDs further evolved in this era, as the obtaining of information is almost real-time with the internet. As a result, the quantity of content for media consumption in CDDs expanded exponentially in this era.

Figure 21 **Elio Qoshi**, (2014), *Skeuomorphic User Interface Imitates Real-Life Objects* [ONLINE]. Available at: https://www.sitepoint.com/road-google-material-design/ [Accessed 12 February 2019].

- **Interface simplification and mobile internet era**. The first commercially successful smartphone with modern form factor is the iPhone from 2007. This marks the beginning of the mobile internet era and the maturity of the touch-based interaction paradigm. In the mobile internet era, media consumption further expanded its usage scenarios. Internet connection expanded to our pocket with the popularization of smartphones, making media consumption occupying the fragmented time in our everyday life; with the invention of tablets, the media consumption in both professional and home scenarios gets intuitive and portable. Media consumption became decentralized as all types of CDDs have independent internet connection without the need to synchronize to the PC. As the functionality of smartphone are getting more and more complex, skeuomorphic user interface saw its limitations on the small screens with its lack of consistent interaction logic. As Sir Jonathan Ive said in WWDC 2013, "*True simplicity is derived from so much more than just the absence of clutter and ornamentation. It's about bringing order to complexity*" **(Ive, cited in Apple 2013, 1:16:21)**, a visual clean-up with deeper consideration of interaction logic and reorganization focusing on the quality of information was long overdue in the mobile internet era.

Moving forward from the focus on the quantity of information, the quality of information presented in CDDs and digital health received unprecedented attention. In the meantime, the user interface design of the mobile internet era saw a great transition from the appearance-centralized skeuomorphic thinking to an information-and-behavior-centralized cogitation. As seen with the popular design languages in the mobile internet era such as the Apple's iOS 7 design guidelines and Google's Material Design, the interface design of CDDs abandoned skeuomorphism's simple imitation of real-life products and became content-centralized with metaphors from the behavior of physical objects. Pseudo Z-axis, digital materials and precise animations were introduced, bringing the interface design in line with human cognition.

Figure 22 **Apple**, (2013), *iOS 7* [ONLINE]. Available at: https://www.apple.com/ios/ios-7/ [Accessed 11 May 2014].

- **The latest GUI explorations on new CDD form factors**. As the latest evolution of CDDs, new device form factors are beginning to appear in the market. With AR, VR and MR devices, the user interface of CDDs are getting integrated into real-life environments, merging the digital world with the physical world. IoT devices are expanding internet connection to even more physical products in people's everyday life, making physical controls more intelligent. Wearable devices is becoming the category of CDDs with the most intimate relationship with human being. With the sensors directly detecting user's physiological indicators, wearable products brings improvements to people's physical and digital health. With these new categories of CDDs, computing processes are beginning to get involved with biological processes, marking the start of media consumption in the moist media format. The user interface of these device categories are still under exploration before the maturity of new interaction paradigms. These new interface formats have a few characteristics in common:
  - The borderline between the physical object and the digital interface gets blurry;
  - New sensors are introduced in CDDs to better understand human behavior;
  - User interface is becoming proactive with certain level of intelligence predicting user's consumption demands.

  In these latest explorations of interface innovations on the new categories of CDDs, we observed an interesting phenomenon that the computer-human interaction in these devices are generally getting their inspiration from earlier technological imaginary in movies, while the interface elements themselves are derived from the interface design of smartphones and tablets.

"New media contains all the hazards of the old, because our technological imaginary continues to be mobilized by the tropic regimes of modernity." **(Griffin 2002, p. 123)**

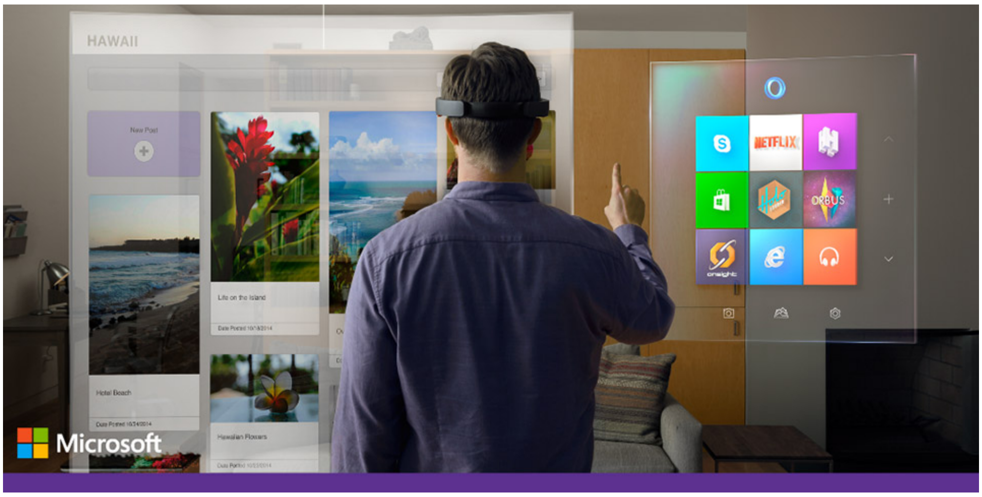

Figure 23 **Williams Pelegrin**, (2015), *3D User Interface of Microsoft's HoloLens MR Headset* [ONLINE]. Available at: https://www.digitaltrends.com/wearables/microsoft-holographic-and-microsoft-hololens-news/ [Accessed 14 May 2018].

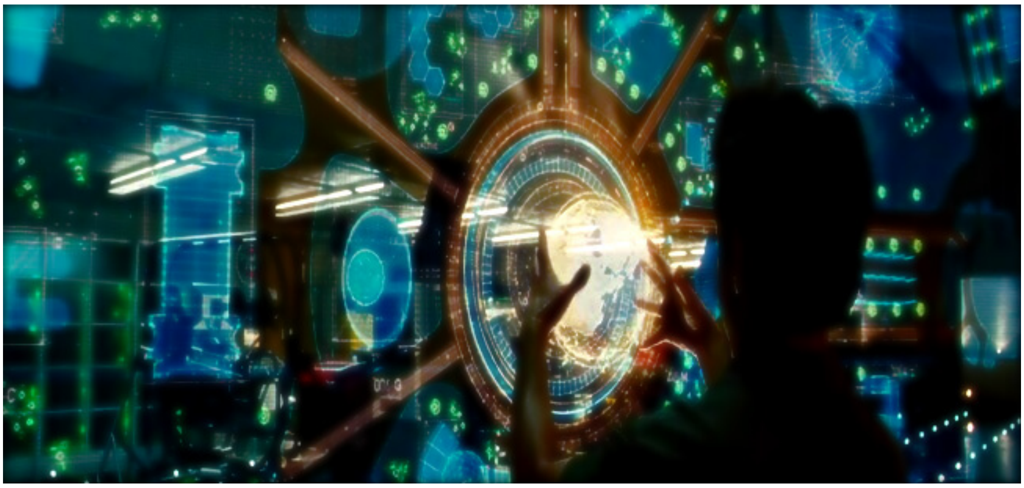

Figure 24 **Thomas Frank**, (2012), *Technological Imaginary of Holographic Interface in the "Iron Man" Movie* [ONLINE]. Available at: https://collegeinfogeek.com/leap-gesture-computing/ [Accessed 17 November 2017].

We summarized the research results of this chapter:

- From the **device form factor** perspective, newer generations of CDDs are generally more portable and have a more intimate relationship with users in their everyday life.

- Analyzing the **usage scenarios**, CDDs popularized from the usage in the publications industry to the general office environment and eventually entered different scenarios in people's personal life. The entertainment and consumption properties of CDDs got enforced during this process while new types of CDDs are occupying every subdivision of the consumer market corresponding to fragmented usage scenarios.

- Viewing the evolution of **interaction paradigms** with different generations of CDDs, the industry moved forward from physical controls to digital controls, from the WIMP paradigm to the touch-based interaction paradigm. With the latest generations of CDDs, more sensors are involved in the interaction process, marking the early explorations of a brand-new interaction paradigm with more proaction and intelligence, establishing an omnidirectional connection with the human sensory.

- Analyzing the **media consumption characteristics**, the media type of CDDs first evolved from simple text to rich text with WYSIWYG characteristics, then got enriched with images, audios and videos with the multimedia PC standard; with the popularization of internet, the quantity of information and the availability of multimedia content were both greatly improved. The media format in CDDs evolved from content output to bi-directional information retrieval and presentation with intelligent curation and personalization. As the latest advancement in the market, biological processes starts to get involved in the media consumption on CDDs, indicating the movement from digital era to post-digital era with the moist media format.

Walking through the history of CDDs and their interface evolution, we observed the eternal trend of the increasing portability of physical devices, the involvement of more human sensory in the interaction paradigms and the injection of media consumption in every time and place of our own lives… some questions have been raised:

What is the technological basis for portability?
What is the impact of media content and its interface presentation upon the industrial design of CDDs?
What is the relationship between the human sensory system and CDDs?
What is going to happen to the design of CDDs in the post-digital era?
Our research continues.

The historical analysis presented in this chapter serves as the background and foundation of our practical research. We further extended our historic research transversally in other chapters:

- In Chapter 2: Geek Thinking, we explored the hardware and technological basis of interface rendering behind CDDs' interface evolution;

- In Chapter 3: Learning from the Gadgets and Chapter 4: Sublimation of the Gadgets, we used the historic timeline from this chapter as the basis of the historic research on the bi-directional influence between the interface design and the industrial design of CDDs;

- In Chapter 5: Case Study, we extended the depth of our historical research by using case studies from different perspectives;

- In Chapter 6: An Integrated Future, we extended our research of media consumption characteristics by substituting our proposal of a universal design system for both the hardware and the interface of next generation CDDs into the media consumption usage scenarios of the moist media era.

Chapter 2

Geek Thinking

The Reconciliation Between Hardware Limitations and Interface Rendering

> Technology marches in seven-league boots from one ruthless, revolutionary conquest to another, tearing down old factories and industries, flinging up new processes with terrifying rapidity.
>
> (Beard 1927)

Chapter 2 Geek Thinking

The Reconciliation Between Hardware Limitations and Interface Rendering

2.1 Introduction and Mind Map

2.1.1 Introduction

As the American philosopher Rosalind Williams said, "*Technology determines history.*" **(Williams, cited in Franssen, 2018)** As the main visual identity factor of CDD categories and the major output method of these devices, the development of display technologies might have been a decisive factor of the evolution of CDD themselves. Serving as the most important media consumption terminals, the information transmitted through CDDs might have altered the history of our social structure and cultural values.

Although sounds very "geeky" to study the hardware technology behind the displays, it is a very good place to start when we are trying to understand the social impact of the popularization of CDDs.

With our detailed research focusing on the historic evolution of user interface design on CDDs described in Chapter 1, we are extending the technological depth of our research in this chapter.

Reviewing the historic research timeline from the previous chapter, we noticed that the evolution of GUI is a non-linear progress. There has been several key events along the history of user interface that pushed GUI's design evolution significantly:

- **The introduction of colors.** The first commercial intent of GUI was realized on monochrome displays; however, it was the popularization of color displays that introduced PCs with GUI into a broader consumer market. This marked the beginning of the PC era.

- **The introduction of motion.** With the development of hardware for graphic rendering, the capacity of displaying videos was introduced to PCs in the consumer market. With the same hardware advancement, motion was introduced as an essential element for interface design under the WIMP paradigm, marking the maturity of GUI on personal computers, forming a firm interface foundation in preparation of the early multimedia era.

- **Sub-pixel rendering.** WYSIWYG is one of the concept basis for GUI. Under this idea, many graphic design concepts such as typography and layouts were introduced to the interface of computing devices. In order to roughly present the appearance of different graphical elements, fonts and images were rendered in the bitmap mode[50] on PC's displays. As the basic unit of bitmap graphic rendering are dots of pixels, with the limited display resolution on PCs during that time, aliasing[51] was unavoidable. As a result, on screen graphics still look quite different from the final printing results. With the rise of the early multimedia era, anti-aliasing technology with sub-pixel level rendering was introduced to various PC operating systems in order to smoothly render interface elements in vector[52]. Sub-pixel rendering enhanced the precision of graphic rendering on a limited hardware basis and it opened up new graphical potentials for the usage of CDDs in more professional and entertainment scenarios.

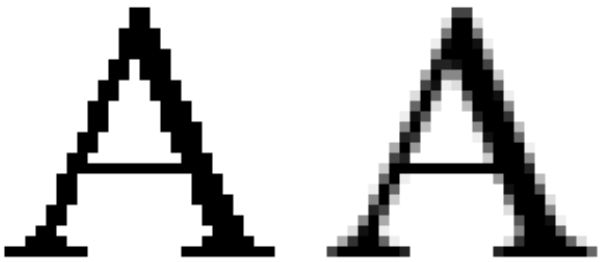

Figure 25 **Eric Z Goodnight**, (2011), *Letter "A" in bitmap mode vs. anti-aliasing* [ONLINE]. Available at: https://www.howtogeek.com/73704/what-is-anti-aliasing-and-how-does-it-affect-my-photos-and-images/ [Accessed 03 May 2017].

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[50] Bitmap mode renders graphics with dots or pixels as the basic unit. For example, bitmap fonts consist of a matrix of dots or pixels representing the image of each glyph in each face and size.

[51] In the world of GUI design, the term "aliasing" refers to the distortion or artifact that results when the shape reconstructed for the pixels in a display is visually different from the original continuous shape.

[52] Vector graphics use Bézier curves, drawing instructions and mathematical formulae to describe each glyph, which make the shape outlines scalable to any size.

- **Physical solution for pixel aliasing.** At the beginning of 2010s, the resolution of displays on CDDs finally reached to the point when pixels became virtually indistinguishable by human eyes. This technological advancement theoretically opens up the possibility of fully replicating the shape of physical objects within the screens, pushing the adoption of skeuomorphism on the interface of CDDs to its peak, marking the beginning of the exponential growth of smartphones.

- **Further pursuit for accurate graphic reproduction.** During the last decade, user interface design had some further advancements adapting to different categories of CDDs. GUI is rendered with richer colors, smoother motion and enhanced precision. The pursuit of accurate graphic reproduction opens up a wide space for imagination for future generations of GUI within AR, VR, MR and wearable devices.

Based on these key events in CDDs' interface evolution history, we are utilizing the comparative analysis methodology to research the GUI design breakthroughs from a technological perspective. In this chapter, our main goal is to link the key events on GUI's evolution history with their hardware foundation.

2.1.2 Mind Map

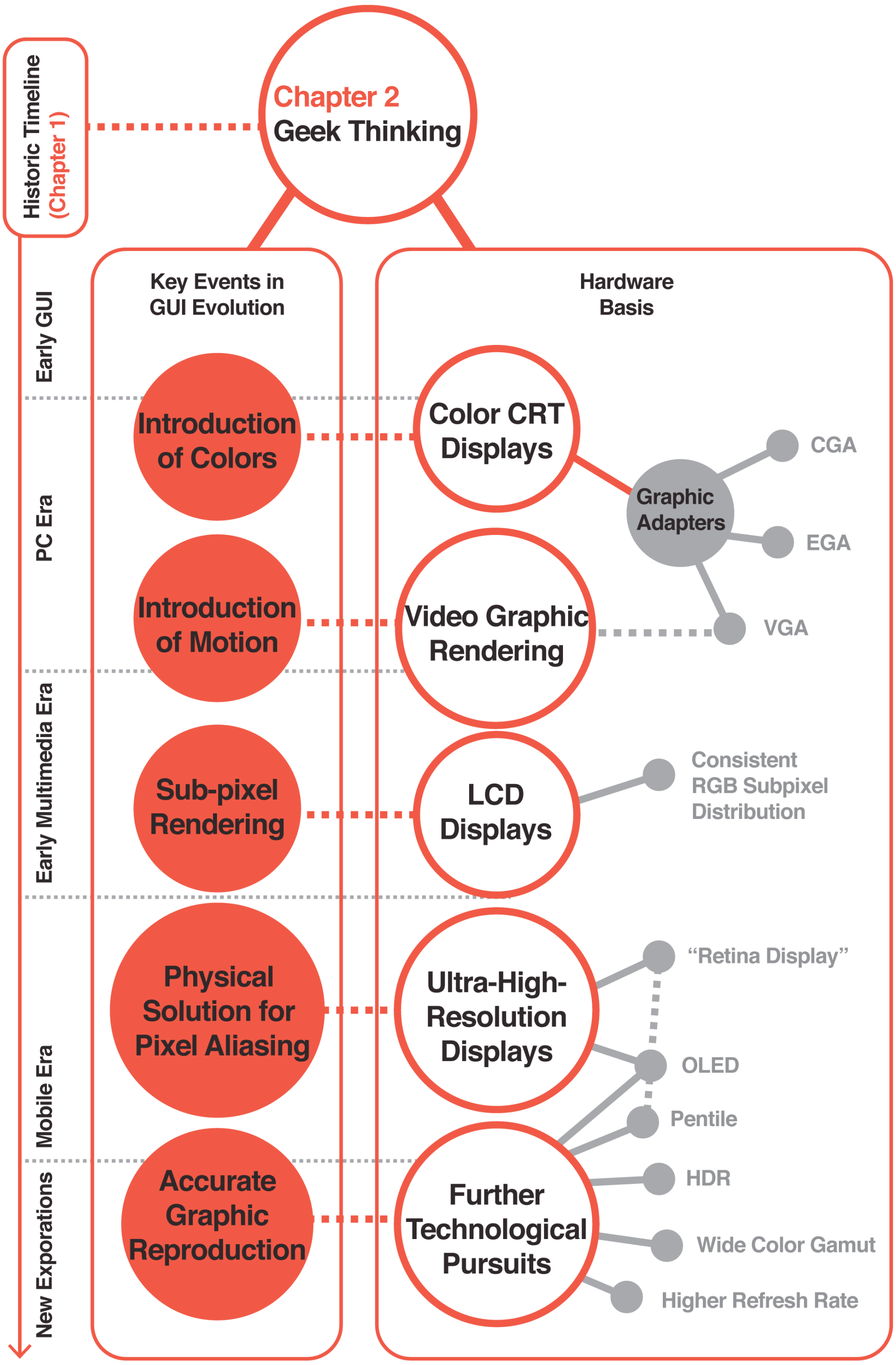

Figure 26 **Heda Weng**, (2019), *Mind Map of Chapter 2*. Courtesy of the author.

2.2 Research Diagram

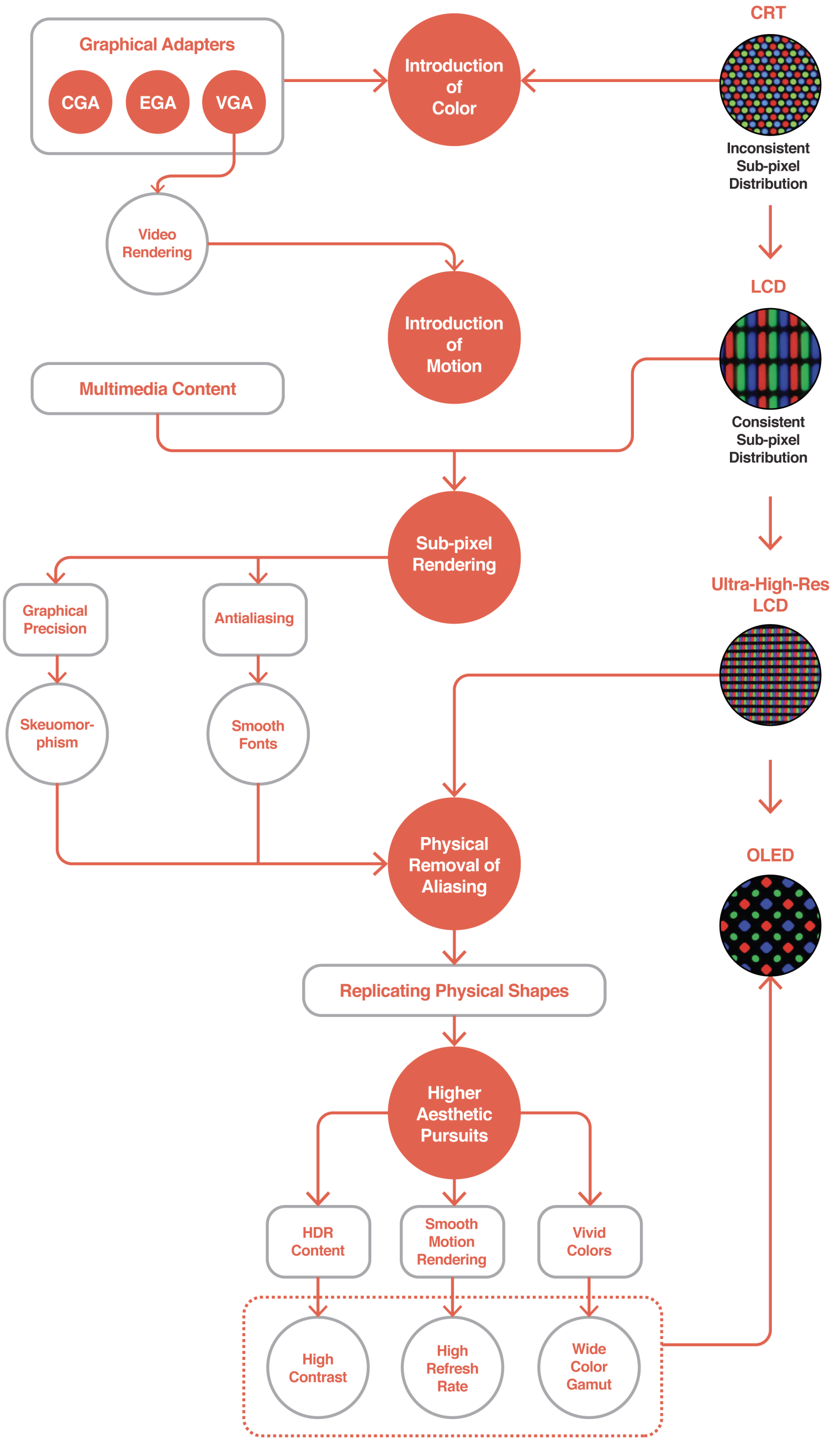

Figure 27 **Heda Weng**, (2019), *Research Diagram of Chapter 2*. Courtesy of the author.

