Visual Reasoning in Ecenomics

An IQP Report
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Abstract

The study was started to determine the possible use of System Dynamics in economics. As it is a greatly visual medium, we must first determine points on which to determine its quality. Then we look back to a previous shift in the view of economics to reveal any parallels there may be. As System Dynamics is such a new field, the time is taken to introduce its form and history before we evaluate its usefulness. It is found that System Dynamics could be quite useful to economics and social science in general though it would require a change in view of those sciences to a more policy driven approach.

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1 Introduction

Visual representations of data are something that took some time to be accepted in economics. They finally were after a shift in the view of the field. The only method for this representation has been graphs for some time. Now a new tool called System Dynamics has been created which serves as a method of visual representation of data though of a slightly different sort. The acceptance of System Dynamics may once again take a shift in a view of sciences which, until now, have had no easy way to test hypothesis.

In the following paper I will start off by talking a bit about visuals as a field in the sciences. They are diverse in their uses and form which makes it a challenge to discuss them as a whole as well as making it challenging to come up with some rubric over which to grade them. They also hold great potential to assist in learning as well as assisting in mental processing.

Following that will be a section on the introduction of graphical analysis in economics. Its introduction was heralded an interesting shift in the fields. It took around 100 years to gradually make its way into main stream of the field and changed the field and its practice as well as its usefulness along the way.

Finally I will talk about System Dynamics and the potential it holds for the social sciences. It is a new field so some space will be devoted to the introduction of the principals surrounding it as well as the conventions used in modeling with it. I will also take the time to analyze the general practice along the same lines as those used to consider standard visuals.

2 Visualization

To properly discuss the idea of visuals, we must first establish what is meant. The connotations of the words visualization and visuals are varied and to properly determine what we mean to clarify understanding. Language and writing are human creations for understanding one another and have the potential to create as much confusion as clarification if not used well[1]. They have that in common with figures. In this paper, visuals will mean anything that is not purely textual in nature. This includes graphs, charts, and abstract models.

In science, and the social sciences especially, there are phenomena which are not actually physical and thus must be represented abstractly. These are especially challenging to analyze and group with other graphics as they do not have a corresponding physical medium from which they comes. This lack of material subjects makes those visual representations all the more important. System Dynamics is one of the modeling conventions which attempt to visualize the physical links and values as well as the more intangible such as happiness or motivation.

Visualization is the process scientists go through to create an image, graph, or the like to convey some natural phenomenon or set of data. More commons methods are graphs or scatter plots. It is not only the representation that is important but also the way in which the information was come by as that may lend its self to a certain type of visualization.

In this way, the visualization may not only convey information about the data but also tell is a bit about the underlying research. In fact, paying "attention to the practices and documents through which researchers visualize phenomena is a way to gain perspective on the whole field of scientific practice.[2]" This idea will be expanded upon further in the history of graphs as we

[1] (Gobert) p4
[2] (Lynch, 2006) p27

can see the parallel of the acceptance of graphs as a form of data representation as the shift in view of the field from a discipline of history to one of science.

With all of the new methods for visualization cropping up, it makes it hard to come up with a standardized system through which to study and analyze them to determine their worth and quality. The same thing which makes it hard is what makes it so important[3]. A number of attempts have been made to create a system which can be used to evaluate visuals in general.

[3] (Trumbo, 2006) p280

2.1 Analysis

As we have discussed, analysis of visuals can be very challenging due to the wide range of methods and forms they take. This is in part due to the various processes that go into creating them. The trend in modern social science had been towards interpreting data[4]. We need to slow down and make sure we are prepared and able to decipher data well before we try to interpret meaning. Without data we're simply guessing, and not necessarily in an educated manner. One we learn to decipher data well, and visual display help greatly in that, the meaning behind the data may reveal its self to us.

There is one man who has become something of a guru in modern visual design and that is Edward R. Tufte[5]. It is to his works we turn to find a rubric on which to determine the efficacy of visuals. Tufte was a professor of statistics at Princeton University when he wrote his first book, *The Visual Display of Quantitative Information*. He was chose to self publish the book but it quickly became a commercial success. In this and his other two books, *Envisioning Information* and *Visual Explanations*, Tufte has tried to convey to the readers four main points about visual representation of data.