2.3 Summary of Research Results

We expanded the technological depth of our investigation in Chapter 2. Based on the key events along the evolution history of GUI, we used the comparative analysis methodology to investigate the relationship between interface rendering methods and graphic hardware.

At the beginning of this chapter, we mapped out these key events throughout the evolution of GUIs on our historic timeline:

- **The introduction of colors** marks the popularization of personal computers and the beginning of the PC era;
- **The introduction of motion** marks the maturity of GUI under the WIMP paradigm and the beginning of the early multimedia era;
- **The introduction of sub-pixel rendering** enhanced the graphical precision under limited display resolution, which plays a key role in the transition from the early multimedia era to the mobile era;
- **Physical solution for pixel aliasing** released the graphical potential on displays with the ability of replicating any real-life shapes with precision, marking the exponential growth of smartphones;
- **Further pursuit for accurate graphic reproduction** marks the beginning of the interface exploration of next generation CDDs such as AR/VR/MR and wearable devices.

Focusing on the technological foundation of GUI on CDDs, we made our research of Chapter 2 with the comparative analysis methodology. We were able to summarize our research results of this chapter with the technological reasons behind the key events of GUI's evolution history:

- **The introduction of colors is the result of the popularization of color CRT displays and the establishment of graphic adapter standards on PCs.** Personal computers were born with monochrome CRT[53] displays and limited

[53] *The cathode-ray tube (CRT) is a vacuum tube that contains one or more electron guns and a phosphorescent screen, and is used to display images.*

graphical potential. GUI started its journey on monochrome monitors and gradually got popularized with the introduction of PCs with color CRT displays: Although limited to a small color set at the beginning, the introduction of colors greatly enriched the design possibilities for the user interface on CDDs, bringing GUI to a sufficient level of usability with an acceptable learning curve facing the broader consumer market.

Figure 28 **Oldskool**, (2015), *The 16 Available Colors with the CGA Standard* [ONLINE]. Available at: http://www.oldskool.org/pc/cgacal [Accessed 12 February 2019].

Technologically, color CRTs is essentially based on the same physical theories as monochrome CRTs: a mask for separating electron beams with a multi-color phosphor-coated layer was added to present colors by combining red, green and blue lights. Similar displays appeared in the market decades ago and got popularized with color TVs. The establishment of hardware standard for graphic adapters[54] was another essential technological basis for color GUI. Since the beginning of the PC era, graphic adapters evolved from Color Graphics Adapter

[54] The expansion card which generates a feed of output images to a display device such as a computer monitor.

(CGA)[55] to Enhanced Graphics Adapter (EGA)[56] and Video Graphics Array (VGA)[57]. With the development of these graphical standards, the palette of the maximum amount of colors that could be displayed in a PC evolved from 16 to 64 and 256 colors; the supported screen resolution increased from 320*200 to 640*350 and 640*480 pixels. The increase of color palette and pixel density enables the possibility of displaying enough windows and controls for office work, making the GUI under the WIMP paradigm suitable for professional usage scenarios.

Figure 29 **Christian Bütikofer**, (2004), *The VGA Standard Enables Video Playback on PCs* [ONLINE]. Available at: https://www.pctipp.ch/downloads/audio-video/artikel/windows-media-player-28296/ [Accessed 27 February 2017].

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[55] *Introduced in 1981, CGA was IBM's first graphics card and first color display card for the IBM PC. It is also the first color computer display standard.*

[56] *The Enhanced Graphics Adapter (EGA) is an IBM PC computer display standard from 1984 that superseded and exceeded the capabilities of the CGA standard. It allows the display of sixteen simultaneous colors from a palette of 64 at a resolution of up to 640×350 pixels.*

[57] *Video Graphics Array (VGA) is a graphics standard for video display controller first introduced with the IBM PS/2 line of computers in 1987.*

- **The introduction of motion is a natural evolution of GUI due to the inclusion of video graphic rendering with the VGA standard and enhanced computing hardware.** During the PC era, VGA became the most widely adopted analog computer display standard; more than thirty years after its birth, we still use the VGA connector for some projectors of today. Other than the support of a rich color palette and a high display resolution, VGA is also introduced with a sufficient connection bandwidth for rendering high-definition videos, expanding the types of media content to be consumed with PCs. The popularization of the VGA standard - along with other hardware enhancements on the speed of CPU, RAM and storage drives under the Moore's law - opened up the possibility of motion rendering on PCs. Transition animation became another essential element of GUI under the WIMP paradigm, marking its maturity at the beginning of the early multimedia era.

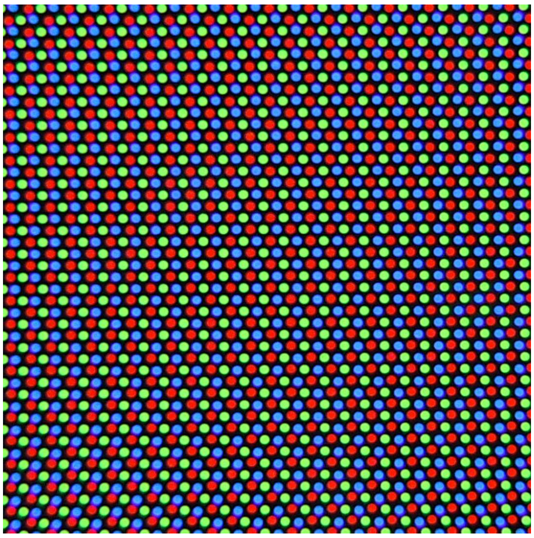


Figure 30 **Superuser**, (2011), *RGB Sub-pixels in CRT Displays Are Not Ordered Within Square Pixels* [ONLINE]. Available at: https://superuser.com/questions/11469/does-subpixel-rendering-technology-such-as-cleartype-have-any-effect-on-crt-disp [Accessed 13 April 2017].

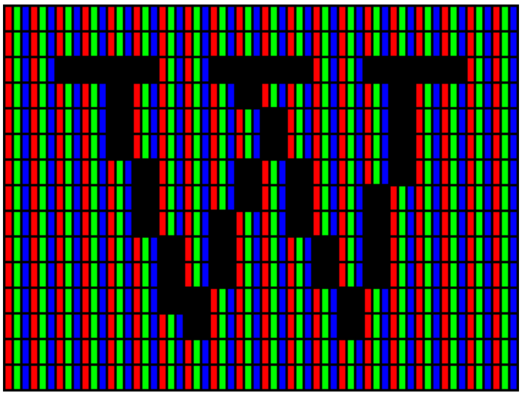


Figure 31 **Alexandru Micu**, (2017), *LCD Displays Have Consistent Sub-pixel Arrangement* [ONLINE]. Available at: https://www.zmescience.com/science/lcd-triple-resolution-subpixel/ [Accessed 15 November 2018].

- **The introduction of sub-pixel rendering is linked with the supplantation of CRT display technology by LCD[58] display technology.** At the beginning of the 21st century, LCD supplanted CRT as the most popular type of PC displays. LCD displays were clearly born with many advantages over CRT: the display panel is completely flat, removing all of the necessity to compensate the distortion caused by the curved glass shell of CRT displays; it consumes far less space, providing many new possibilities for the industrial design of PCs; LCD is also more energy efficient, reducing the space redundancy for heating problems. Most importantly, unlike CRT displays, LCD displays for PCs are manufactured with consistent RGB sub-pixel distribution: each pixel on a LCD display has a square shape; each pixel consists of three sub-pixels of red, green and blue color; the order of sub-pixels is consistent throughout the whole panel.

[58] *A liquid-crystal display (LCD) is a flat-panel display or other electronically modulated optical device that uses the light-modulating properties of liquid crystals.*

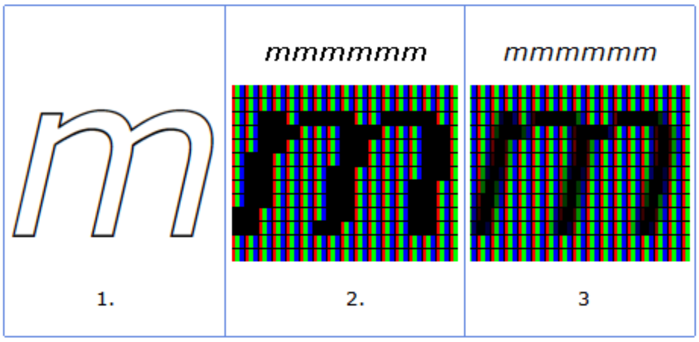


Figure 32 **Hanli Wang**, (2012), *Sub-pixel Antialiasing of the Letter "m" on LCD Displays* [ONLINE]. Available at: https://www.researchgate.net/figure/1-letter-m-in-italic-2-whole-pixel-rendered-m-with-jagged-edges-3_fig1_261387148 [Accessed 12 February 2019].

Consistent RGB sub-pixel distribution brings the advantage that with certain algorithm in the software, each sub-pixel could be utilized directly for interface rendering. If we consider sub-pixels (instead of pixels, in the case of CRT) as the basic unit of LCD displays, with the same display resolution, the number of the minimum unit for interface rendering has an instant growth of 3 times. Adapting to these characters of the LCD display, the minimum consistent unit in the display technology became the sub-pixels. The technology of sub-pixel rendering dates back to the end of the 20th century, when *Microsoft announced ClearType at COMDEX in 1998*. **(Sinofsky, 2009)** In order to take advantage of the characteristics of LCD displays, sub-pixel rendering as anti-aliasing solution was finally introduced to the public by being integrated into various PC operating systems such as Windows Vista and Mac OS X. With this new interface rendering technology, the precision of interface got further enhanced. For the first time, GUI is precise enough to be observed from a closer distance. Sub-pixel rendering technology opens up the possibility of utilizing LCD displays in smaller sized devices, making them a suitable technological choice for phones. The interface visual styles and rendering technologies got carried over to the first generation of smartphones such as the iPhone and the Palm Pre, opening up a brand-new epoch of personal computing: the mobile era.

- **The physical solution for pixel aliasing was brought out by the popularization of ultra-high-resolution displays.** As described above, smartphones were born with LCD displays and sub-pixel interface rendering. The display of the first generation smartphones in the consumer market had a pixel density in between 100 and 200 ppi[59], which was slightly more precise than the LCD displays found on the laptops during the same era. However, as smartphones were designed for light computing and digital content consuming, their entertainment property got emphasized. As a result, the aliasing effect on the display of smartphones became a bottleneck for their software user experience.

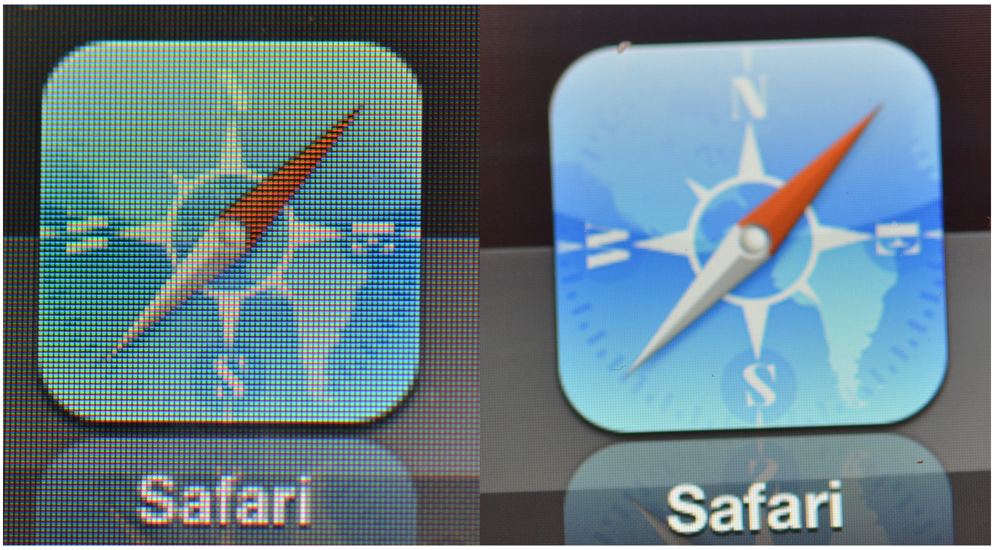
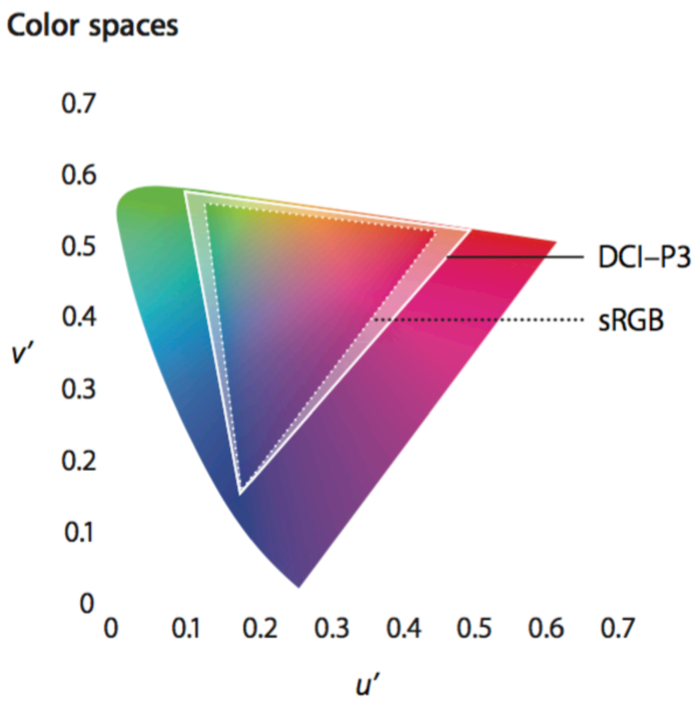


Figure 33 **Anand Lal Shimpi**, (2012), *Ultra-High-Resolution Displays Physically Removes Aliasing* [ONLINE]. Available at: https://www.anandtech.com/show/5655/physical-impressions-of-the-new-ipad-retina-display-shots [Accessed 12 February 2019].

With the evolving technology, the pixel density of smartphone displays gradually got increased to a level where individual pixel is virtually unperceivable within normal observing distance. Represented by the "Retina Display" introduced by Apple in 2010 with the iPhone 4, displays with similar pixel density rapidly got popularized in the fast-growing smartphone market. Ultra-high-density displays gradually expanded their application to other CDD categories such as tablets, PCs and wearable devices, eliminating the necessity of compensating pixel aliasing in the software. In modern CDDs from the mobile era, any shape from the physical

59 Pixels per inch (ppi) is a class of measurement for the pixel density (resolution) of an electronic image device.



world could be smoothly rendered without noticeable deformation caused by the pixels in the digital world, bringing GUI's level of precision to a brand-new phase.

Figure 34 **Apple**, (2012), *DCI-P3 Color Gamut Is Able to Display Colors with More Vibrancy in Comparison to the sRGB Standard* [ONLINE]. Available at: https://www.apple.com/imac/ [Accessed 05 May 2013].

- **The further pursuit for accurate graphic reproduction is related to some new advancements on CDDs' display technology** such as the popularization of OLED displays, the introduction of HDR, the application of color profiles with wider gamut and the further promotion of display refresh rate. In the last decade, display technologies on CDDs continue to evolve in several areas: pixel density, color gamut and refresh rate. All of these advancements further improved the preciseness and smoothness of CDDs' user interface. The material used to manufacture displays got updated once again, as OLED[60] became a new generation of mainstream material utilized for CDDs' displays after CRT and LCD. On an OLED display, each sub-pixel is an individual LED which could be totally

[60] An organic light-emitting diode (OLED) is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current. They are used to create digital displays in devices.

switched off, bringing the possibility of displaying true black color without any light leaking. This greatly enhanced the contrast and dynamic range of the display, improving the experience of HDR video content consuming. Furthermore, OLED displays are built above a plastic film, making them flexible enough to be folded in three-dimensional shapes. These advantage of the OLED material opens up the possibility to design and manufacture displays in non-planar form factors. On wearable devices, OLED displays can follow the form of the device and take advantage of the device's surface as much as possible; on head-mounted AR/VR/MR devices, OLED displays curve around the lenses in order to adapt to user's eyesight even better. Further technological pursuits on the displays represented by the application of flexible OLED displays is the beginning of a new era of display technology, opening up a huge space of imagination for both the interface and the industrial design of next generation CDDs.

Figure 35 **Pilar Bernat**, (2014), *Flexible OLED Displays Curving Around the Edges of Smartphones* [ONLINE]. Available at: https://www.zonamovilidad.es/noticia/9336/noticias-tecnologia-/samsung-galaxy-note-edge-llega-a-espana-en-exclusiva-con-vodafone.html [Accessed 12 February 2019].

After all these “geek thinkings” talking about the evolution of display technologies and talking in all of the technological terms, we have some further curiosities:

What happened to the industrial design of CDDs when new generations of display technologies get mature?

As the major output method on CDDs, how does display collaborate with other input and output portals in certain interaction paradigms?

Case study needed.

Our research in Chapter 2 brings us a vision beyond GUI’s visual evolution. With the in-depth research focusing on the technological reasons and the hardware basis of the key events in GUI’s evolution history, we initially established a bridge between the hardware (physical) part and the software (immaterial) part of CDDs. In the following chapters, we made some further explorations based on the research results of this chapter:

- In Chapter 4: Sublimation of the Gadgets, according to the evolution history of display technology, we further explored the industrial design adaptations to the physical and technological characters of display types;
- In Chapter 5: Case Study, we further extended the scope of our technological research. Focusing on the development of graphic rendering technology, we made a case study focusing on the graphics of gaming consoles; related to our research of display types, we made separate case studies focusing on the evolution of CDDs’ input and output methods.

Chapter 3

Learning from the Gadgets

The Reapplication of Classic Industrial Design Theories on the User Interface of Consumer Digital Devices

"People who are really serious about software should make their own hardware."

(Kay, 1982)

Chapter 3 Learning from the Gadgets

The Reapplication of Classic Industrial Design Theories on the User Interface of Consumer Digital Devices

3.1 Introduction and Mind Map

3.1.1 Introduction

At the beginning of our research, we set out with the objective for the comprehension of the relationship between the user interface and industrial design of CDDs. As the first step to research this bi-directional relationship, in Chapter 3, we started out by analyzing industrial design theories' influence on the user interface design of CDDs.

Similar to Chapter 2, our research in this chapter is also mapped out on the historic timeline of GUI's evolution. As a first step, we took out basic interface components from the GUI of each era and analyzed them along with the industrial design of their CDD carrier.

From another perspective, we carried on with our research by analyzing the dimensions of the user interface on CDDs. GUI design started out from carrying traditional graphic design over to computer screens. Analyzing by dimensions, traditional graphic design is an expression form in 2D space; correspondingly, focusing on the design of physical objects, industrial design is realized in 3D.