The first of these is the importance of visuals. Tufte's works are littered with examples of graphics which illuminate information that may have been lost in the data otherwise. In this, he is trying to show rather than simply tell us that graphics are an integral part of the analysis of data. One such example is Dr. John Snow's dot map of a cholera epidemic (Figure 1). On the map we can clearly see that outbreak was centered on the Broad Street pump. No other form of data would so clearly display this.

[4] (Grady, 2006) p224
[5] (Grady, 2006) p222

Figure 1: Dr John Snow's map of a cholera epidemic

Dr Snow's map also serves to illustrate another point Tufte sought to make. Visuals, as well as facilitating the understanding of information, can then be used to strengthen the very same argument. Dr Snow used his map to convince the city to remove the handle of the pump to try and stop the epidemic. Another of Tufte's examples of the power of visuals in arguments is the case of the space shuttle Challenger launch. Many of the aerospace engineers at NASA tried to get the launch delayed but none of them succinctly showed the connection between the forecasted weather and a weakness in the shuttle materials. In his discussion of this case he also shows us the broad range of the nature of visuals. Tufte describes something that happened during the hearings after the disastrous launch. A member of the hearing asked for a glass of ice water and once he received it he put the o-ring into the glass momentarily. When he drew it out again the weakening of the material could clearly be seen. That was a very simple visual which made the case quite clear. Tufte's focus on this application shows his interest in policy driven applications of graphical representation of data.

The next point is one which makes Tufte a perfect person to learn from to analyze the general field of visuals. He believes that the most successful graphs are those that use universal design principals to address specific situations[6]. I'll speak further about Tufte's universal design principals later in the section.

The final point that Tufte wished to show was that good analysis requires that the work be aesthetically pleasing. This final point is something of a sum of all the previous point. What Tufte believes visuals should portray is the elegance of complexity being cleanly shown, helping reveal the information, and leading to a logical conclusion about the data.

All of this speaks to what one ought to try and achieve when visualizing data but not how. In this we refer to the principals Tufte puts forward: the smallest effective difference, parallelism

[6] (Grady, 2006) p222

and small multiples, and visual narratives[7]. These are perfect categories on which to evaluate all types of visuals.

In talking about the smallest effective difference, Tufte says it best:

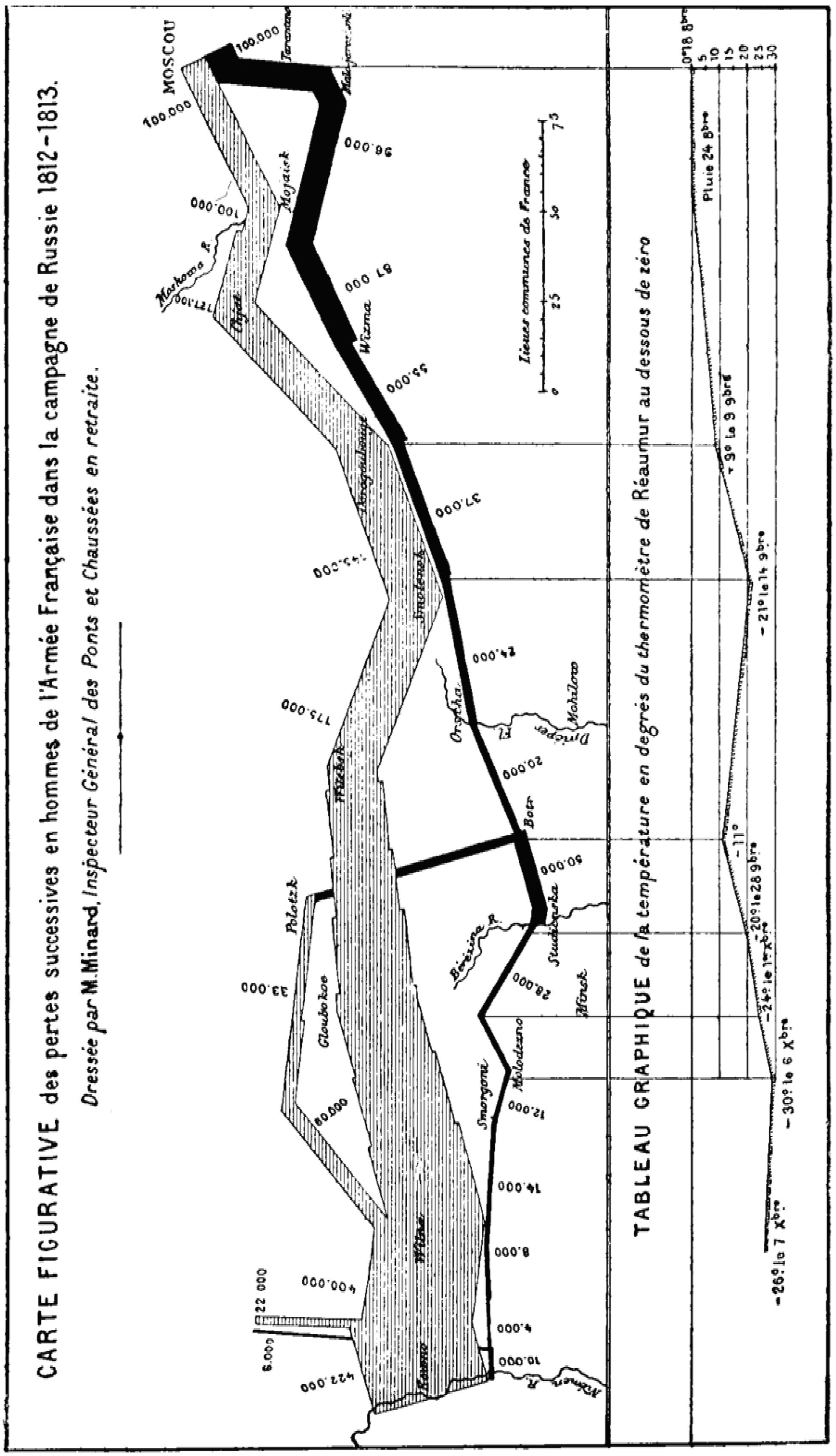
> "Relevant to nearly every display of data, the smallest effective difference is the Occam's razor of information design. And often the happy consequence of an economy of means is a graceful richness of information for small differences allow more differences.[8]"

To help analyze how well this is accomplished, Tufte introduces the data-ink ratio. Quite simply, it is the ratio of the amount of ink used on data versus the total ink used to print the graphic[9]. The goal would obviously be to approach a value of one, thus reducing all non-data ink.

The idea of parallelism and small multiples is to facilitate comparison by increasing the data density of the graphic. Parallelism is illustrated in maps. They contain a myriad of data and overlay it on one area by using different lines. There are road and topography as well as political boundaries and, in some cases, land cover. All of this means there is more related data together in an area. This can lead to revelations or realizations that may not have otherwise been seen. Small multiples are similar accept that the related data is reduced in size and placed in close proximity.

Tufte's interest in visual narratives goes back to the idea of general design principals showing the specifics of a situation. The idea is that the most complete graphic possible would convey the whole story so that no other graphics are needed. This is the principle that many of Tufte's favorite images portray including the one which he claims is the greatest chart ever created, Charles Minard's Chart of Napoleon's march on and from Moscow (Figure 2).

[7] (Grady, 2006) pp. 236-242
[8] (Tufte E. R., Visual Explanations, 1997) p73
[9] (Tufte E. R., 1983) p93



X^{bre} = December 9^{bre} = November 8^{bre} = October

Figure 2: Charles Minard's Chart of Napoleon's march on and from Moscow

Tufte himself created a format for data called the sparkline which displays all of these principals well[10]. The idea behind the creating of the sparkline format was to have data-intense, design-simple, word sized graphics (Figure 3). As we can see at a glance, the time series are paired down to the smallest possible without losing any of the information. In the case of the medical example we can see right away, without even being a trained professional, when the patient was outside of the normal range as well as their current values and what each sparkline represents. Not only that, but there is enough data in close proximity that any connection between the values the variables would be clearly seen. The whole story of a patients hospital stay is plainly visible.