With metaphors of layers, motions and digital materials, GUI design sits in between traditional graphic design and industrial design's dimensions. Observing the usage of metaphors of 3D objects on GUIs from each historic era is another perspective to analyze industrial design's impact on CDD's user interface evolution. As screen-to-body ratio continues to grow, "*some may see the role of industrial designers diminishing as user interface design continues to permeate product development, other concurrent trends actually emphasize industrial design skills in interface design.*" **(Tannen and Turpault 2010, p. 27)**

Although the physical body of CDDs seems to leave less visual impact nowadays, the phenomenon of applying industrial design theories into interface design is more and more observable.

3.1.2 Mind Map

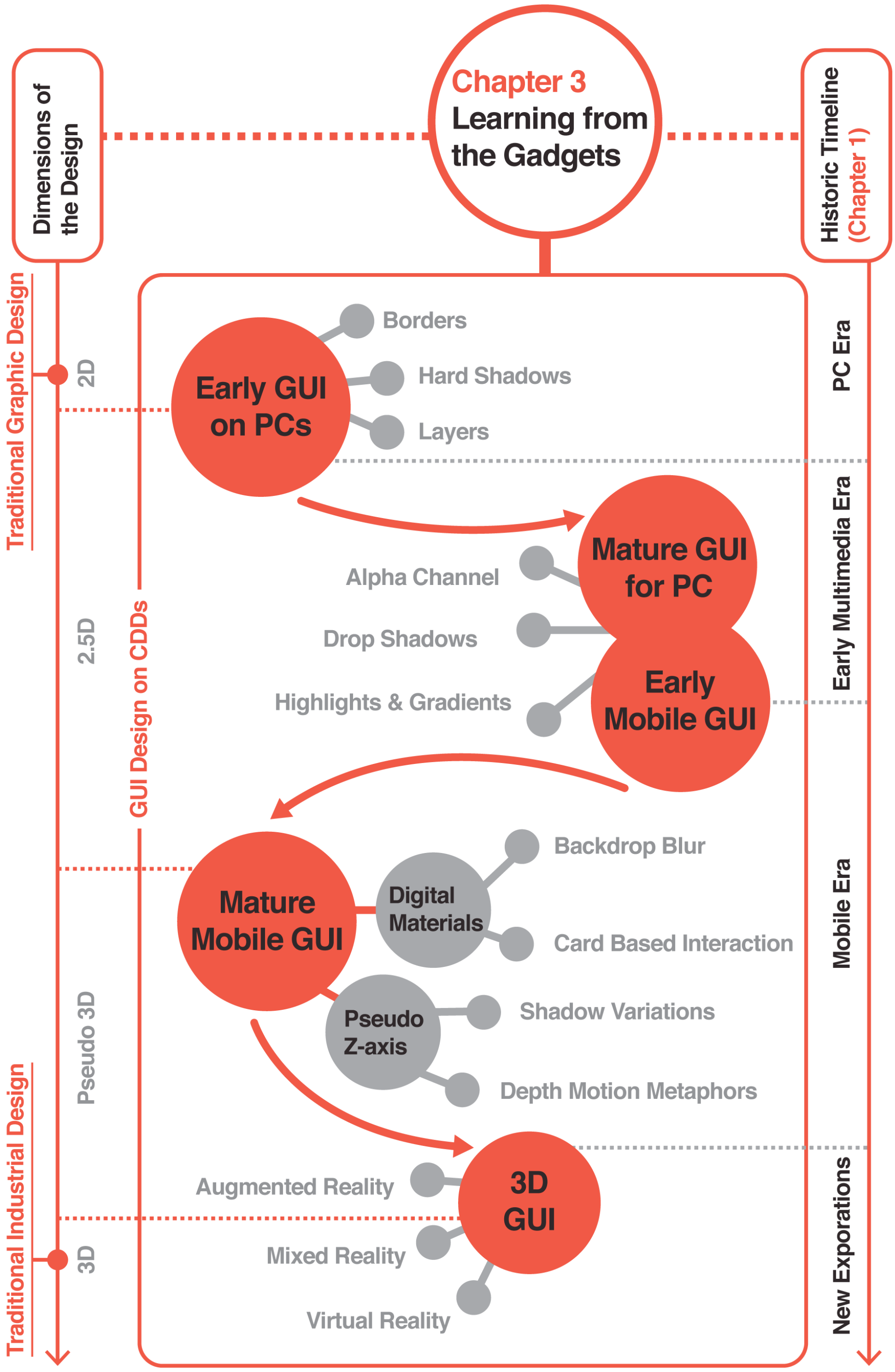


Figure 36 **Heda Weng**, (2019), *Mind Map of Chapter 3*. Courtesy of the author.

3.2 Research Diagram

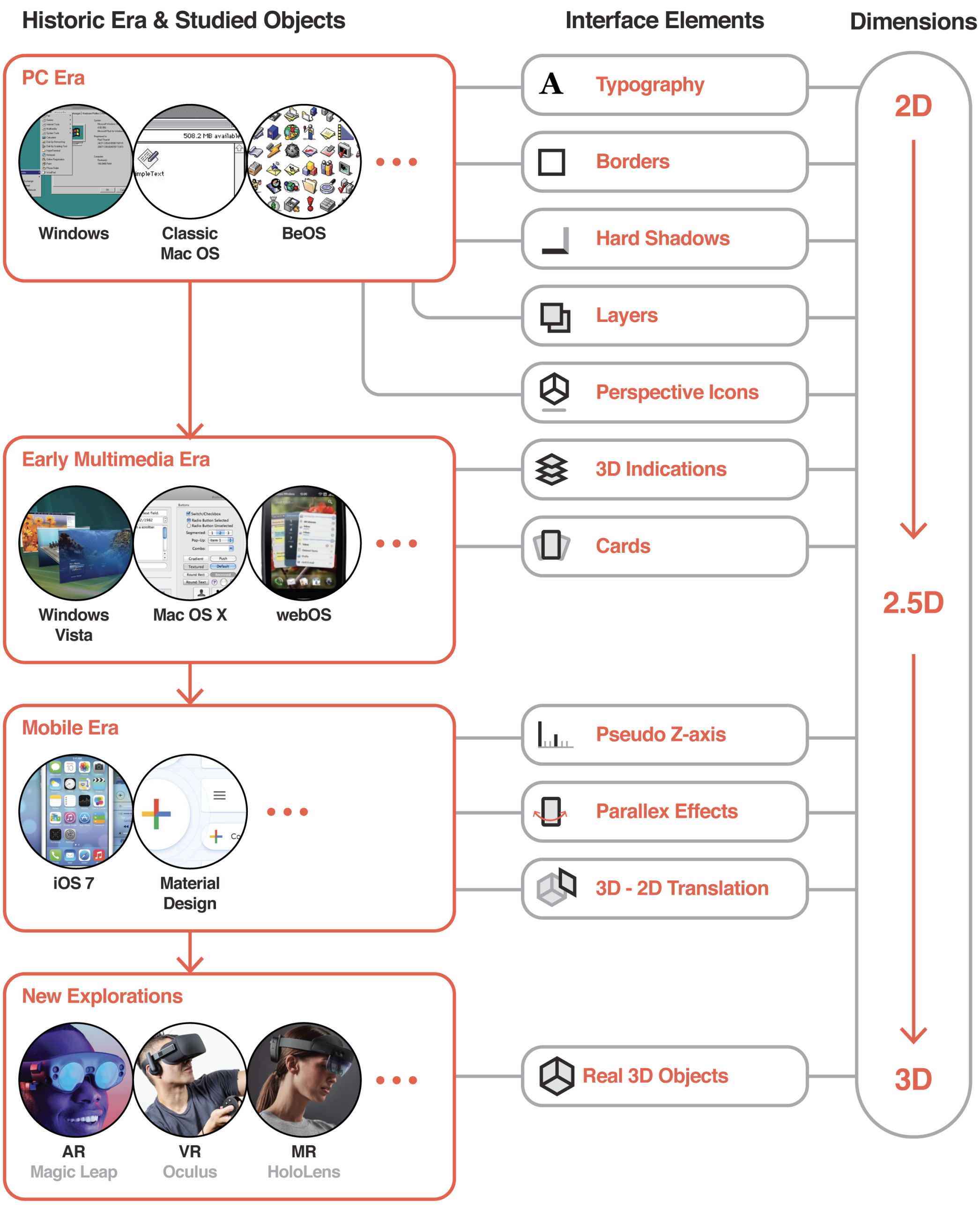


***Figure 37 Heda Weng**, (2019), Research Diagram of Chapter 3 Courtesy of the author.*

3.3 Summary of Research Results

In order to analyze the influence of industrial design on the GUI, based off of our historic timeline, we extracted the basic visual concepts from the user interface of the PC era, the early multimedia era, the mobile era and the new exploration era.

- **At the beginning of its history, GUI design introduced some traditional graphical design concepts into computer interface.** Comparing to its predecessor (text-based user interface), other than being more intuitive, GUI design also utilized the display space with more efficiency by allowing user interface elements laying over each other. Building upon limited hardware rendering power, GUI design took the experience of traditional graphical design techniques such as borders and hard shadows to express the Z-order[61] of graphical layers. As pure graphical elements, the icons in PC operating systems showed even more obvious hint of the real world by the usage of perspectives.

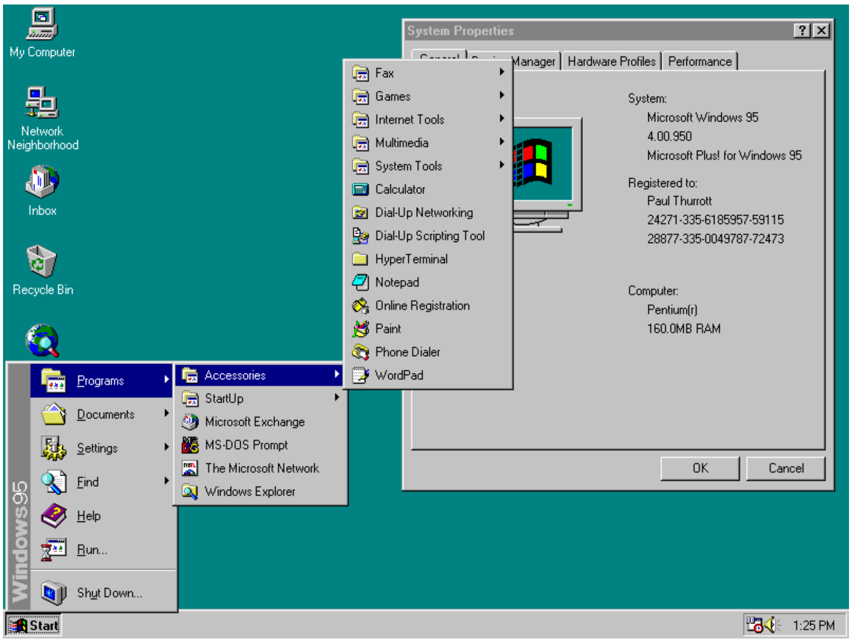


Figure 38 **David Grossman**, (2017), *Windows 95 Uses Borders And Hard Shadows to Indicate Layers* [ONLINE]. Available at: https://www.popularmechanics.com/technology/a27928/22-years-later-windows-95/ [Accessed 11 May 2018].

61 Z-order is an ordering of overlapping two-dimensional objects, such as windows in a stacking window manager, shapes in a vector graphics editor, or objects in a 3D application.

Figure 39 **BeOS**, (2006), *The Icons in BeOS Were Designed with 3D Perspective* [ONLINE]. Available at: http://www.iconarchive.com/show/be-box-icons-by-be-os.html [Accessed 23 October 2014].

- **During the early multimedia era and the beginning of mobile era, some visual hints of 3D space and imitations of physical materials were introduced into GUI.** As graphical hardware power continue to increase, PCs were able to display vivid colors with smooth gradient between them. These advancements prepared the technological basis of rendering different shades of drop shadows, transparency and blurs. Higher pixel density in the displays also unlocked the possibility to use rich textures in interface rendering. An skeuomorphic obsession of visually imitating real-life materials appeared in both PC and smartphone operating systems. In order to pursuit the hardware-and-interface consistency, the user interface elements during that era imitate the materials utilized in their hardware carrier: Windows Vista introduced a frosted glass material to imitate the glass-covered display design in PCs; the Aqua theme of Mac OS X evolved with Apple's hardware design by migrating from an acrylic visual style to brushed metal and frosted metal textures; early smartphone operating systems such as webOS and iPhoneOS took this trend even further by adding highlight to almost any actionable interface elements... Although aesthetically redundant, with the introduction of gradients, highlights, drop shadows, alpha channel and rich texture, skeuomorphic user interface introduced the concept of digital material for the first time.

Figure 40 **Tom Warren**, (2017), *Windows Vista Added 3D Space Indications and Translucent Materials* [ONLINE]. Available at: https://www.theverge.com/2017/4/11/15241580/microsoft-windows-vista-end-of-support [Accessed 18 December 2018].

Figure 41 **Luke Dormehl**, (2017), *Card Based Interface Language of webOS* [ONLINE]. Available at: https://www.cultofmac.com/502864/iphone-x-palm-pre/ [Accessed 17 November 2018].

- **In the mobile era, pseudo Z-axis and behavioral imitation of physical objects introduced to express the spacial relations between interface element.** Introspecting the disadvantages of Skeuomorphism in GUI such as visual distraction, power consumption and design workflow redundancy, mobile interface reached its maturity by applying visual simplification and switching the focus to information design. "*By building interfaces using a system of layers, we solve tricky design problems, flexibly adapt to a variety of screens, and create new patterns that will point the way to future interactions.*" **(Lanier, 2014)** In order to maintain mobile GUI's intuition, card-based user interface further developed the concept of layers with extensive usage of drop shadows introduced the concept of pseudo Z-axis to GUI design. Different shades of shadows were used in Google's Material Design to express the depth and distance in the Z-axis of user interface elements; on Apple's operating systems, translucent materials with different "thickness" were introduced with different degrees of backdrop blur effect. Furthermore, taking advantage of gyroscope data, mobile GUI is able to present some parallax effects when user moves their devices to express the spacial relations between interface elements.

Figure 42 **Apple**, (2013), *iOS 7 Uses Parallax Effects Between Home Screen Icons and Background* [ONLINE]. Available at: https://www.apple.com/ios/ios-7/ [Accessed 11 May 2014].

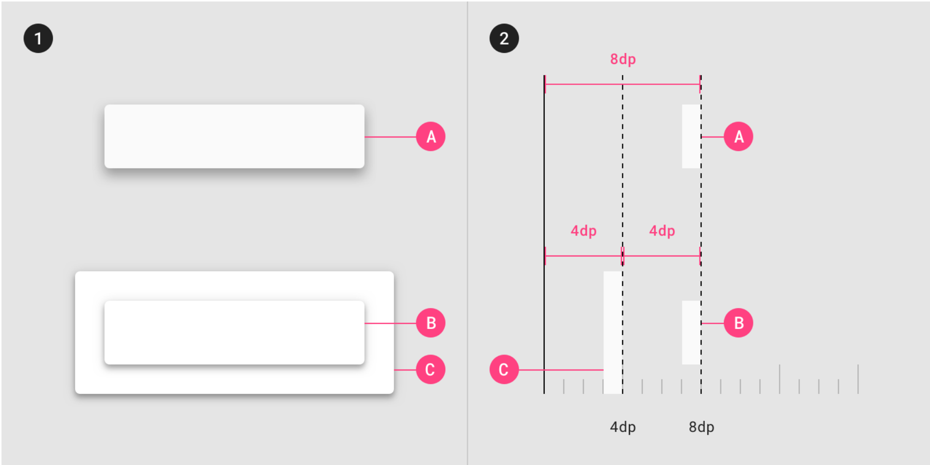


Figure 43 **Google**, (2017), *Google's Material Design Translates Distance on Z-axis into Drop Shadows* [ONLINE]. Available at: https://material.io/design/environment/elevation.html [Accessed 11 November 2018].

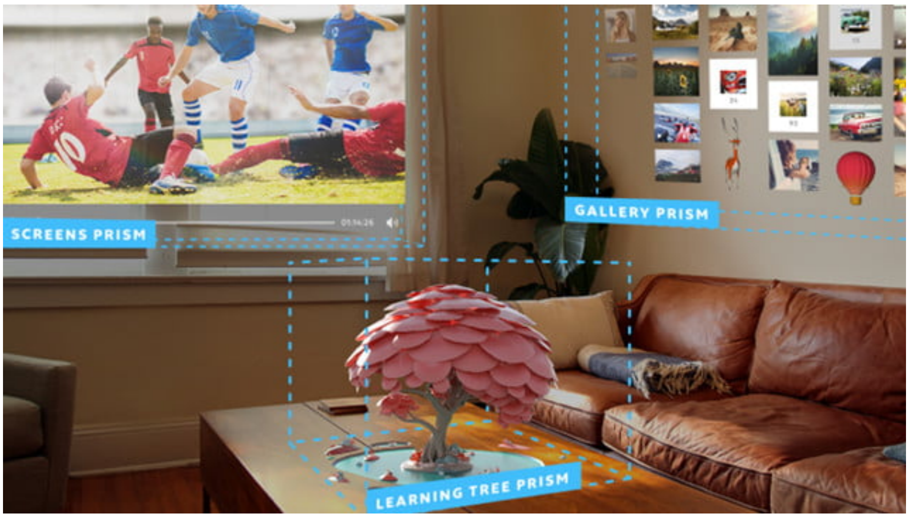


Figure 44 **Sean Hollister**, (2018), *Real 3D Interface Elements in the Magic Leap AR Device* [ONLINE]. Available at: https://www.cnet.com/news/magic-leap-leak-our-first-look-at-magic-leaps-user-interface/ [Accessed 15 January 2019].

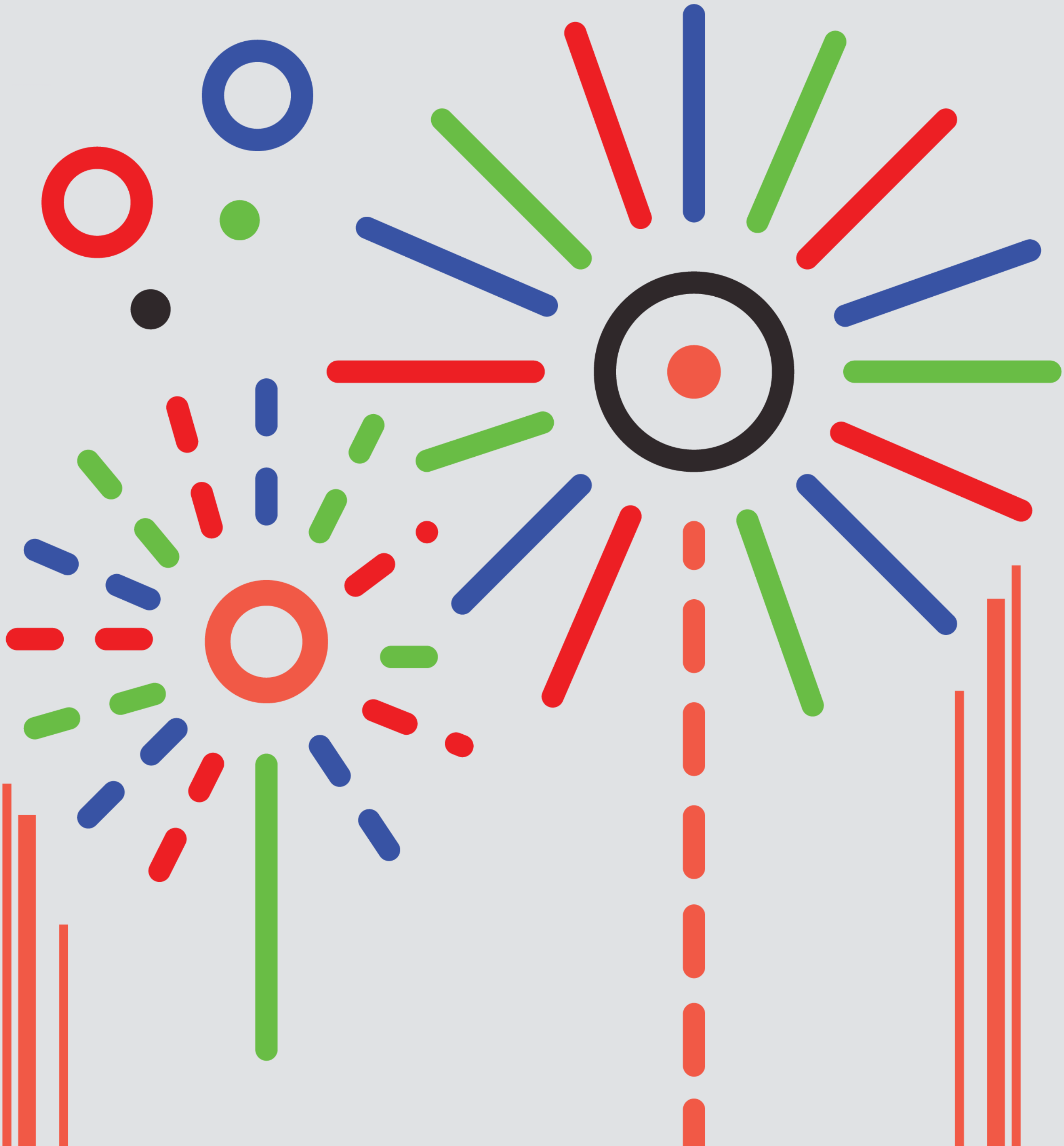
- **As the latest generation of CDDs, AR/VR/MR devices come with GUI in real 3D space.** As the basic concept of AR/VR/MR devices, the user interface of these types of CDDs replaces or integrates with the physical environment. As an extension of this 3D nature, all of the user interface elements on these devices are distributed in a real 3D space. Early intents of directly placing 2D interface elements in the AR/VR/MR environment has yet to see commercial success due to their uncorrespondence with the human cognition. As the latest explorations of CDDs' user interface, real 3D objects are getting introduced as interface elements into the AR/VR/MR environment. Among the three, AR technology is the closest to its maturity as it is getting initial popularization by integrating into major mobile platforms. Both Apple's ARKit and Google's ARCore SDK allows rendering real 3D elements with cameras capturing the movements of objects in the physical world. With these technological advancements, 3D GUI components are born with the ability of replicating both the appearance and the behavior of objects in the physical world; furthermore, the fabrication of 3D GUI elements could be directly integrated into an industrial design workflow as they share the same toolkits.