Figure 3: Medical sparkline

Different sciences have their own specific types of visuals. The time series is common among all sciences but there are others which are more unique. One of these is the diagramming conventions used in electrical and computer engineering. With visual conventions determined for each part used in the circuits, it allows for easy display and understanding of complex circuitry. In the field of computer science there has been recent increase in the study of human and computer interaction. Now that computers have become so much more visual, the aesthetics and functionality of visual displays has become much more important. Studies try to determine the best way to facilitate understanding and ease of work in software.

[10] (Tufte E. R., Ask E.T.: Sparklines: theory and practice, 2009)

2.2 Potential in Learning

It is argued that visuals require more knowledge than text does since everyone learns to read in elementary school[11]. That is a bit deceiving. It's true that there is a certain amount one must learn before understanding standard charts but with the jargon thrown around in scientific material, reading text becomes just as difficult as graphs if not harder. Once a student does gains visual literacy it helps in many ways.

First off is the manner in which graphical information is available versus textual information. Textual information is presented linearly, with the order and connections determined by the writer. Visuals have that advantage that all of the information is displayed at once and the manner of absorption is determined by the student[12]. This allows for more variability in learning styles. This is the reason why Tufte, who I discussed earlier as a guru of modern graphical design, prefers handouts to power point slides[13]. This fact that the learner determines the absorption of the information means that the student is more engaged making the visual learning process more active and constructive[14]. This means that the information is retained better.

Visual learning does not only help in the retention of information currently being displayed. It has been show that knowledge of visuals may assist in accuracy and quantity of over all data retention[15]. It is easier for people to remember an image which portrays the important values of a data set than to remember each individual value. As seen in the sparkline I spoke about before, each individual value is not so important to discern as are the key points such as highs, lows, and current values as well as the general trend of data. This help in

[11] (Gobert) p5
[12] (Gobert) p3
[13] (Tufte E. R., Ask E.T.: Sparklines: theory and practice, 2009)
[14] (Gobert) p6
[15] (Gobert)p7

remembering does not only apply to the standard graphical formats however. It has also been found that learning about modeling conventions leads to better understanding of complex world systems[16]. This would help better equip students for decision making in the real world.

As we can see, despite the hurdle that may present itself in initially learning the understand visuals, the reward for taking the time is great. It is something which can help learners of all ages. There are a number of programs working on introducing models to public schools around the United States.

[16] (Gobert) p8

3 Graphs

In this day in age the use of graphs in economics is standard practice. Be it an earning, inflation, or supply and demand curve, the visual display of data in graphical form is integral to discovery and understanding in modern economics. This was not how it always was; the use of graphs was not always common place in Economics. When the use of graphs started it required a monumental shift in thinking about the nature of the field. As in most new inventions or discoveries, there is a lag between the initial find and the proliferation of said technology. The shift was not only in economics. The modern view of science, as we hold it today, took some time to take hold. There was a movement, now called the scientific revolution, which gave birth to modern science based on the scientific method. Before this shift in economics could begin, the tools, in this case graphs, of modern science had to be invented as they are applied to economics.

3.1 Invention

The first person credited with creating a chart resembling the modern graph is Joseph Priestley[17]. Priestley was a scientist who lived in the 18th century most notable for his discovery of oxygen, having isolated it as a gas. He also helped found Unitarianism which, along with his support of the French Revolution, got him run out of England. He fled to the United States. Priestly died in Northumberland County, Pennsylvania.

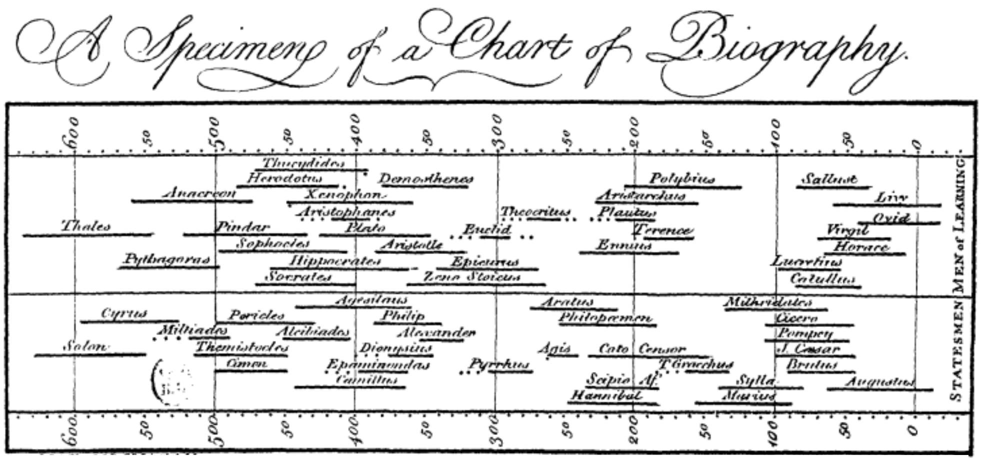


Figure 4: Fragment of Joseph Priestley's *Chart of Biography* (1765)

In 1765, however, he had created *A Chart of Biography* (Figure 4) to assist in his *Lectures on History*. In his chart, Priestley showed the lives of famous people by lines of varying lengths depending on the lifetime of each person. These lines were drawn corresponding to a timeline drawn along the bottom edge of the chart. He also divided the chart in half, putting men of learning above and statesmen below.

The ground braking aspect of his chart was the use of a horizontal time axis. The marking of standardized time intervals with even intervals of distance was the first of its kind. It was the first step towards the modern time series graph as we use it today. Still lacking however,

[17] (Morgan & Maas, 2002) p100

is the vertical axis with similar regular markings to more easily display and compare magnitudes[18].

The man to first create and use the modern time series graph in economics was William Playfair. He himself said that “geometry had long before been applied to chronology with great success; he was actually the first who applied it to matters of finance.[19]”

William was the son of reverend James Playfair. William’s father dies when he was only 13. This meant that William’s training was left to his elder brother John. John had been trained in mathematics and the natural sciences and was familiar with the writings of many empirical thinkers of the Scottish Enlightenment. In training his younger brother, John had William create a chart of daily temperatures. That daily chart is what William later credited with inspiring him towards the use of time series graphs in economics[20].

William also spent some time apprenticed to Andrew Meikle, an engineer, and later working for James Watt as a draftsman. It was during that time working for Watt that they charted many aspects of Watt’s steam engine[21]. It was also during that time that William met Priestley. In fact, it was Priestley’s charts that inspired William’s bar graphs[22].

William finally revealed his application of graphs to the field of economics in *Commercial and Political Atlas* published in 1786 (Figure 5). These early charts were produced using an engraved copper plate. The ink was wiped such that it would only remain in the engraved charts and then transferred onto the paper by applying pressure[23]. The fact that this

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[18] (Morgan & Maas, 2002) p102
[19] (Morgan & Maas, 2002) p105
[20] (Spence, 2000) p79
[21] (Morgan & Maas, 2002) p105
[22] (Spence, 2000) p79
[23] (Spence, 2000) p79

method was not compatible with the type set printing man that the charts in the *Atlas* had to be inserted independently from the pages of text.