Summarizing the research results of Chapter 3, we observed a continuous conceptual and visual migration from 2D space to 3D space in the evolution history of GUI. Accompanying this dimension migration was GUI elements' transition from visual imitation of physical materials to behavior imitation of physical objects. The constant influence from physical world to the digital world and the frequent reference of industrial design theories in user interface design motivated the aesthetic and functional enhancements of the GUI on consumer digital devices.

Let's look at the question the other way around.

What is the impact of user interface design upon the industrial design of CDDs?

Our research in Chapter 3 is the first step to study the bi-directional influence between the user interface design and the industrial design of CDDs. In this chapter, we were able to summarize the application of industrial design theories on GUI along the evolution history of CDDs. As a continuation of our research from another perspective, in Chapter 4, we went one step further by researching user interface design's influence on the industrial design evolution of CDDs.



Chapter 4

Sublimation of the Gadgets

The Influence of User Interface Innovations on Industrial Design Theories

Form ever follows function, and this is the law. Where function does not change, form does not change.

(Sullivan 1896)

Chapter 4 Sublimation of the Gadgets

The Influences of User Interface Innovations on Industrial Design Theories

4.1 Introduction and Mind Map

4.1.1 Introduction

“Form follows function” is one of the most important concept in the world of industrial design. As CDDs serve as media consumption devices, the content is gradually occupying more visible surface area in these devices through the expansion of displays. The form of CDDs follows the function of media consumption, as a result, the interface design (for digital content) has a huge impact on the industrial design (for physical device body) of CDDs.

In Chapter 3, we researched and summarized the influence of industrial design theories upon the graphical user interface of CDDs. As the second step for the comprehension of the relationship between the user interface and industrial design of CDDs, in this chapter we continued with a reversed direction by observing the impact of user interface design on the industrial design evolution of CDDs.

With the basic industrial design rule of form following functionality, the essential element to define a CDD category is the combination of its functional components; meanwhile, the pursuit of integrity and aesthetic value is a sign towards the maturity of the industrial design of a certain CDD category; in this phase of industrial design evolution, external influences are generally more observable. Based off of our historic timeline, in this chapter we researched CDD categories with different form factors and made an in-depth analysis of the evolution of their material and structure. Focusing on the design integrity and aesthetic value in the industrial design evolution of mature CDD categories, we further extracted GUI’s visual influence upon the physical body of these devices.

On the other hand, as the major piece of hardware presenting the user interface of CDDs, the form factor of the display itself has its own impact on the industrial design of these devices. The influence of on-screen GUI design upon the overall appearance of CDDs could be measured by the evolution of their screen-to-body ratio. Continuing with the results of the display technology research from Chapter 2, we analyzed the spatial requirement and the achievable screen-to-body ratio with CRT, LCD and OLED technologies. Finally, we summarized display type's influence upon the industrial design of CDDs.

4.1.2 Mind Map

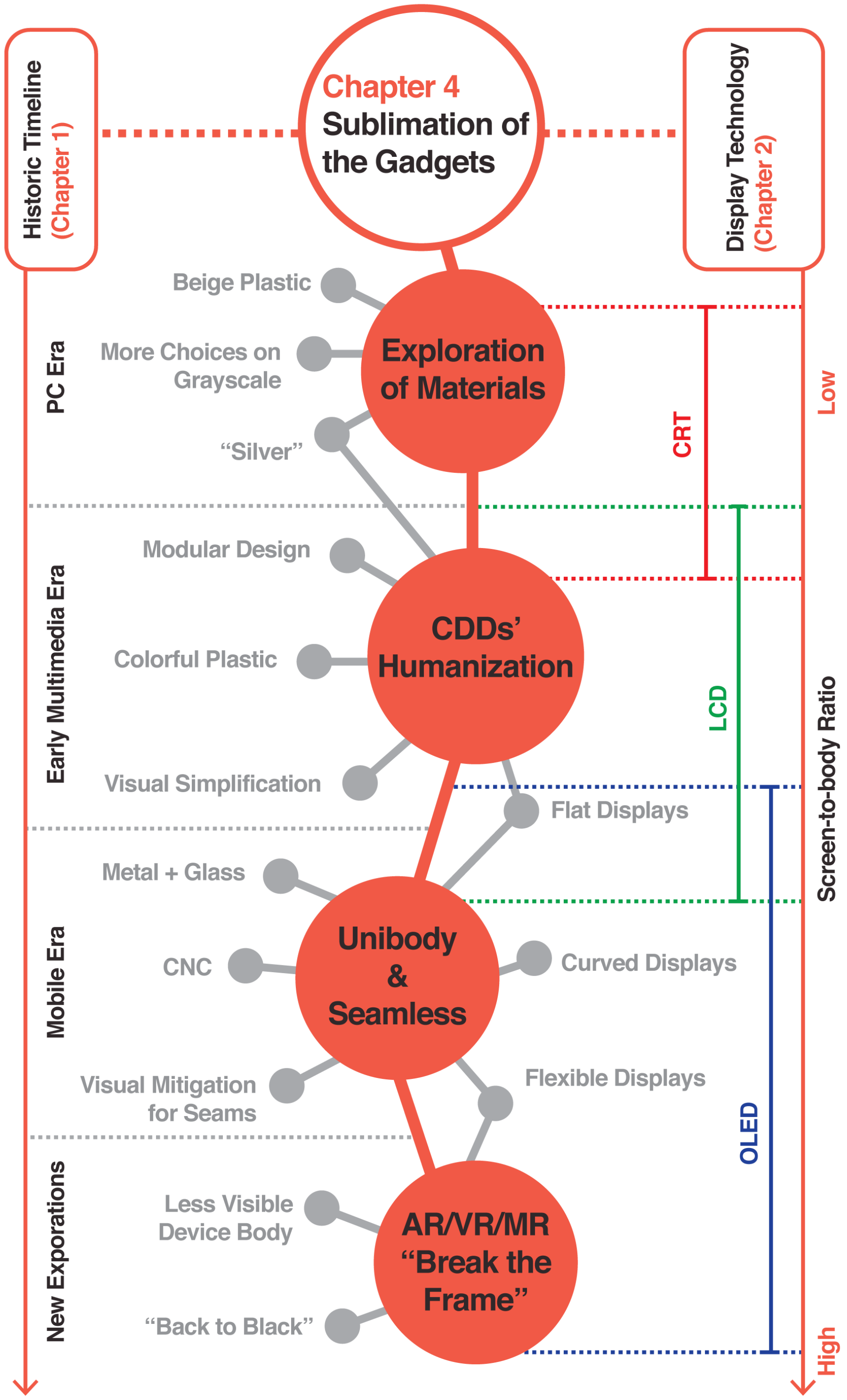


Figure 45 **Heda Weng**, (2019), *Mind Map of Chapter 4*. Courtesy of the author.

4.2 Research Diagram

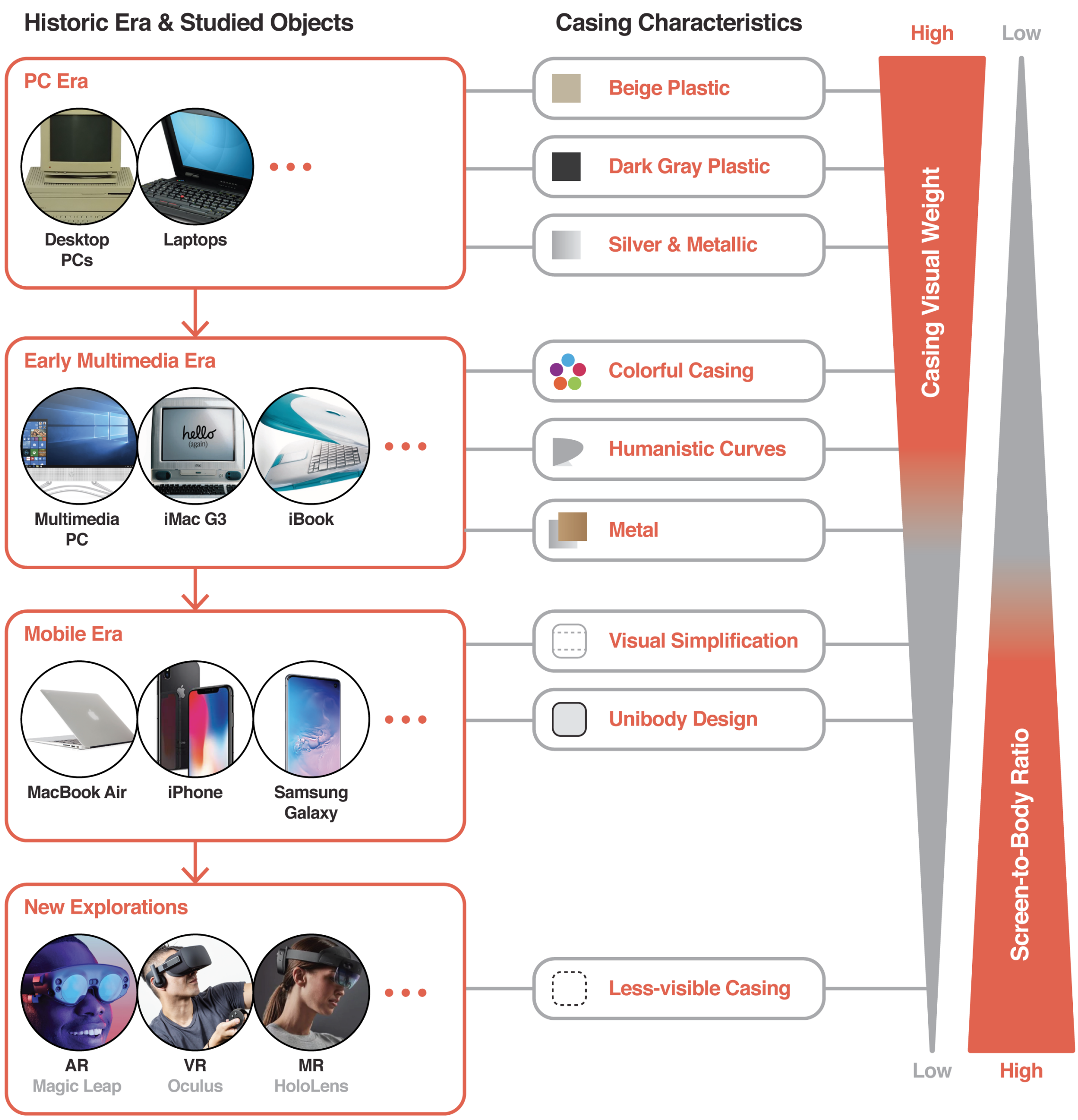


Figure 46 **Heda Weng**, (2019), *Research Diagram of Chapter 4*. Courtesy of the author.

4.3 Summary of Research Results

In Chapter 4, we extended our research from the previous chapter by switching to a reversed perspective and summarizing the influence of user interface innovations upon the industrial design of CDDs.

Similar to the previous chapter, we mapped out the shaping characteristics, material choices and manufacturing processes of the physical body of CDDs in our historic timeline:

Figure 47 **The Centre for Computing History**, (2011), *Beige Was the Most Popular Casing Color in Early PCs* [ONLINE]. Available at: http://www.computinghistory.org.uk/det/211/Apple-Macintosh-IIfx/ [Accessed 13 March 2015].

- **With CRT displays setting a limit on the physical space, the industrial design evolution of PCs started with material explorations.** CRT display technology consumes a huge amount of space in order to place its vacuum tubes and electron guns. Physically larger than the input devices and computing components combined, CRT displays largely limited the space for imagination of the industrial design for early generations of PCs. The exploration on the industrial design of PCs began with materials. At the beginning, in order to attack the consumer market, beige plastic became the principle material for the outer casing of personal computers as its warmer color mitigates user's sense of distance to high-technology devices and brings a user-friendly impression. Later down the timeline, as LCD displays made the laptop form factor possible, darker colors in the grayscale were applied on PCs in order to visually reduce the devices' weight and create an ultraportable impression. High-end PCs also began to experiment plastic with silver and other metallic colors in order to create a harmonious combination with metal components in their casing. During the PC era, the industrial design of CDDs is rather functional, material and color alterations were the few intents of elevating the aesthetic value of these devices. We have not encountered many phenomenons of interface design's influence upon the industrial design of CDD products during the early PC era.

Figure 48 **Frugal Propellerhead**, (2016), *An Early Laptop (ThinkPad 701c) in a Dark Casing Color* [ONLINE]. Available at: http://frugalpropellerhead.blogspot.com/2016/02/the-portable-workstation.html [Accessed 07 November 2017].

- **During the early multimedia era, corresponding to PC's entertainment properties, its industrial design gained a humanistic coat of paint.** As PCs gained the capacity of presenting multimedia content such as music and videos, the entertainment properties of these devices got strengthened. Serving as home media center and major media consumption portals, newer generations of PCs began to appear with humanistic designs. Colorful and translucent materials were applied on the casing of these computers, where liberal curves were also common design elements; the inner structure of these devices were rather modular in order to satisfy the frequent hardware upgrades during that period. During the early multimedia era, we could already observe the beginning of screen-to-body ratio increasements as LCD became the dominating display technology. Corresponding to the growth of screen size, CDDs in the later stage of the early multimedia era began to see visual simplification in the industrial design of their casing.

Figure 49 **EveryMac**, (2002), *iMac G3 Used Liberal Curves And Colorful Plastics* [ONLINE]. Available at: https://everymac.com/systems/apple/imac/specs/imac_333.html [Accessed 12 February 2017].

- **CDD's industrial design gradually adopted a minimization trend in the mobile era.** Traditionally, a gadget is a combination of various functional modules, each module satisfies a certain portion of the product's functionality. The seams in the assemble of gadgets made sense as they indicate both the manufacture process and the range of each functional module. However, in the mobile era, as the input and output methods of smartphones are both integrated into the touch screen, the functionality of CDDs are no longer represented by the physical modules. Instead, CDDs' functionalities are realized with computing power and presented by software interface. As a result, the seams in the industrial design of CDDs became visual interruption. During the last decade, CDDs' industrial design took some aesthetic inspirations from the seamless digital world and entered a trend of visual simplification. Seamless unibody has become the most popular design language on high-end CDD products; instead of a combination of many different materials, the casing of some smartphones only consists of metal and glass; curved OLED displays are utilized in smartphones to visually and physically mitigate their display bezels. The screen-to-body ratio of CDDs have been further elevated in smartphones, making the display covering most of these devices' top surface. User interface has replaced the physical casing as the component of most visual weight in various CDD product categories.

Figure 50 **9to5Mac**, (2011), *The Aluminum Unibody Casing of MacBook Air* [ONLINE]. Available at: https://9to5mac.com/2011/11/21/unibody-on-ultrabook-metal-on-the-outside-plastic-on-the-inside/ [Accessed 25 April 2015].

Figure 51 **Apple**, (2017), *The Edge-to-Edge Display on iPhone X* [ONLINE]. Available at: https://www.apple.com/iphone-X/ [Accessed 08 June 2018].

- **With AR/VR/MR devices, displays are becoming the only visible hardware component in real usage scenarios. The industrial design of CDDs' physical body continues to fade into the background.** Independent AR/VR/MR devices generally come with head-mounted displays. The user interface of these new categories of CDD products replaces or integrates with the physical environments, making user interface the only visible components in the usage scenarios of these devices. In order to minimize the visual interruption from the device casing and to provide an immersive user experience, the industrial design of AR/VR/MR head-mounted displays are fading into the background. Visually, the casing of these devices generally adopts a transparent or dark appearance. The further simplification of casing design further elevates the importance of GUI in these next-generation CDD platforms as user interface becomes the concentrated expression of both the aesthetics and functionalities of these devices.

With the research of Chapter 4, we observed a constant growth of screen-to-body ratio in all CDD categories that elevates the visual importance of digital interface in the overall appearance of devices. Additionally, the evolution of display technologies unchained the screen on CDDs from a flat surface. Flexible displays physically present 2D interface elements in higher-dimension curved surfaces. At the same time, the visual style of user interface design transformed designer's cognition of the necessity of physical seams in the industrial design of CDDs' physical body. As the functionality of CDDs are expressed concentratively in their software applications, physical seams between hardware components are no longer indication of user-facing functional modules. New generations of manufacturing processes such as CNC[62] and supersonic welding[63] were applied in order to achieve seamless industrial designs on CDDs. With AR/VR/MR devices, as the user interface is directly integrated into the physical world, the only visible part of these devices' physical body is the display itself. In actual use cases, the industrial design of these devices' physical body fades into the background; as a result, most current CDD products in this category choose to adopt a either transparent or dark physical appearance to provide a more immersive user experience. The minimization of physical body and the maximization of digital interface could be considered another influence that GUI design applied upon CDD's industrial design.

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[62] *Computer numerical control (CNC) is the automated control of machining tools and 3D printers by means of a computer. A CNC machine processes a piece of material to meet specifications by following a coded programmed instruction and without a manual operator.*

[63] *Supersonic welding is a manufacture process of connecting various pieces of plastic into one integrated piece with supersonic waves.*

Figure 52 **Malcolm Owen**, (2018), *Casing of Head-mounted Display Is Not Visible to Its User During Usage* [ONLINE]. Available at: https://appleinsider.com/articles/18/05/31/what-makes-a-good-ar-or-vr-headset-and-why-apple-is-positioned-to-dominate-the-space [Accessed 03 January 2019].

Combining the research results of Chapter 3 and Chapter 4, we were able to close the loop of our research on the bi-directional influence between the industrial design and the interface design of CDDs.

"*Form and function are one.*" **(Wright 1939)**

Industrial design serves the physical body; whereas interface design serves the digital content.

The physical body and the digital content of CDDs are serving the same purpose of media consumption - this results in the intense bi-directional influence between industrial design and interface design; it paves the way of integrating both design sections in the same design workflow.

As a further confirmation of our research results, we put our theory into practice by analyzing the hardware and software design evolution history of Apple Inc. in the case study chapter.

Chapter 5

Case Study

Chapter 5 Case Study

5.1 Introduction and Mind Map

5.1.1 Introduction

Based on the research results of the first 4 chapters, as an extension to strengthen both the depth and the breadth of our research, we selected several topics for case study:

- **The design history of gaming consoles**. As a category of CDDs focusing on entertainment, gaming consoles invest their hardware power heavily on the graphics. As a result, different types of graphical technologies have been pioneered in gaming consoles, then applied to other generic CDD categories. Studying the design history of gaming consoles provides us an in-depth understanding of the graphical hardware and display technology evolution on CDDs.