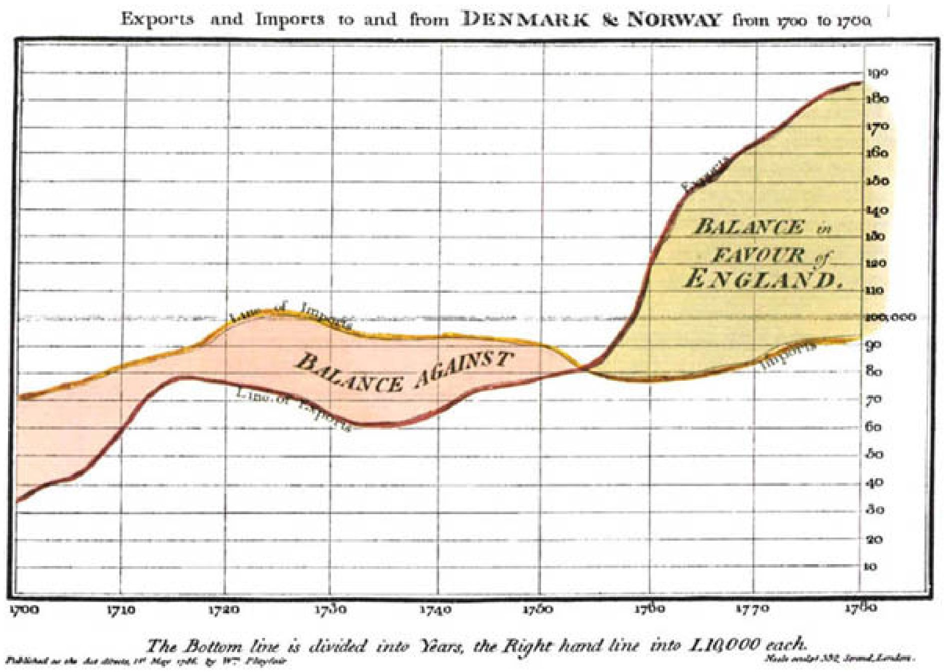

Figure 5: Time series graph from William Playfair's *Commercial and Political Atlas* (1786)

In speaking with Watt, William had been advised to include the tables of data from which his graphs had been derived as "for the charts now seem to rest on your own authority, and it will naturally be enquired from whence you have derived them.[24]" Watt was correct in his assumption that economists of the day would not feel comfortable with charts of economic data. There was a general mistrusted all senses, sight included, believing that they could be too easily deceived[25]. As the first recorded published use of charts in economics, the field was not generally accepting of them.

The wide scale doubt of the use of charts in economics was due in part to men like René Descartes. Descartes was a French philosopher who has been dubbed the father of modern philosophy. Ironically, he was also the inventor of the Cartesian coordinate system which made many commune graphs possible[26].

Descartes was one of the first modern philosophers to write at length about the sciences. 'Descartes had "perceived the necessity, in studying the laws of Mind, of abstracting entirely

[24] (Spence, 2000) p78
[25] (Spence, 2000) p77
[26] (Spence, 2000) p78

from analogies of Matter.[27]" At that point in time, economics was viewed as a matter of the mind as it still is to some extent. This is visible with economics being categories as a social science. More so than that, Descartes was against studying the human condition with scientific methods.

This can be seen plainly from the statement he is most well know for and which, he believed, is the fundamental statement for all science: I think therefore I am. In his statement he wished to convey the idea that only thought can be trusted as being un-erring in the study of self. Human behavior in any kind of market, or the study of economics, was considered an extension of the human nature. Thus its study could only be trusted to the mind and not any other of the senses such as sight.

It was because of this that William Playfair, when publishing his work, was required argued the usefulness of charts in economics to such a great extent. Priestley also had to argue the validity of his *Chart*. He took four pages to convince readers of the use of horizontal lines as depictions of the life spans of famous historical figures[28]. Much the same as Priestley's innovation with the horizontal time axis, Playfair was required to justify the geographic calibration of the vertical axis. Playfair came up with a brilliant analogy. He related the height corresponding to a value of money as coins stacked up each night after a shop closes or a worker gets paid[29].

To counter these strongly held beliefs about the lack of accuracy and trustworthiness of the senses Playfair cited sights aid in understanding, expression, and remembering[30]. He noted various properties of vision that made the use of graphs powerful. First he noted that the eye was

[27] (Morgan & Maas, 2002) p103
[28] (Morgan & Maas, 2002) p100
[29] (Morgan & Maas, 2002) p105
[30] (Morgan & Maas, 2002) p105

a good judge of proportions as well as being a good deal quicker than mental analysis of data tables. Along with this it also made the act of remembering data much easier. This was because while recalling a shape and trend of a graph from memory is one act, to recall a data table requires an effort for each value. He also observed that graphical charts assisted in the recognition of trends which could grant more insight into the workings of an economy. The last and most obvious of the advantages that Playfair mentioned was the fact that it livened up the data, making it far less dry.

3.2 Proliferation

However, before graphs could be successful in economics, a shift had to occur in the view and practice of economics. There were matching shifts happening across many fields in the pursuit of reason[31]. First of all there were the works of philosophers such as Descartes but that was not the only hurdle. Up to this point, economics had been viewed as a branch of history and "history is the narrative linking events like wars, their causes, outcomes, and how these involved and affected the motives for action of those involved.[32]" It wasn't until economists began to shift their view towards economy as a science that graphs truly began to be accepted

3.2.1 As History

Economists originally believed each point is history needed to be viewed as a whole. Only through contemplation of each of these instances could they hope understand the motivation of the individuals at any given point. To work like this, it would obviously require the context of each person's actions to truly understand them. So it was that view of their methods which lead to their strong attachment to the particularity of events in history[33].

Dugald Stewart was one of the economists of the day who opposed the shift in the vision of economics. He was a philosopher of the same period and, ironically, a friend of Playfair's older brother John[34]. Stewart was most notable for canonizing economics and history as the greatest contribution that the Scottish Enlightenment made to the world of science. He also firmly believed in the view of economics as a most noble branch of history.

He thought that economics was and should remain a pursuit of the mind and abstract thought alone without incorporating mathematics or statistics. Stewart believed that there were

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[31] (Cook, 2005) p182
[32] (Morgan & Maas, 2002) p102
[33] (Morgan & Maas, 2002) p98
[34] (Spence, 2000) p78

two distinct categories of science represented by the opposing actions observation and reflection[35]. These go along with Descartes view of matter and mind.

Stewart used Adam Smith as an example of the strength of his view of economic as history and solely a pursuit of the mind. Adam Smith was a Scottish philosopher who lived a generation before Stewart and Playfair. He was also a pioneer of modern economics. Having lived before Playfair's invention of the use of charts in economics, he stands as a great example of the strength of Stewart's view of economics though not necessarily of its sole use above and beyond quantitative economics.

3.2.2 As Science

Though this view of economics as history was held by the majority at that time, eventually economists realized the usefulness of mathematical economics. They began to realize that a series of events could be more than that as a set of data points[36]. Economists "no longer considered the individual data as themselves historical events, but as representing, when taken together, a functional or dependent relation between two things.[37]" This new view of data representing relationships opened the door for the use of charts in discovering trends. The use of graphs or curves along with tables was seen as something analogous to the laboratory of the natural sciences[38].

William Stanley Jevons was one of the proponents of the new view of economics. He began his life working in the natural sciences. Jevons didn't start working on economics right away but managed to have a fundamental affect on the field. It was his work that finally started the shift in thought about the nature of the field of economics. It was his work, along with that of

[35] (Morgan & Maas, 2002) p103
[36] (Morgan & Maas, 2002) p99
[37] (Morgan & Maas, 2002) p113
[38] (Cook, 2005) p188

a few others, that began to help economists view their work as a science instead of a branch of history.

He worked to develop a quantitative method for economics[39]. It was his familiarity with the work of statistics that drove him. Throughout his life he worked to unite the fact finding of statistics with the causal search of economics[40]. Jevons' initial effort towards this goal included attempting to publish a project called a Statistical Atlas. It would have been a book of time series diagrams to be used for analysis and policy design[41]. He never managed to get it published. He did however have a few notable studies in which he used graphs. One of his more successful works was a study on Autumnal pressure on money markets.

In October of 1865 there was a heavy withdrawal of coin from the Bank of England. Many economists of the time worried because they thought it was due to a variety of accidently contributing factors. Jevons, however, argued that it was simply an annual tide in money markets. Where an irregular fall of reserves in the Bank of England would be something to worry about and could signal serious problems in