- **History of the design of Apple Inc.'s products**. As one of the pioneers that pushed graphical user interface into consumer market and one of the few manufacturers that survived throughout the PC era, the early multimedia era and the mobile internet era, Apple has one of the most complete product line and design history of CDDs. We made a case study of Apple's design history from both the hardware and the software perspective in order to complement with our historical research. Additionally, this case study gives us another chance to observe the bi-directional influence between the industrial design and the user interface design based off of product line evolutions.

- **The history of input methods on CDDs and the history of output methods on CDDs**. As essential components of CDDs, input and output methods directly relate to user's sensory system in any use cases. They are both integral parts of the technological basis of computer-human interaction. With two case studies focusing on the evolution of both input and output methods, we had an in-depth understanding of the interaction paradigms throughout the evolution history of CDDs and further comprehension on the evolution of media consumption behaviors.

5.1.2 Mind Map

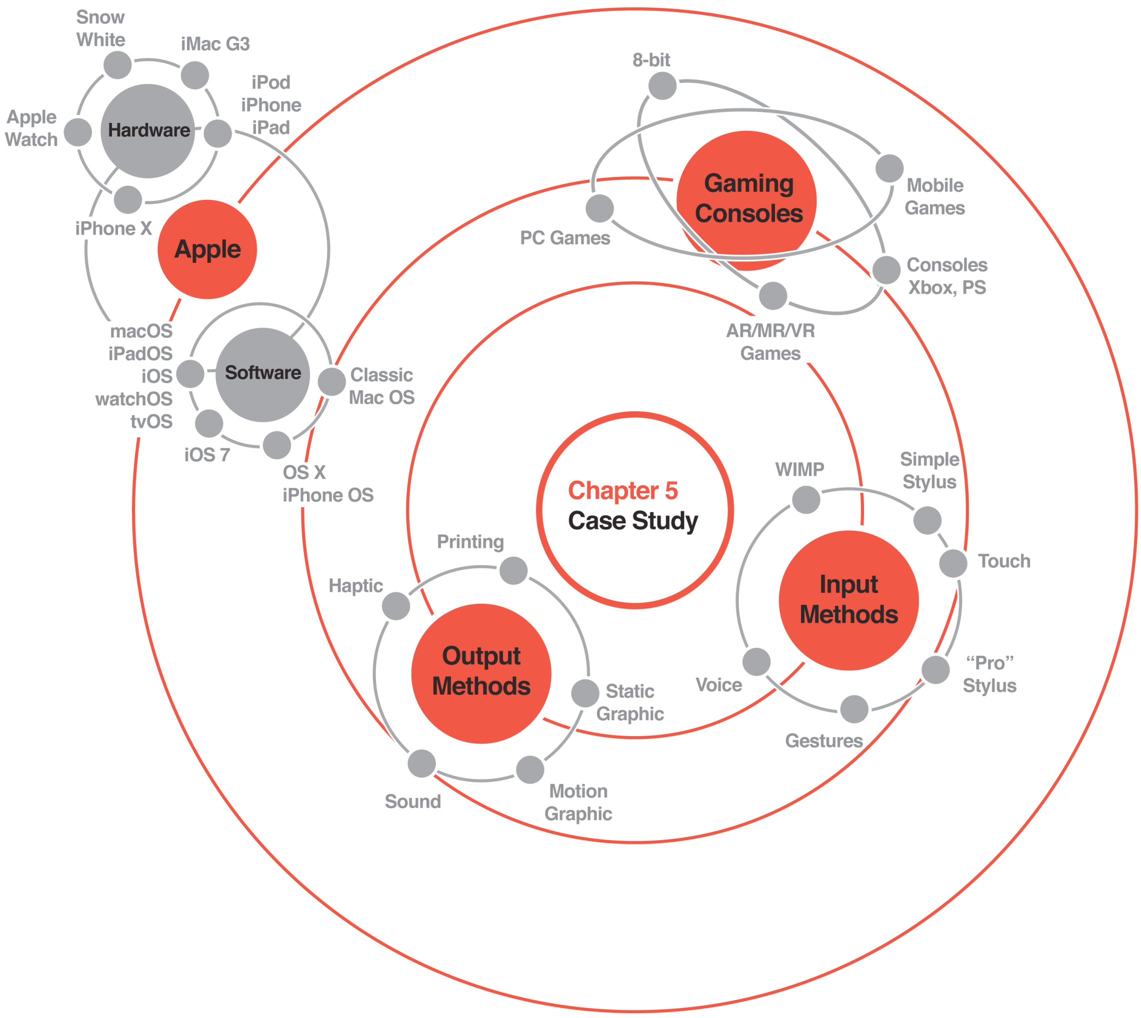

Figure 53 **Heda Weng**, (2019), *Mind Map of Chapter 5*. Courtesy of the author.

5.2 Research Diagram

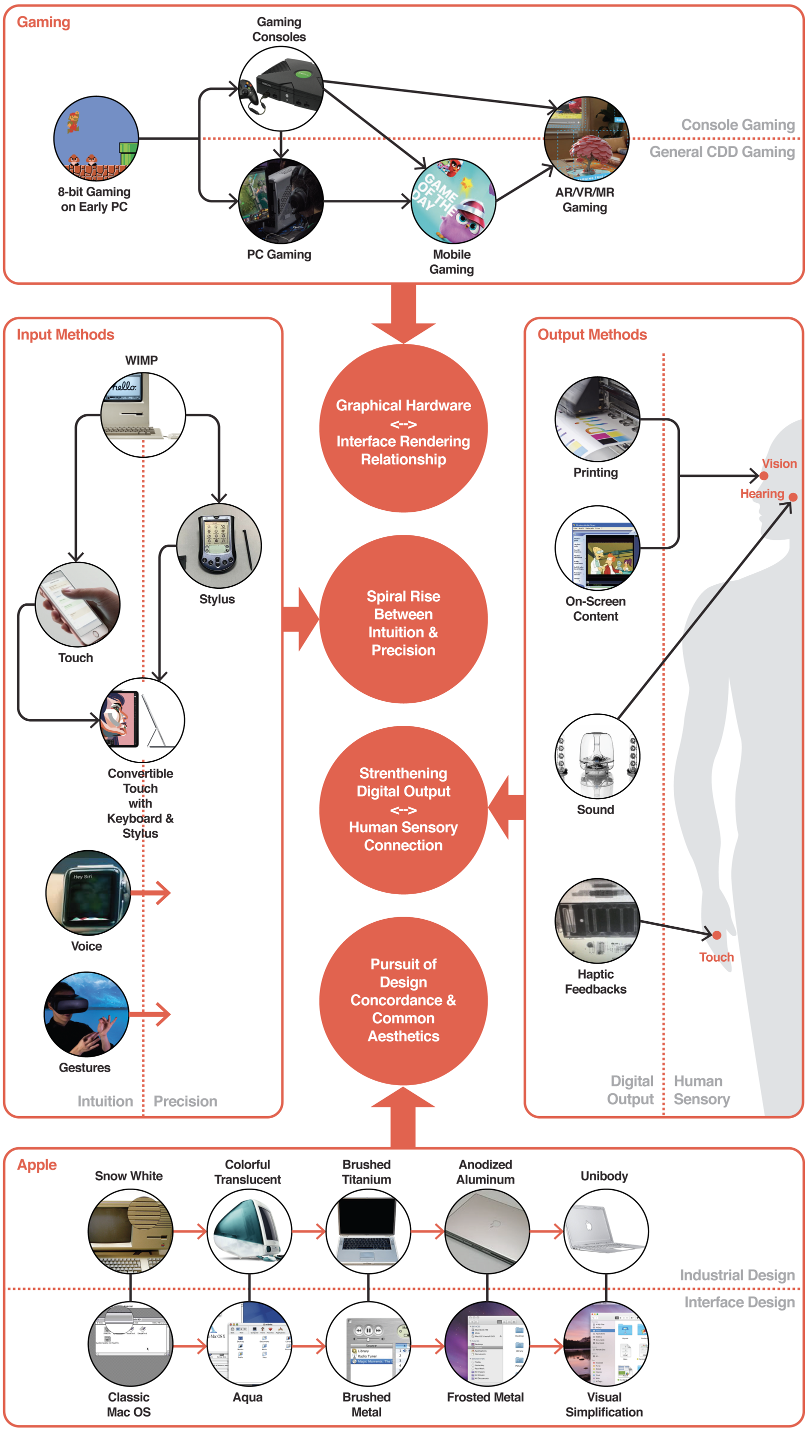

Figure 54 **Heda Weng**, (2019), *Research Diagram of Chapter 5*. Courtesy of the author.

5.3 Summary of Research Results

With the completion of the research focusing on the product-based materials focusing on the history, technology, user interface design and industrial design of CDDs in the first 4 chapters, we selected a few specific perspectives to develop our case study. Focusing on the graphical computing power, input method, output method and a complete CDD product line evolution history, we further diverged the range and depth of our research.

- **In the case study of gaming consoles,** we made an in-depth analysis of the evolution of gaming interface in both console games and games in other generic CDD categories. At the beginning of gaming on CDDs, simple 8-bit games controlled by keyboard was added to PCs as a non-core recreational functionality in order to attract users from the consumer market.

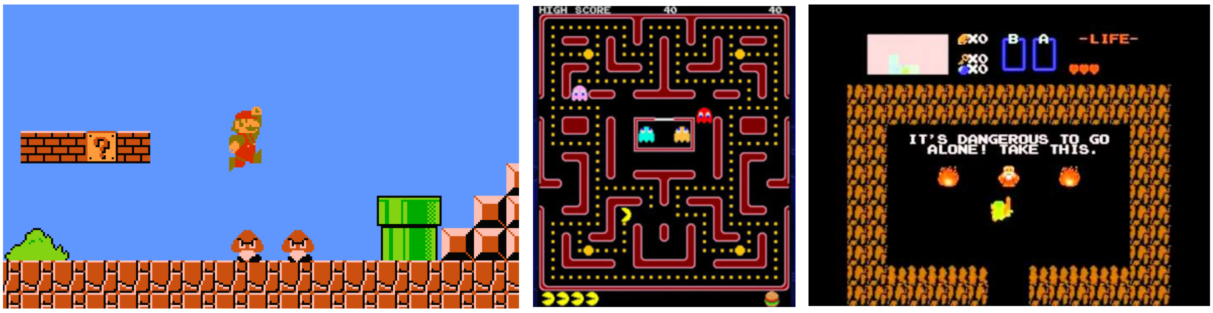

Figure 55 **Hey Poor Player**, (2016), *8-bit Games* [ONLINE]. Available at: https://www.heypoorplayer.com/2016/07/05/top-5-graphically-impressive-8-bit-games-2/ [Accessed 15 May 2017].

Figure 56 **Matthew Hughes**, (2017), *The Xbox Console* [ONLINE]. Available at: https://thenextweb.com/gaming/2017/10/23/you-can-now-buy-but-not-play-original-xbox-games-from-the-xbox-marketplace/ [Accessed 12 February 2018].

With the advancements of graphical hardware and the segmentation of the consumer market, gaming on CDDs developed two branches: as a hardware development branch, gaming consoles such as the Xbox and the Play Station appeared as specialized device focusing on home entertainment experiences; as a software development branch, computer and mobile games drew support from application distribution channels such as Steam, App Store and Google Play Store in generic CDD platforms to cover a larger user base. In order to provide similar experiences and cross-platform gaming functionalities, video games became an important motivity in pushing the advanced graphical rendering technologies developed on gaming consoles into generic CDD categories such as PCs and smartphones.

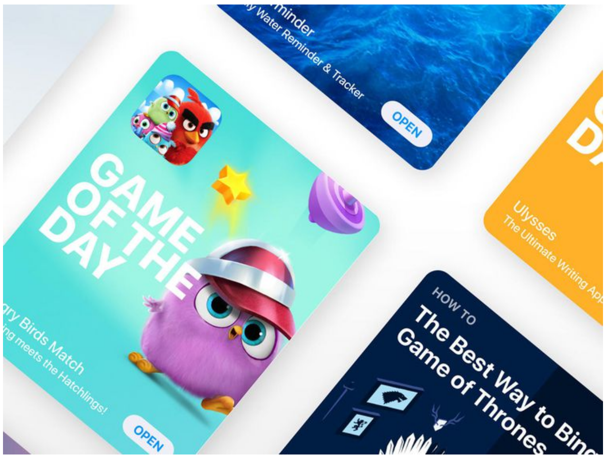

Figure 57 **Apple**, (2018), *Mobile App Stores As Gaming Distribution Channels* [ONLINE]. Available at: https://www.apple.com/ios/app-store/ [Accessed 03 January 2019].

Figure 58 **Jonathan Nafarrete**, (2018), *AR Gaming with ARKit on iOS* [ONLINE]. Available at: https://vrscout.com/news/wwdc-apple-shared-ar-app-experiences/# [Accessed 19 November 2018].

With the research results of this case study, we could summarize that gaming is CDD's experimental field of graphical technology. In the latest generations of CDDs, we could observe the same phenomenon: when AR/VR/MR devices were first introduced into the consumer market, gaming was marketed as the core functionality of these platforms; later on, the graphical rendering techniques of these video games were expanded to software with generic purposes, expanding AR/VR/MR's usage scenarios into the professional and media consumption world.

Figure 59 **Liam Martin**, (2019), *Immersive Gaming Experience in the VR Environment* [ONLINE]. Available at: https://www.express.co.uk/entertainment/gaming/1102355/PlayStation-VR-price-cut-Sony-PSVR-Starter-Pack [Accessed 12 February 2019].

- **In the case study of Apple's Design evolution,** we summarized Apple's design evolution history for both the hardware product lines and the interface of software platforms. We focused our observation in the bi-directional influence between the industrial design of Apple's hardware assembly and the aesthetic orientation of Apple's user interface.

  The first mature industrial design language in Apple's hardware product line history was the "snow white" design language created by Hartmut Esslinger's[64] Frog Design. The basic character of this design language was the usage of beige plastic with rounded corners and vertical/horizontal lines for ventilation. On the first few versions of classic Mac OS[65], which was the Apple's major software platform by then, we could easily encounter with some influences from the "snow white" design language: the whole software interface is framed in a rectangular

[64] Hartmut Esslinger (1944 -) is a German-American industrial designer and inventor. He is best known for founding the design consultancy Frog Design Inc.

[65] Classic Mac OS is the common term referring to the operating system on Apple's Macintosh Computers before the release of Mac OS X. The first versions of classic Mac OS was called "System Software", until Mac OS became the official name for the operating system with Mac OS 7.6.

shape with rounded corner to compensate the curved surface of CRT display; the window titles are wrapped in horizontal lines. Under the constraint of graphical rendering technology of the moment, the software interface already came with some extra design flavor to reflect the appearance of its hardware companion.

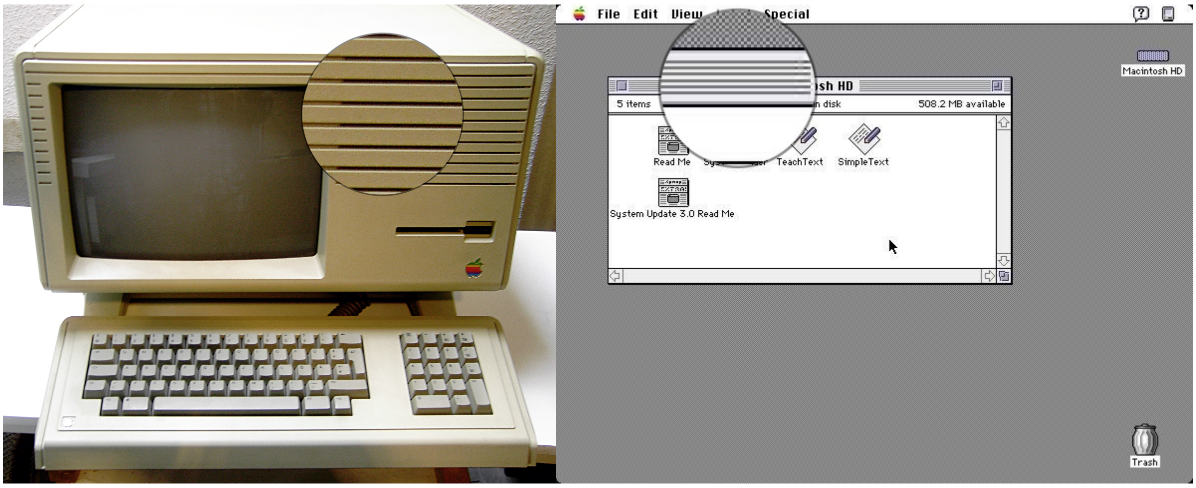

Figure 60 **Heda Weng**, (2019), *The "Snow White" Design Language and The Stripes of Window Titles in Classic Mac OS*. Courtesy of the author.

During the decade of 1990s, Apple faced commercial struggles and its design language remained almost the same until the iMac G3 came out in 1998. At the same time, Apple's main software platform evolved into a new phase: Mac OS X with the "Aqua" user interface. At this moment, the visual style similarity between the iMac hardware and the Aqua interface became very obvious: actionable user interface elements such as buttons and scroll bars are imitating the colorful translucent plastic material used in the back of computer; a stripped texture filled both the empty space of the background of windows and the white plastic frame around the screen; the usage of large radian curves was introduced on both the hardware body and the software interface of Apple during that period.

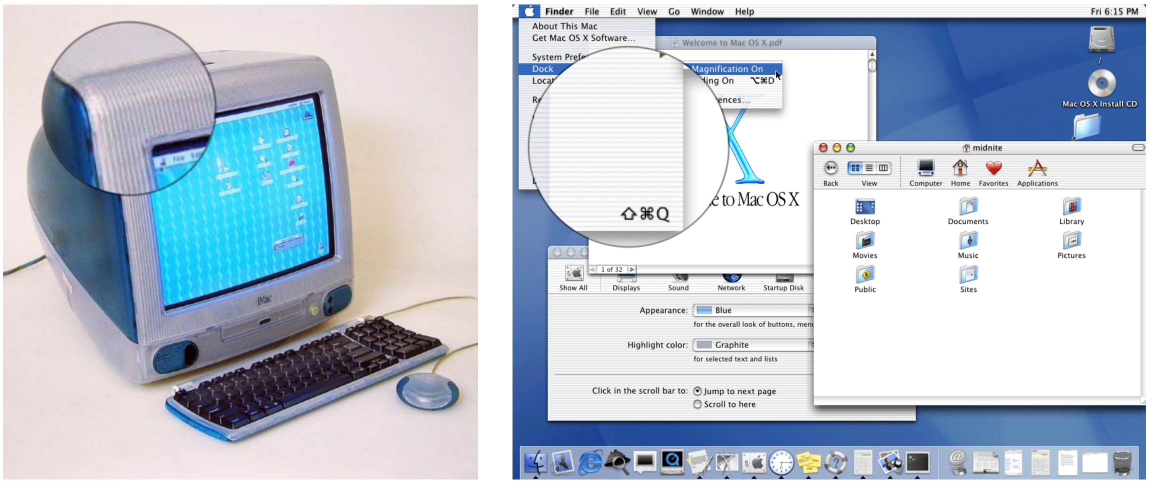

Figure 61 **Heda Weng**, (2019), Mac G3's Translucent Plastic With Mac OS X's Aqua Style. Courtesy of the author.

Since the beginning of Mac OS X and the Aqua user interface style, the software interface of Apple came with an obsession of imitating the material of hardware body: with the translucent plastic of iMac G3, Mac OS X came with colorful acrylic interface controls; with the brushed titanium body of PowerBook G4, Mac OS X used a similar brushed metal texture as the material for window backgrounds; with the aluminum unibody design of MacBook Air, the window material was replaced with a frosted gray texture... The appearance imitation of real-life materials on Apple's software also expanded to its mobile software platform: iOS.

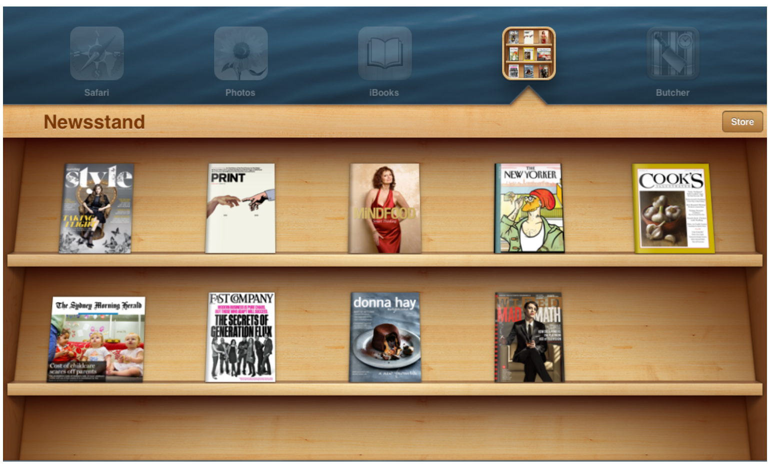

Figure 62 **Sam Gibbs**, (2011), *Skeuomorphism in Apple's "Newsstand" App* [ONLINE]. Available at: https://www.gizmodo.co.uk/2011/10/ios-5s-here-but-whats-in-newsstand-for-us-brits/ [Accessed 14 August 2015].

The first few generations of Apple's mobile software were totally skeuomorphic. With the smaller screen size on mobile devices, the disadvantages of skeuomorphic interface was comprehensively exposed: the imitation of real-life objects used up the limited screen space and visually distracted users from useful information; the usage of complicated textures consumed the limited graphical power of mobile chips; the skeuomorphic aesthetic orientation forced software designers to focus on the appearance rather than the functionality, leading to applications with visual complexity but limited capability.

As a corrective act of the skeuomorphic design language, Apple simplified its user interface with iOS 7 and OS X Yosemite. These new design languages focus on the logic and behavior of user interface components, rather than the superficial imitation of hardware materials. A pseudo Z-axis was first introduced on iOS with translucent digital materials and parallax animations based on the detection of movements from iPhone's gyroscope. As a continuation of this visual simplification, haptic feedback was also introduced to the iPhone, making user interface components feel like physical controls when an action happens. The behavioral imitation of software interface to hardware controls in Apple's platforms was the result of the integral consideration of software and hardware as a unified entity. The combination of hardware sensor data with software display techniques enables software interface's potential to directly react to use behavior without active input.

Figure 63 **Heda Weng**, (2019), *Aluminum Unibody Design And OS X Yosemite's Visual Simplification*. Courtesy of the author.

With the case study of Apple's design evolution, we could summarize that the consistency between the GUI design and the industrial design of CDDs has been strengthened along their historical evolution. The design of software grew from visually hinting its hardware carrier to directly imitating the real-life hardware materials to behaviorally imitating physical objects through deeper integration with hardware sensors and output devices. CDDs' industrial design is getting simplified while their interface design is becoming physical, bringing all the design subjects in CDDs in similar dimensions. Apple's pursuit of design concordance and the common aesthetic development in both hardware and interface design inspires us to further research the design of CDD as a unified workflow.

- **In the case study of the history of input methods on CDDs,** we further extended our research of the interaction paradigm evolution. From WIMP to touch interface, input methods have been playing part of the receiver of use commands.

The WIMP (windows, icons, menus, cursor) is the representative interaction paradigm of the software platforms in the PC era. It was also the first mature GUI interaction paradigm. As the initial purpose of GUI was to represent computing interface in an intuitive way for the introduction of PC in the consumer market, graphical elements such as windows and icons were introduced in the WIMP to help user quickly understand the functionality behind the interface. In order to also improve on the precision of inputs, mouse and its cursor were introduced to the highlight the current actionable item the in PC interface. WIMP and its keyboard / mouse input method was a great start point for GUI evolution as it contained consideration for both intuition and precision.

Figure 64 **Heda Weng**, (2019), Pointing Devices: Mouse, Trackpad and Track Ball. Courtesy of the author.

During the PC era and the early multimedia era, the input methods on personal computers remained almost the same with the expansion of the concept for cursors: in order to integrate the functionality of mouse into laptops, trackballs and trackpads were introduced as alternative pointing devices. Laptops became a portable form factor for PCs; at the same time, there were more aggressive intents to shrink the functionality of PCs into an even smaller form factor. With these intents, PDA[66] was born. For their minimal size, PDAs were not able to deliver the WIMP experience with full-sized keyboards and pointing devices. Stylus was introduced for PDA in order to provide an input method with sufficient precision for text input and content selection. However, as an additional piece attached to the main device, stylus compromised on its intuition. In comparison to other major CDD categories, PDA was short-lived with limited acceptance in the consumer market.

[66] *A personal digital assistant (PDA), also known as a handheld PC, is a variety mobile device which functions as a personal information manager.*

Figure 65 **Joanna Cabot**, (2013), *The Palm Pilot PDA and Its Stylus* [ONLINE]. Available at: https://teleread.com/check-out-my-first-ever-ebook-reader/index.html [Accessed 03 July 2015].

In the mobile internet era, smartphones became the much more adopted replacements for the purposes that PDAs failed to deliver. One of the key reasons of the success of smartphones was the intuitive touch interface. Touch interface inherited the concept of cursors by using our fingers as pointing devices: the tapping action became the equivalent interaction of mouse clicks. With the introduction of touch interface, the level of input method's intuition on smartphones surpassed the keyboard and mouse input on PCs

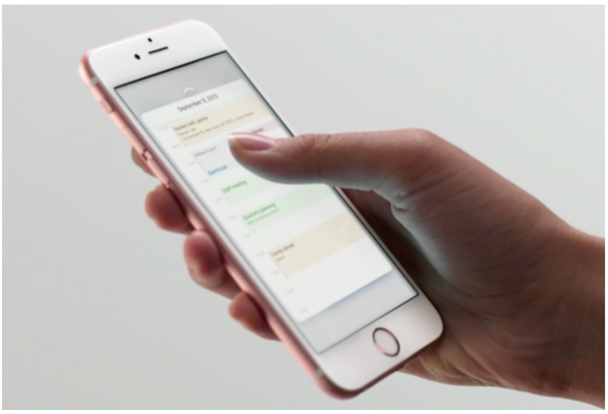

Figure 66 **Apple**, (2015), *Touch Screen As the Major Input Device on Smartphones* [ONLINE]. Available at: https://www.apple.com/iphone-6s/ [Accessed 12 March 2016].

A few years after smartphones got introduced into the consumer market, tablets became another category of CDDs with the touch input method. As tablets were designed to become a category that sits between the PCs and smartphones, their use cases went beyond media consumption. With a larger screen size, tablets have the potential to be utilized for light productivity tasks; however, the lack of keyboard and mouse limited the efficiency and precision of tablets' input workflow. Detachable keyboards and pressure-sensitive styluses were introduced as accessories of tablets to complement the input efficiency of the touch interface, forming a new interaction paradigm in between PCs and smartphones.

Figure 67 **Apple**, (2018), *The Reintroduction of Keyboard And Stylus on Tablets* [ONLINE]. Available at: https://www.apple.com/ipad-pro/ [Accessed 12 February 2019].

Traditional input methods such as keyboard, mouse and touch all depend on the movement of our hands. In the recent years, the industry expanded the research on input methods by integrating voice commands as an auxiliary input methods. Based on computing devices' skills of analyzing human languages, voice assistants are able to translate our voice into computing commands for task execution. Talking is a very intuitive way to interact with our digital devices, however the precision of task execution is limited on today's CDD categories. As the latest industry movement on enhancing the precision of voice input, technology leaders such as Google, Amazon and Apple are using neural networks and machine learning to improve both language understanding and task execution for their digital assistants. As an industry hotspot, voice input has the potential to liberate our hands from computer-human interaction and become the basic input methods for next-generation CDDs such as AR/VR/MR and wearable devices.

Figure 68 **Chris Hoffman**, (2018), *Voice Input for Virtual Assistants* [ONLINE]. Available at: https://www.howtogeek.com/fyi/siri-is-getting-custom-voice-actions-in-ios-12/ [Accessed 12 November 2018].

With the case study of CDDs' input methods, we observed a spiral rise of both intuition and precision for computer-human interaction. The improvement on input intuition is the key to smooth out the interface learning curve of new categories of CDDs and has been an decisive element for their success in the consumer market; the improvement on input precision is the key to unlock the productivity potential of CDDs and has been an important factor for their expansion in professional use cases.

- **In the case study of the history of output methods on CDDs,** we focused on the computing result delivery and media content presentation evolution of these devices.

CDDs deliver the content that they carry through various output methods. The information delivered by output methods are then received by our sensory system, completing the cycle of media consumption within the computer-human interaction process. Commonly recognized sensory systems include our body parts for vision, hearing, touch, taste, smell, and balance. The current output methods on CDDs already have the capacity to cover the first three.

As the first successful category of CDDs, PC with GUI were initially designed for publication use cases. With the idealization of the WYSIWYG concept, display output combined with printing became the first two major type of CDDs' output methods. Both printing and on-display graphical delivering were targeting user's vision. With the continuous improvement on screen resolution, color reproduction and graphical rendering, display is the most important output method for almost all categories of CDDs.

Beginning in the early multimedia era in the evolution history of CDDs, sound became another essential output method in the world of CDDs. The ability of delivering sound unlocked PC's potential of delivering common entertainment media formats such as music and videos, popularizing CDDs as the media center of home entertainment and personal media consumption.

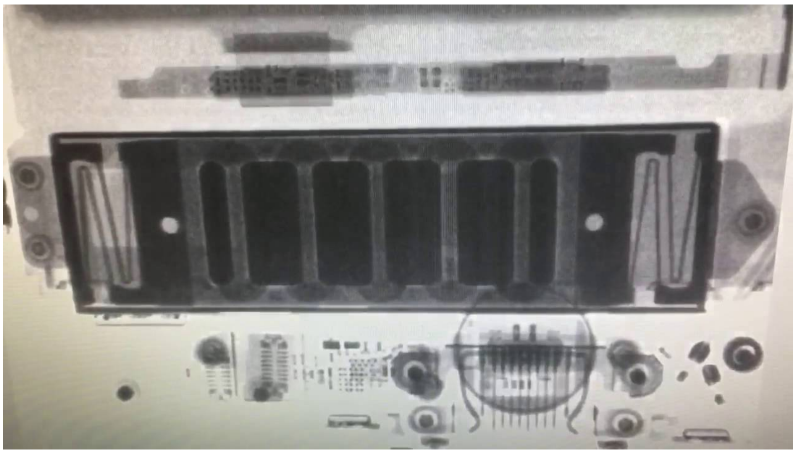

Figure 69 **iFixit**, (2016), *The Inner Structure of "Taptic Engine" for Haptic Feedbacks on iPhone 7* [ONLINE]. Available at: https://www.ifixit.com/Teardown/iPhone+7+Teardown/67382 [Accessed 08 August 2017].

As a recent advancement on touch interface CDDs, haptic feedbacks became an additional output method for smartphones and wearable devices. As a technological evolution of vibrators, the haptic engines in CDDs are able to deliver authentic physical feels during user's interaction with the touch interface, further extending the ability of real-life object imitation on GUI elements.

With the case study of the evolution of CDDs' output methods, we observed the expansion of digital information delivery format though different types of human sensory systems such as vision, hearing and touch. The research results of this case study gave us a hint that the user experience of CDDs in the post-digital era will continue to strengthen its connection with the human sensory system, leading us to an immersive future of computer-human interaction.

Complementing the research results from the previous chapters, our research in Chapter 5 further extended our understanding of several key points in both the industrial design and the user interface design of CDDs:

- The relationship between graphical hardware advancements and the evolution of interface rendering;
- The pursuit of design concordance and the common aesthetic development in both hardware and interface design;
- The spiral rise of both intuition and precision for computer-human interaction through input method evolution;
- The strengthening connection between digital outputs and human sensory.

These case study results replenished the relevance between our historic research, technological research and the bi-directional research regarding the relationship between the industrial design and the interface design of CDDs.

With the hardware advancements in next-generation CDDs, what will happen to their interface?

With the design concordance and the common aesthetic development in hardware and software, is a unified design system for both viable?

Will the participation of biological processes in computing be the result of further pursuit of intuition and precision in computer-human interaction?

We composed our answer in the next chapter of our research.

Combining our research results of the first five chapter, by analyzing the design of hardware components and interface objects in an integral way, in the next chapter, we were able to sublime our research by making our proposal of a unified design system for both the hardware and the interface of next-generation CDDs in the post-digital era.

Chapter 6

An Integrated Future

The Great Unity of User Interface and Hardware Design

Moist mind…

is digitally dry, biologically wet,
and spiritually numinous
combines Virtual Reality with
Vegetal Reality comprises bits,
atoms, neurons, and genes…

is interactive and psychoactive…
is at the edge of the Net.

(Ascott 2000, p.3)

Chapter 6 An Integrated Future

The Great Unity of User Interface and Hardware Design

6.1 Introduction and Mind Map

6.1.1 Introduction

With all of the research results from the previous chapters as our theoretical and practical basis, we set out with the intention to answer these two questions in the research of this chapter:

What are the characteristics of the next generation of CDDs?
What could be a design workflow for these future devices?

To answer the first question, we analyzed the latest internet technologies related to media consumption; to answer the second question, we made our exploration for a unified design system for both the industrial and the interface design of CDDs in Chapter 6.

The creation of this unified design system should take the latest generation of CDDs as its major target. As we analyzed in our historic research, the evolution of CDDs are related with the content that they present. In the post-digital era, internet connection serves as the basic source of content. At the beginning of this chapter, we first analyzed the current state of connection-related technologies and researched the potentials that these technologies could bring to the next generation of CDDs.

From our technological research, we observed the continuous growth of screen-to-body ratio on different categories of CDDs. Focusing on the recent state of CDD design, we noticed two interesting phenomenons related to the display: screens are being added to devices and accessories that traditionally do not include or only include limited GUI; meanwhile, the latest form factors for CDDs such as head-mounted AR/VR/MR devices take their display as the only object that appears in the vision of their users. Both of these phenomenons are clear indications of the continuous elevation of display's importance on the next generation of CDDs. In AR/VR/MR devices, the computer-human interaction becomes immersive; users are interacting directly with the objects that appears in their field of view, regardlessly if they are 3D interface elements or physical objects.

"*Whilst the world at large is only just coming to terms with the Net and the computerisation of society, another media shift is occurring, whose consequences are likely to be even greater. The silicon dry digital domain of computers is converging with the wet biological world of living systems.*" **(Ascott, 2000)**

With a closer integration with the human sensory system, this interaction model already includes some participation of biological process, making moist media the possible content consumption model in future generations of these devices.

With the background research for both the content and display basis on next generation CDDs, we made our exploration on the creation of a unified design system for both their hardware body and their software user interface from different perspectives:

- **From the dimension perspective**, our unified design system is built within the same dimension. All design components in this system is based in 3D with the ability of transitioning into flat graphic objects by projection in the 2D space;
- **From the shaping and rendering perspective**, this unified design system is using the same shaping system for both physical objects and digital components. All design components are built with curvature continuity in order to be rendered and/or manufactured with a smooth appearance;
- **From the workflow perspective**, our unified design system takes the creation of an integrated workflow for both user interface designers and industrial designers working on the same device as an important goal.

Last but not least, we experimented our proposal of our unified design system by substituting this new system into a fictional process for the interface design of CDDs and created a validation demo in Oculus Quest as an additional way of validation for our research results.

6.1.2 Mind Map

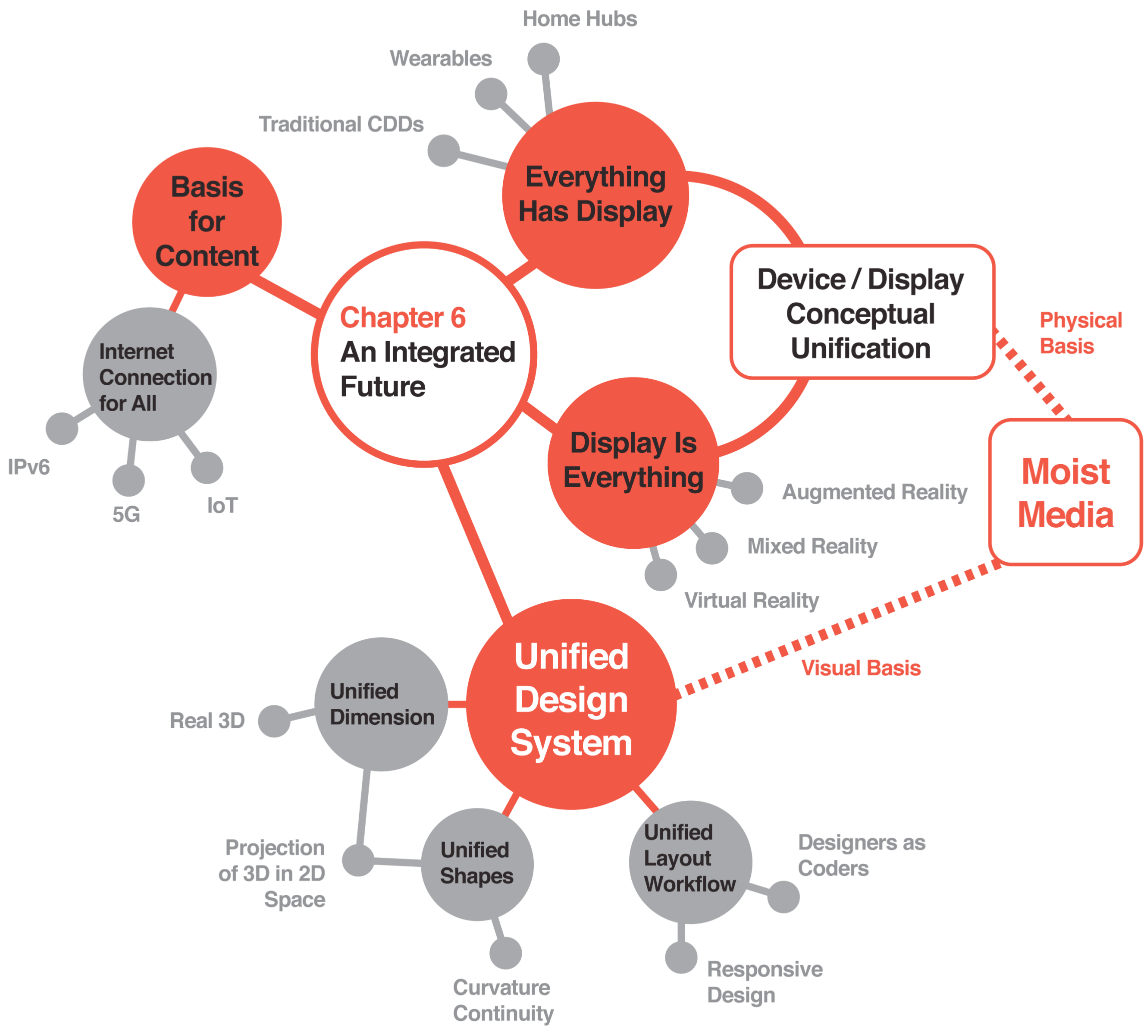

Figure 70 **Heda Weng**, (2019), *Mind Map of Chapter 6*. Courtesy of the author.

6.2 Research Diagram

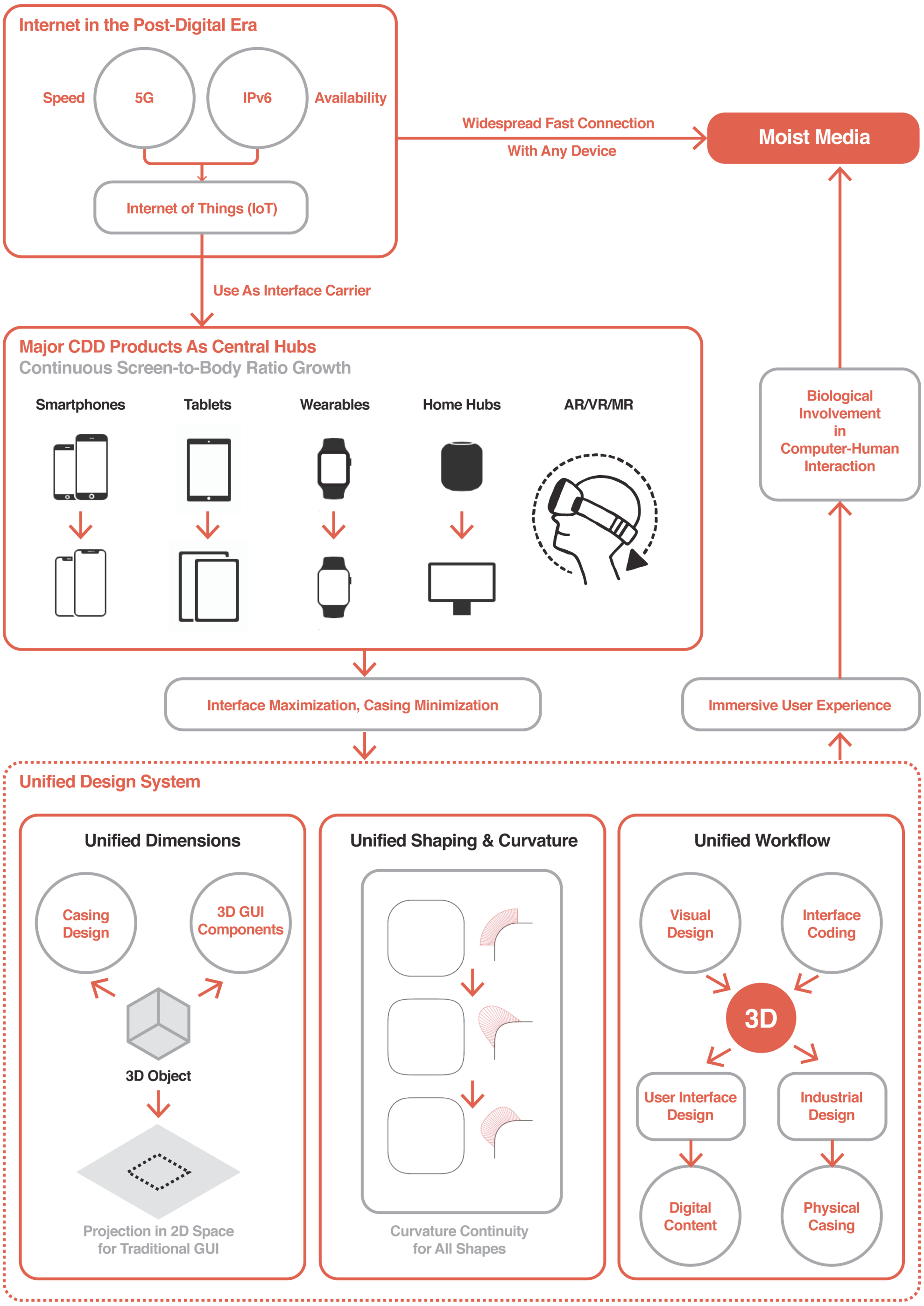

***Figure 71 Heda Weng**, (2019), Research Diagram of Chapter 6. Courtesy of the author.*

6.3 Summary of Research Results

As a sublimation of the research for all the previous chapters, in Chapter 6 we further explored the possibility of the creation of a unified design system for both the software (immaterial) and the hardware (material) parts of CDDs.

Targeting the next generation of CDDs facing the market requirements of the post-digital era, our proposed design system for these devices is built with the consideration of the current state and the future possibilities of these devices:

- **Internet connection is the material basis and the source of the content** for next generation CDDs. We first researched the latest internet connection technologies rolling out into the consumer market. The two most important technologic standards for the next generation of internet connections are IPv6[67] and 5G[68].

  Devices on the internet are assigned a unique IP address for their own identification. However, the currently standard protocol for IP address distribution (IPv4) which was deployed at the beginning of the internet only allows about 4.3 billion individual IP addresses, which is even less than the current world population. As a basic character of the post-digital era, each user owns a set of different categories of CDDs to fit their necessity of media consumption in different use cases; additionally, accessories which traditionally take CDDs as central hubs are also gaining more independence with their own internet connection. In order to solve the address exhaustion problem of the IPv4 protocol, IPv6 was introduced into the market as the next-generation standard for address distribution of the internet. IPv6 is a 128-bit protocol, which means approximately 3.4×10^{38} available addresses could be distributed for all of the digital devices in the world.

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[67] Internet Protocol version 6 (IPv6) is the most recent version of the Internet Protocol (IP), the communications protocol that provides an identification and location system for computers on networks and routes traffic across the Internet.

[68] 5G is generally seen as the fifth generation cellular network technology that provides broadband access.

Another decisive factor for media consuming through the internet is the connection speed. When internet connection was first introduced into the consumer market, the connection speed could hardly deliver clear images; after the development of 3 decades, average CDD users are able to stream 4k videos on any of their devices. Fast speed internet connection mostly replaced the traditional workflow of transmitting data with physical storage media, such as floppy disks, CD/DVDs and even portable hard drives. With instant internet connection, we also store our personal data in the cloud, and fetch them whenever we need it.

However, another important part of CDD's media consumption workflow is still being executed on device: computing and information processing. With the introduction of 5G standard, the internet connection speed could scale up to 430Mbit per second, which opens up a new possibility for CDDs' computing and information processing workflow also being executed in the cloud. In other words, the current design pressure of compressing great computing power into smaller size devices will be released with the introduction of the 5G standard, leaving more flexibility for the industrial design of portable digital devices.

"*Future wireless systems will include myriad smart features and applications to make 5G the most intelligent and dominant wireless technology thus far.*" **(Al-Falahy 2017)** The introduction of IPv6 and 5G provides the possibility of internet connection with enough speed for any object in our daily life. In the future, any product could be considered as a digital device, and a huge proportion of them will be able to take advantage of the displays of the CDDs to display their own interface, similar to the use cases that we could already experience with smart home products. In the post-digital era, with IPv6 and 5G internet connection, CDDs will continue to play an important part of our digital lifestyle as they become the interface carrier and the central hub for internet of things (IoT). This is another evidence of planned obsolescence in the world of CDDs, as a wider range of the previous "dumb" version of everyday objects fall into disuse as they would not have the ability to connect with everything else. As IoT devices are not quite popularized in the today's consumer market, their impact remains to be seen.

"*That's a reality that will unfold one day with internet-connected versions of everything. You've heard the horror stories about Samsung Smart TVs slowing* *down to uselessness with every update, or suddenly getting ads all across the menus before obsolescence, but what happens when it's actually part of your house?"* **(Internet of Shit 2016)**

- **Display is becoming an important standard to distinguish "central hub" CDDs and accessories.** With the new characteristics of on-device internet connection in the post-digital era, CDDs are becoming the interface carrier of digital accessories with the IoT concept. The existence of display in a device is becoming an important standard to distinguish CDD central hubs and digital accessories.

  In reality, some major categories of CDDs, such as PCs, tablets and smartphones are already serving as the central hub of digital accessories. For example, smart home devices such as smart light bulbs and smart thermostats generally come with the absence of physical controls; the functionality of these accessories are realized through certain communication protocols with users' CDDs, as the control interface for these home accessories is presented as applications or software plugins within the screen of the latter. In order to satisfy this new use case, new categories of CDDs such as smart TVs, home hubs and smart displays are becoming popular in the consumer market as the specialized central hub and interface carrier for IoT accessories.

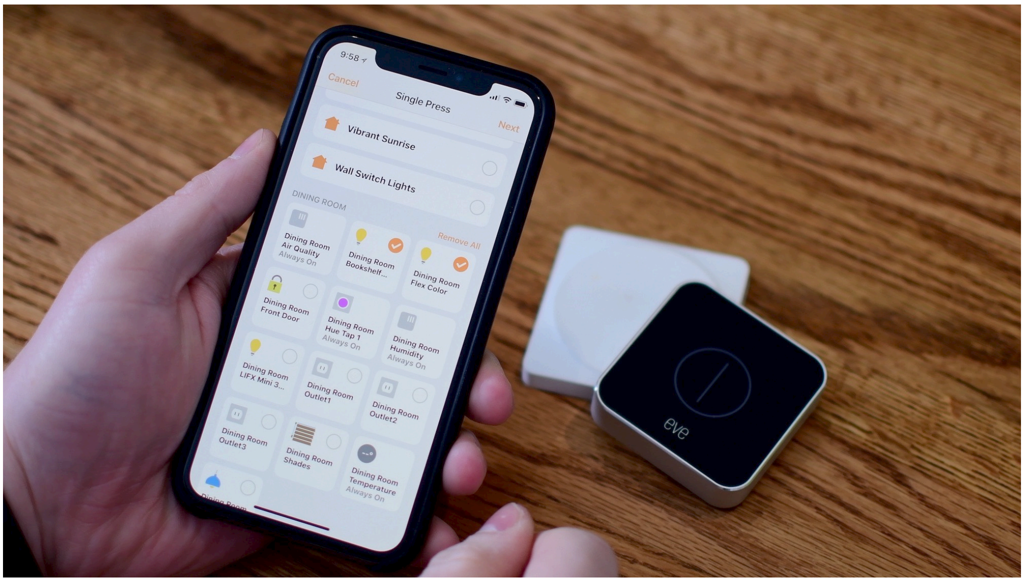

Figure 72 **Andrew O'Hara**, (2018), *Mobile Phone as Interface for Home IoT Devices* [ONLINE]. Available at: https://www.idownloadblog.com/2018/02/06/homekit-automation-how-to-create-toggle-button/ [Accessed 08 January 2019].

On the other hand, devices that were traditionally considered as accessories are gaining their own display and software interface. Wearable devices are assembled with larger displays and greater computing power. Modern generations of wearable device operating systems such as Apple's watchOS and Google's Wear OS enabled the possibility for these devices to execute tasks independently without synchronization to smartphones. With these advancements, wearable devices could be considered as one of the candidates of next-generation central hub CDDs with the ability to control and present the interface of other IoT accessories.

Figure 73 **Apple**, (2018), *The Growth of Screen-to-Body Ratio on Apple Watch (Left: Apple Watch Series 4; Right: Apple Watch Series 1-3)* [ONLINE]. Available at: https://www.apple.com/watch/compare/ [Accessed 05 November 2018].

- **With the growth of screen-to-body ratio, the trend of replacing physical controls with on-screen interface will continue.** With the evolution of interaction paradigms throughout the history of CDDs, displays have been playing an increasingly important part in the process of computer-human interaction. Screen-to-body ratio on CDDs has been constantly growing, bringing software interface closer to the human eyes by occupying more space in our field of vision.

  As another new category of CDDs that is getting popularized in the consumer market in recent years, AR/VR/MR devices brings GUI one step further by directly merging software interface into our vision. On AR/MR devices, digital interface is fading into the background of real-life physical objects by synthesizing the digital world with the physical world. VR devices come with an immersive virtual environment by fully covering the viewable range of user's eyesight. With these new forms of computer-human interaction, displays are becoming the only visible module in the industrial design of CDDs in the AR/VR/MR category.

With the research results on the current state and the future possibilities for the next-generation CDDs, we believe that a conceptual unification of displays and devices is happening. All the central-hub-purpose CDDs are now equipped with displays; in the meantime, the display is occupying a greater proportion of the visible surface on CDDs, ultimately becoming the only visible component in user's vision. The device/display conceptual unification forms the physical basis of moist media consumption in the post-digital era.

After the background research on the characteristics of the next-generation CDDs, we proposed our own imagination of the unified design system for both the software (immaterial) and the hardware (material) parts of CDDs:

- **The unification of dimension system.** In the industrial design and user interface design of CDDs, components with different dimensions are involved. Physical components from a traditional industrial design process as well as the digital objects in AR/VR/MR devices are generally created in 3D; digital interface objects in flat screens for other CDD categories such as PCs, smartphones, tablets and wearables are designed in 2D with pseudo Z-axis and space metaphors.

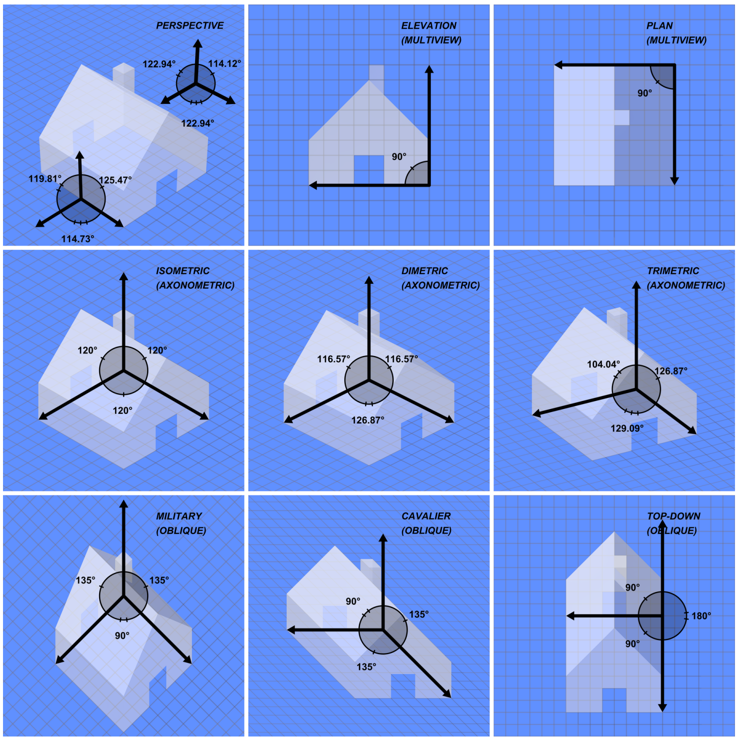

Figure 74 **Wikipedia**, (2009), *Projection of 3D Objects in 2D Spaces* [ONLINE]. Available at: https://commons.wikimedia.org/wiki/File:Graphical_projection_comparison.png [Accessed 18 March 2016].

By dimension, any 2D shape could be generated by projecting 3D object into a flat surface. In our unified design system, all components are created in 3D. According to the use case, physical components and interface objects for AR/VR/MR environments are utilized as-is; in the meantime, 2D interface elements for flat screens are generated by projection, and the depth in the Z-axis can be translated into shadows or backdrop blurs.

- **The unification of shaping curves.** In the world of industrial design, in order to manufacture products with smooth surface transitions, curvature continuity is a frequently used technique. Curves are also frequently used in traditional GUI design, especially for the rounded corners of interface components. With the growth of computing power and the inclusion of ultra-high-resolution displays on CDDs, the calculation and real-time rendering of Bezier curves for curvature continuity on digital interface is no longer a technological challenge. In our unified design system, the shaping curves of any object should contain curvature continuity.

Figure 75 **Apple**, (2017), *Using Curvature Continuity, iOS Interface Elements Align Perfectly With the Casing Shape of iPhone X* [ONLINE]. Available at: https://www.apple.com/iphone-X/ [Accessed 09 November 2017].

- **The unification of layout workflow.** Each category of CDDs comes with its own display size and interaction paradigm. In order to take advantage of the display space adequately, interface layout for the same content should be organized differently according to device category.

As a trend for interface design in recent years, responsive design was introduced as the standard method of adjusting the layout of GUI according to display size. With the introduction of AR/VR/MR devices, display types are expanded from flat displays to head-mounted curved displays. Other than display size, interface dimension is another factor to consider in the organization of interface layout. In our proposed design system, the concept of "responsive design" is slightly expanded: in addition to adjusting the interface layout according to display size, the layout is also rendered in 2D or 3D spaces with the corresponding variations of interface components.

To finish our research development, we proposed a workflow for the creation process for both the hardware design and the software interface design of the next generation CDDs:

- Under the same shaping system with curvature continuity, both physical and interface components are created in three-dimensional space;
- Industrial materials and manufacturing process are then selected for physical objects, while digital materials should be created for interface components;
- In preparation for interface rendering in flat screens, create the 2D variation of interface components by projecting 3D objects into 2D space with the Z-axis depth translated into shadows and backdrop blurs;
- As the last step of interface building, create 2D and 3D layout templates for interface elements according to the display type.

We practically verified our proposed design system with a demo in "6.4 Verification of the Proposed Design System".

6.4 Verification of the Proposed Design System

In order to verify the proposed universal design system for user interface design and industrial design, we put our design workflow into practice.

First of all, we decided to select the Oculus Quest VR headset as our target device. Oculus Quest's technology is based on the Android platform, as a result, the coding of its native software interface is comparable to smartphones.

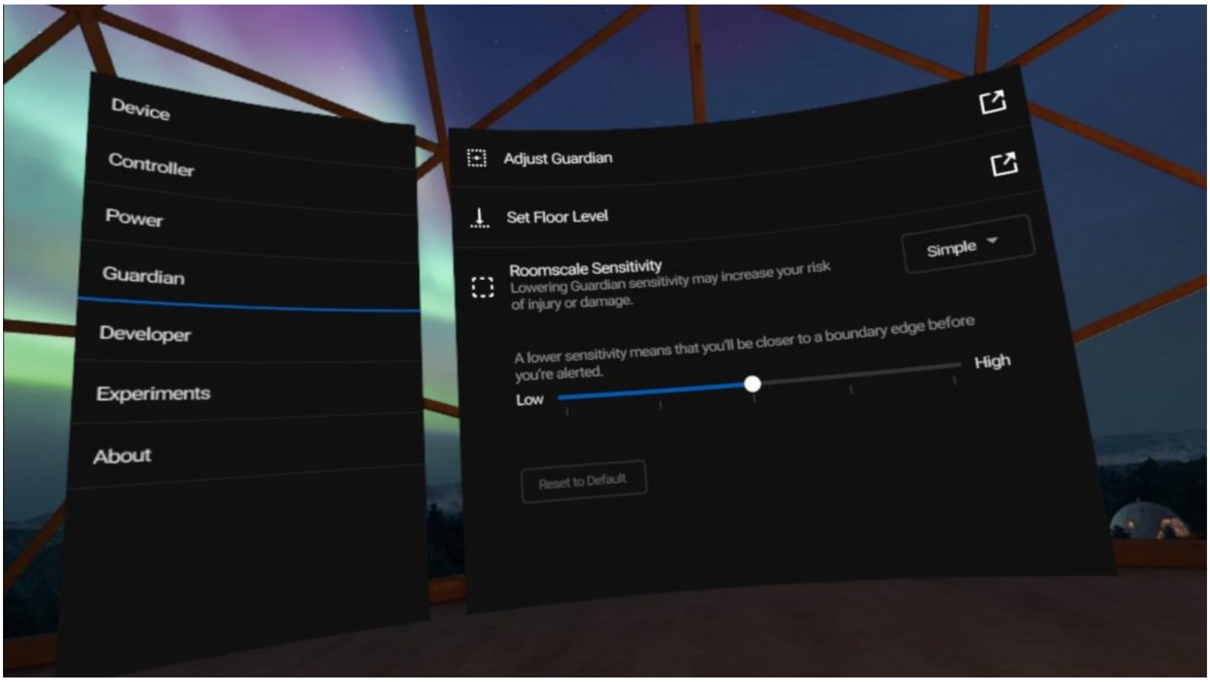

Figure 76 **Heda Weng**, (2019), *Default Android User Interface of Oculus Quest.* Courtesy of the author.

Secondly, we selected Unity 3D as the main development tool for our verification demo. Typically serving as a development toolset for 3D gaming, Unity integrates well with 3D models from industrial design software; on the other hand, Oculus has native SDK for software development in the Unity 3D environment.

Last but not least, we selected Blender as our tool for 3D modeling. Blender is open source and widely used in 3D creation for both industrial design and media art. In addition to its shaping toolset, it also allows us to code complicated curves with Python in order to simulate the shaping system with curvature continuity that we proposed.

Figure 77 **Heda Weng**, (2019), *Combining Coding with 3D Modeling in Unity 3D*. Courtesy of the author.

Figure 78 **Heda Weng**, (2019), *Testing Interface Component Demo in Oculus Quest*. Courtesy of the author.

Based on our tech stack of Oculus Quest, Unity 3D and Blender, we were able to achieve a technological verification of our proposed universal design system: by using 3D modeling software that was typically used in the workflow of industrial design, we created our user interface elements for the VR environment. With the bodily sensation hardware array integrated in the Oculus Quest device (infrared cameras, gyroscope in handheld controllers, ray-casting technology[69]), we had a sneak peek of how human sensory (vision, hearing, body gestures) could be integrated into the usage of the next generation CDD.

This demo experience in the Oculus Quest VR environment was immersive as expected. Wearing the head-mounted display made the edge of display disappear (at least from the user's perspective); in the meantime, as the controllers are rendered as virtual hands, interactions with the on-screen components feels almost as natural as playing with physical objects.

> **Is our computer-human interaction in this immersive environment still a pure mechanical process?**
> **It doesn't feel like one.**

"*Between the dry world of virtuality and the wet world of biology lies a moist domain, a new interspace of potentiality and promise.*" **(Ascott 2000, p.1)**

Our demo with the intention of verifying the viability of our proposed design system might have given us a sneak peek of how does moist media consumption in the post-digital era feel like.

> **What is the future of a world full of next-generation CDDs? Is the future going to be an *Orwellian* style nightmare, or our creativity gets emancipated when CDDs become a biological extension of our sensory?**
> **Only time will tell. Remember?**

"*Technology is neither good nor bad; nor is it neutral.*" **(Kranzsberg, cited in Mims 2017)**

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[69] The usage of ray-surface intersection tests to solve a variety of problems in 3D computer graphics and computational geometry. In a VR environment, it refers to using the relative position of the controllers as the cursor in the software interface.

Conclusiones

Conclusions

Conclusions

As we developed our research developing both theoretically and practically, we evaluated our research results corresponding to our generic and specific objectives, and generalized these research results into out generic and specific conclusions.

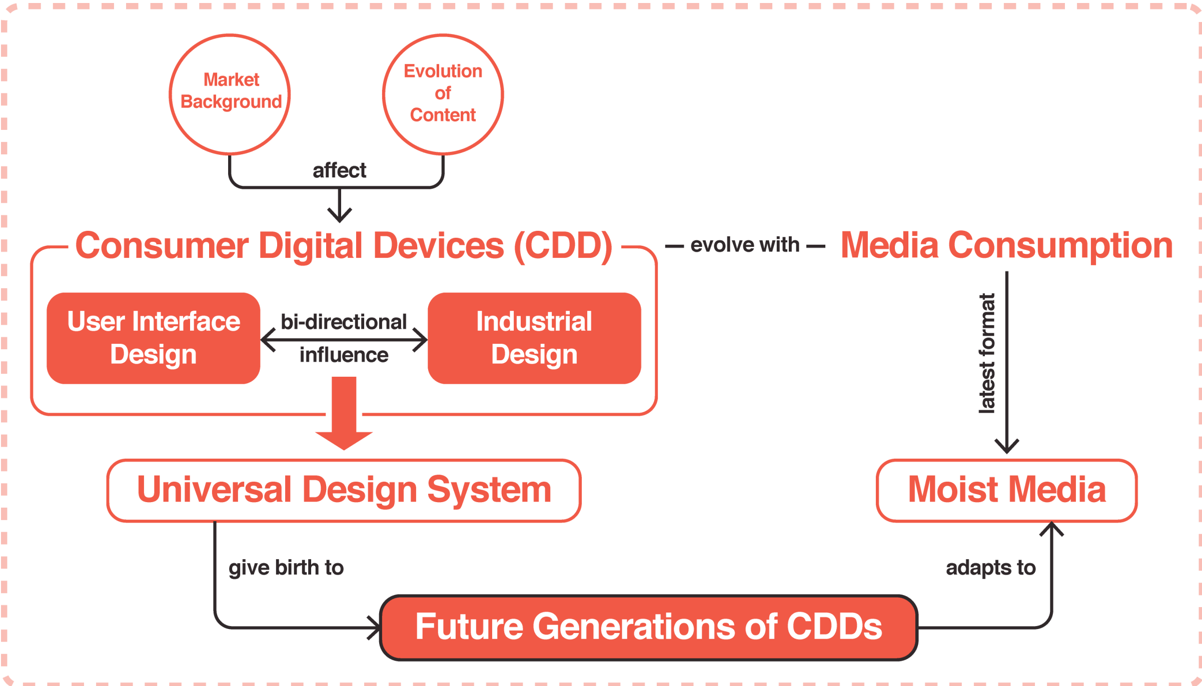

Figure 79 **Heda Weng**, (2019), *Diagram of Conclusions*. Courtesy of the author.

Our generic conclusions include:

- The market background and the evolution of content plays a key role on the design evolution of CDDs;
- CDDs evolve with the evolution of media consumption. These devices are playing and will continue to play a key role in the post-digital lifestyle;
- The established design workflow and the design values of CDDs are resulted from the characteristics of consumer market and the necessities of mass production;
- A universal design system for both the industrial design and the user interface design of CDDs can be established; this design system elevates the design value of CDDs and further improves the user experience of this type of devices.

Our specific conclusions include:

- Industrial design theories and workflows are getting increasingly introduced into the world of user interface design and the presentation of media content in CDDs;

- The evolution of user interface and the technological advancements behind this process have a huge impact on the industrial design of the physical body of CDDs.

We made a summary of conclusions:

Classical industrial design theories and modern innovations of interface design have an increasing bi-directional influence on each other. A universal design system for both the hardware (material part) and the software (immaterial part) of CDDs can be established and future generations of CDDs would benefit from this system in both their design value and their design workflow.

To finish our research, a revision of our hypothesis and an evaluation of the completion of our initial expectations is made. Our hypothesis resulted positive and our objectives are fulfilled with satisfactory.

Part 1 Evaluation of Research Results

As the first step to make our conclusions, we evaluated our research results and achievements in the research development.

We summarized our research results in the chapters presented in the research development part of this thesis:

- With the research presented in Chapter 1: Looking back in history, we reviewed the interface design history of CDDs to obtain a panoramic view across different device form factors and different time periods since the conceptual beginning of this product category;
- In Chapter 2: Geek Thinking, we expanded the technological depth of our investigation. Based on the historical research finished previously, we focused on the evolution of hardware basis of graphic computing and the interface rendering limits set by hardware;
- Based on the interface evolution of CDDs in the market, we summarized the phenomenons of re-applying classical industrial design theories on the user interface design of CDDs in Chapter 3: Learning from the Gadgets;
- Correspondingly in Chapter 4: Sublimation of the Gadgets, we made our research from the reversed perspective by summarizing the influence of user interface innovations upon the industrial design of CDDs;
- With the completion of the research focusing on the product-based materials focusing on the history, technology, user interface design and industrial design of CDDs, we selected a few specific perspectives to develop our case study. Focusing on the graphical computing power, input method, output method and a complete CDD product line evolution history, we further diverged the range and depth of our research in the Case Study chapter;
- As a sublimation of the research of all the previous chapters, we further explored the possibility of the creation of a unified design system for both the software (immaterial) and the hardware (material) parts of CDDs and made our planning

for the integration of this design system in the design workflow for CDDs in the post-digital era corresponding to the requirement of moist media consumption.

The major purpose of the evaluation of research results is to assure the fulfillment of all of our generic and specific objectives. We analyzed the correspondence between our initial objectives and research results graphically:

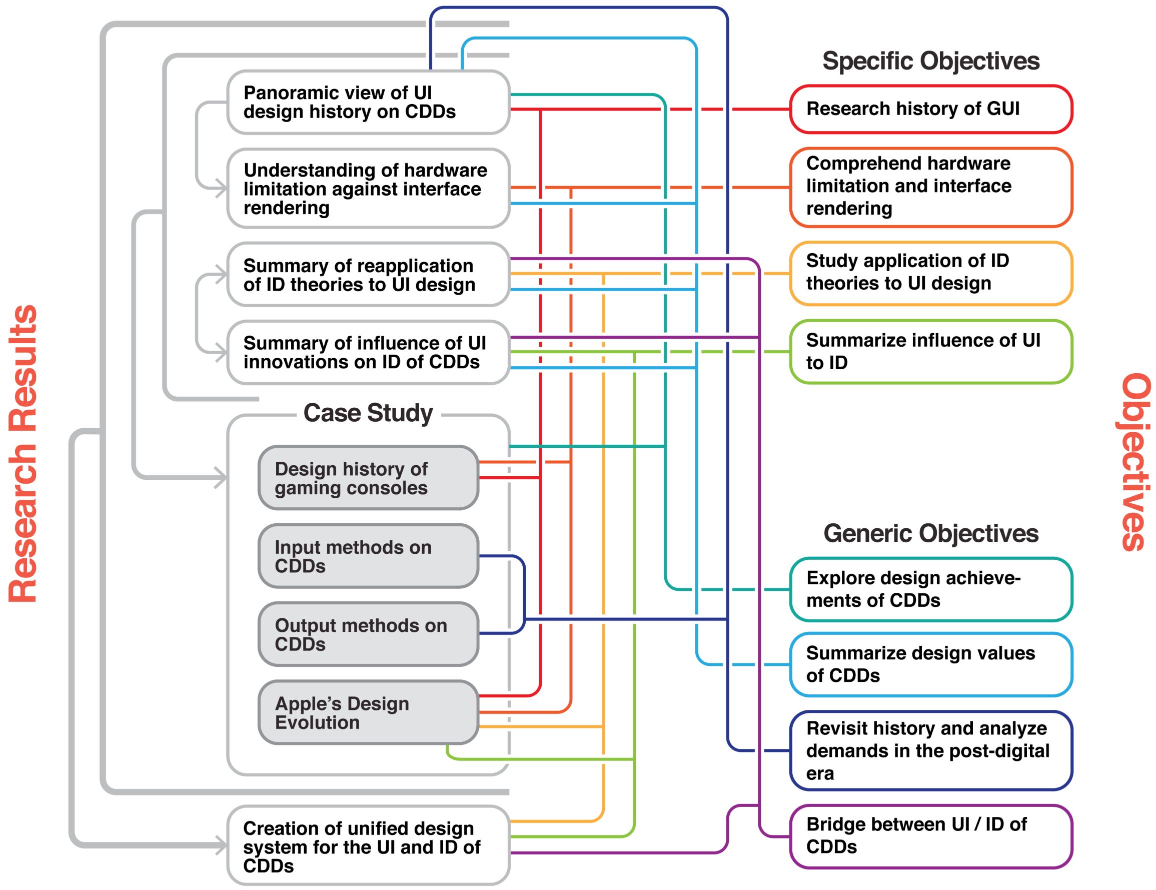

Figure 80 **Heda Weng**, (2019), *Correspondence Between Objectives and Research Results*. Courtesy of the author.

As indicated in the diagram above, by evaluating our research results, we came to the confirmation that our research covered all of the objectives that we set up.

Part 2 General and Specific Conclusions

As we evaluated our research results and confirmed the fulfillment of all of our generic and specific objectives, we further abstracted these research results into general and specific conclusions.

Focusing on the design workflow and design system of CDDs, we made our generic conclusions:

- **The market background and the evolution of content plays a key role on the design evolution of CDDs.** Summarizing the research results focusing on the history of graphical user interface on CDDs, we can conclude that since the very beginning of CDDs, pursuing the diversification for data consumption usage scenarios has been an important market trend; media content with different format and length are then invented to adapt to these new usage scenarios, which requires the popularization of new generations of CDDs with the adequate interaction paradigms tailored for the new media types.

- **CDDs evolve with the evolution of media consumption. These devices are playing and will continue to play a key role in the post-digital lifestyle.** CDDs are born to fulfill the market demand of data consumption and have always been evolving with the vicissitude of media. Since the birth of CDDs, the difficulty of the media consumption has been greatly reduced. The popularization of CDDs leads to a great enrichment in people's lifestyle. Data consumption with CDDs at any time, any place is an important characteristic of the digital lifestyle. Facing the post-digital era, the demand for more intuitive media consumption continues to grow, requiring CDDs to adapt to the human sensory system even further, leading to the fusion of biological processes and computing, giving birth to a new media type: moist media. New generations of CDDs designed for the consumption of moist media will become an essential part of the post-digital lifestyle.

- **The established design workflow and the design values of CDDs are resulted from the characteristics of consumer market and the necessities of mass production.** As an essential part of everyone's social lifestyle in the digital era, the demand for CDDs is enormous; as digital devices, the computing power of CDDs follows the Moore's law, which means they are born with planned obsolescence. With these natural characteristics, securing the yield rate and fulfilling the requirements of mass production are prioritized in the design of CDDs. These requirements shaped the current design workflow for CDDs. The design values of CDDs are not only reflected in aesthetics: from the immaterial perspective, the values of CDDs' interface design is also represented in the advancements of computer-human interaction studies and the design innovations pursuing enhanced user experience for data consumption; from the material perspective, the values of CDDs' industrial design are also represented in the new industrial technologies and material processing methodology applied to their mass production.

- **A universal design system for both the industrial design and the user interface design of CDDs can be established; this design system elevates the design value of CDDs and further improves the user experience of this type of devices.** In our research development, we explored the possibility of the universal design system for the creation of a new generation of CDDs and intended to integrate this design system into CDDs' current design workflow. This new design system brings the hardware (material) and the software (immaterial) part of CDDs together, giving birth to an immersive user experience, creating a whole new type of interaction paradigm in the post-digital era. Under this design system, the look and feel of interface elements and physical components are designed with the same guidance, simplifying the overall design workflow and manufacturing process of CDDs.

Focusing on the bi-directional influence between user interface design and industrial design on CDDs, we came up with our specific conclusions:

- **Industrial design theories and workflows are getting increasingly introduced into the world of user interface design and the presentation of media content in CDDs.** The usage of metaphors is already playing an important part in the user interface design of CDDs. In order to smooth out the learning curve in these devices, the design of interface elements in CDDs takes the rules of the physical world and the human intuition into account. With the expansion of displays, the shapes and curves of user interface elements are required to be designed cohesively with CDDs' physical body in order to provide a harmonious user experience. For the latest categories of CDDs such as AR, VR and MR devices, user interface is directly integrated and/or replaces the physical environment, making the rules of industrial design applicable to the digital interface elements.

- **The evolution of user interface and the technological advancements behind this process have a huge impact on the industrial design of the physical body of CDDs.** Different from most gadgets, as media consumption devices, the functionalities of CDDs are represented by displayed content instead of physical components. In the process of media content maximization on CDDs, without the purpose of functionality indication, the seams between the physical component on CDDs become no more than visual interferences. With the growth of screen-to-body ratio, graphical user interface is gradually covering most of the surface of CDDs, blurring the division between CDDs' content and physical body. User interface innovations motivate the simplification of the industrial design of CDDs. Technological advancements facilitates the mass production of seamless and unibody designs, making the dematerialization characteristics of interface design appearing on the physical body of CDDs.

Summarizing our generic and specific conclusions, classical industrial design theories and modern innovations of interface design have an increasing bi-directional influence against each other. A universal design system for both the hardware (material part) and the software (immaterial part) of CDDs can be established and future generations of CDDs would benefit from this system in both their design value and their design workflow.

Part 3 Revision of the Hypothesis and the Evaluation of Its Completion

In order to further evaluate our conclusions, we made a revision of our hypothesis:

A connection point between classical industrial design theories and modern innovations in the world of interface design can be found, and the future of CDD requires a universal design system for both its hardware and software.

Our hypothesis is proved positive by our conclusions. A universal design system for both the hardware (material part) and the software (immaterial part) of CDDs provides a better decision-making mechanism between mass production limits and design innovations for CDD manufacturers and adapts to the intense bi-directional influence between the industrial design and the user interface design of these devices. As the dimensions of the user interface gets connected with the hardware design in this new design system, future categories of CDDs inspired by this system would provide a seamless and holographic experience between their physical body and their virtual content.

We evaluated the completion of our investigation from two perspectives:

For designers and manufacturers of CDDs, the creation of this unified design system streamlines the design workflow throughout the conception, creation and production of CDDs, provides better design consistency in the final products and elevates the design value of this type of devices.

For users in the consumer market, the creation of this unified design system streamlines the learning curve for the usage of this type of devices, provides a better user experience, and most importantly, adapts CDDs to the post-digital lifestyle and the consumption of moist media.

In summary, by theoretically analyzing the possibility of the creation of the universal design system for both the hardware and the software of CDDs and putting it into practice, we completed our investigation satisfactorily fulfilling all our initial expectations.

"*Scientist-artists originally conceived and designed bridges. The power-structure-behind-the- king, seeing great exploitability of the bridge for their own advantaging, accredited workers and materials to build bridges.*" **(Fuller 1981, cited in Vesna)**

We expect the result of our investigation to inspire the creation of future categories of CDDs and encourage a further exploration of design systems in both aesthetic and technical ways, connecting the world of fine arts and design with the world of technology. In "*Part 4 Future Directions for Further Research*", we analyzed the points for possible extended research from the perspectives of interface design, industrial design, software engineering, digital art and bio art.

Part 4 Future Directions for Further Research

As we developed our research in this thesis with transdisciplinarity in mind, the universal design system for CDDs described in our conclusion can be developed in the future as further extensions.

Industrial design and user interface design are the core academic areas involved in this thesis. In our conclusion, we unified the design process of both areas for CDDs by merging the dimensions, shaping-curvature systems and workflow. As a direction for further research, even more industrial design techniques and visual indications can be introduced into the world of user interface. We expect the research results of this thesis to facilitate the in-depth study of **digital materials** and **physical behavior imitation** for interface components.

Software engineering is the technological basis of our research. In our technological verification of the proposed design system, we used a mature tech stack based on existing hardware and software platforms such as the Oculus Quest VR headset, Unity 3D and Blender. For future research, **the creation of a specialized design toolset** adapting to our universal design system can be researched. We expect further streamlining of our proposed 3D modeling - 3D/2D rendering - interface exporting workflow by integrating the whole process in the same toolset, simplifying the technological requirement for designers involved in this workflow.

Digital art and bio art are the major academic areas with the most potential of a creative sublimation for the research results of this thesis. As a current state, CDDs are already serving as a professional toolset for digital artists and creative codes. With our research, we made our study of the current state and the potentials of next-generation CDDs such as VR/AR/MR devices. We believe that the research results of this thesis can be further extended in digital art with the creation of **installation art and interactive demos in the VR/AR/MR environments**. We also see the potential of a further academic development by involving more human sensory and biological process in the computer-human interaction process adapting to the characteristics of moist media consumption in the post-digital era. A further study of the interaction with moist media can also lead to **an artistic and philosophic study of the relationship between human being and digital devices when bio processes are involved in computer-human interaction**.

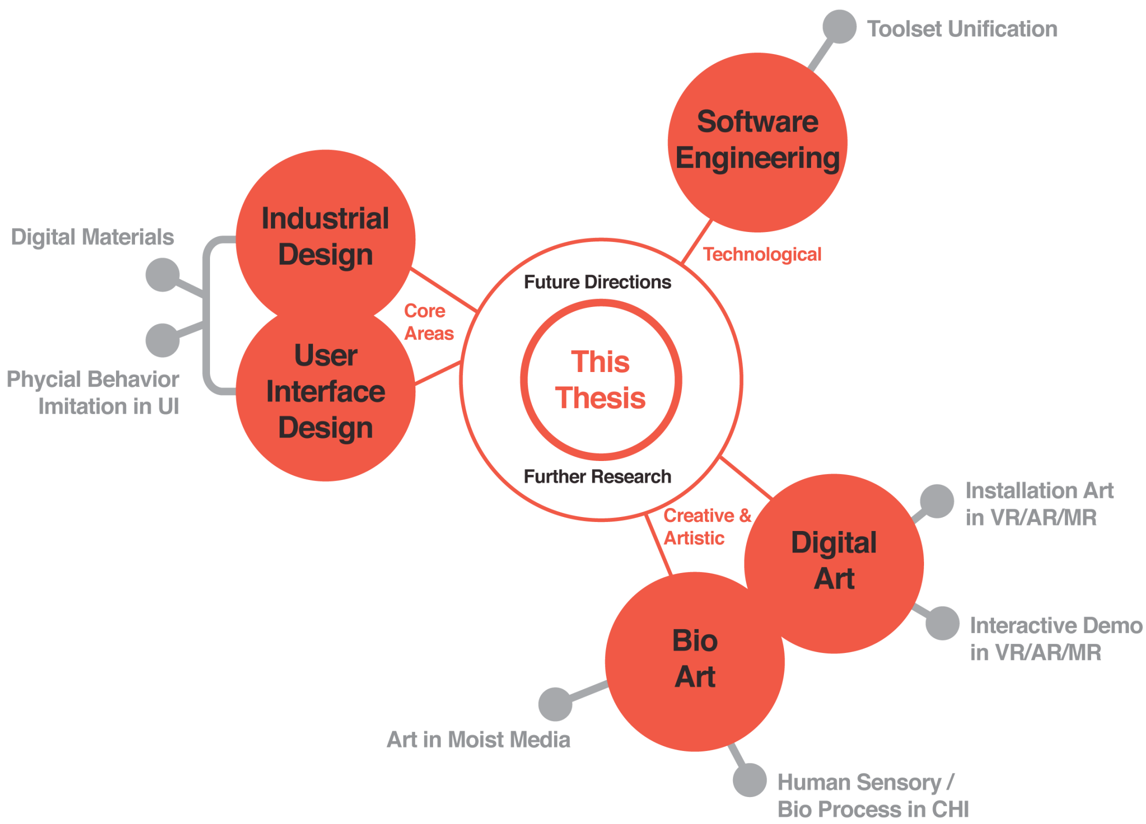

Figure 81 **Heda Weng**, (2019), *Future Directions for Further Research*. Courtesy of the author.

With the future directions of study that we proposed, we hope that our research process and research results described in this thesis can pave the way of further studies in the creative potential of CDDs and serve as our inspiration and contribution to the academic research for industrial and interface designers, software engineers, creative coders and most importantly, digital artists.

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Bibliography & References

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