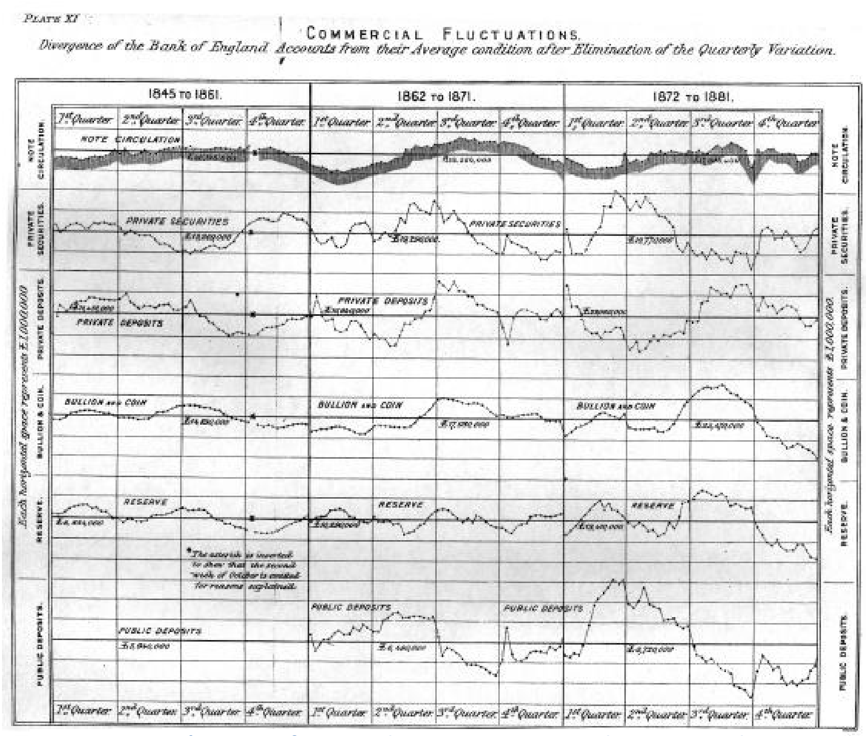


Figure 6: Jevons' Diagram from *On the Frequent Autumnal Pressure in the Money Market and the Action of the Bank of England*

39 (Spence, 2000) p79
40 (Morgan & Maas, 2002) p112
41 (Morgan & Maas, 2002) p115

the future, ebb of a normal annual tide would simply be something to prepare for in advance without a real worry for the long term. To this end, Jevons average out the variation of the quarters to try and find the normal variations of coin reserves (Figure 6[42]). He found that there was in fact a natural cycle and the drop was nothing over which to panic[43].

3.2.3 Acceptance

It wasn't until the Jubilee of the Royal Statistical Society and the associated issue of the *Journal of the Royal Statistical Society* that charts entered the main body of economic works. Various articles in the issue contained graphs to back up their hypotheses including one by Pierre Émile Levasseur. Levasseur's article contained almost every graphical chart know at the time (Figure 7[44]). Also at the conference was a talk by Alfred Marshall arguing in favor of the integration of statistics in graphical form. He viewed the use of charts in economics as an engine of scientific inquiry within the field[45]. Another use that Marshall argued for was the use of charts to archive data in a visual manner making it much easier for references and detection of trends. He argued that the causes of historical events could be seen through the

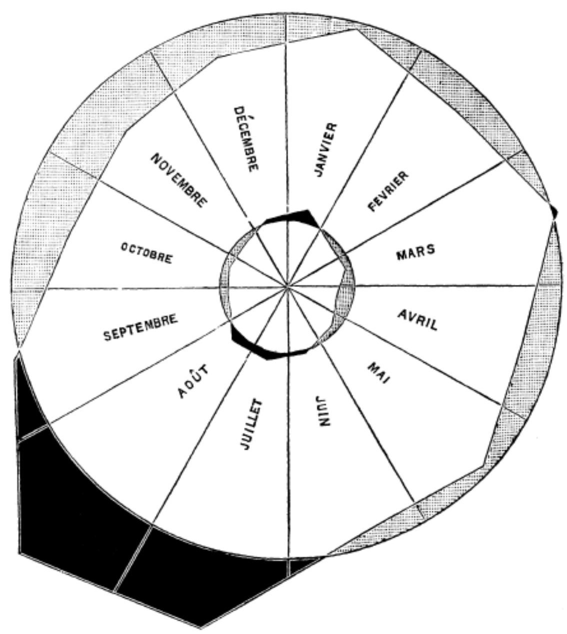


Figure 7: Levasseur's chart of Infant Death

[42] (Morgan & Maas, 2002) p117
[43] (Morgan & Maas, 2002) p116
[44] (Levasseur, Jubulee Volume 1885) p233
[45] (Cook, 2005) p188

use of charts. Through his talk he showed that history was no longer the aim of economists, they had set their sights on causal explanations[46].

Not only did Marshall argue in favor of charts but through his own innovation, the deductive power of charts was shown[47]. Marshall was an accomplished English economist and was responsible for publicizing the supply and demand curve model as well as a number of other theories. In the case of Marshall the introduction of math and visual reasoning can be traced, in part, to his participation and distinction in the Cambridge Mathematical Tripos[48]. In the study for the Tripos, Newton's *Principia*, as well as other works, were studied which were heavy in geometry and visual reasoning. Many students from the Tripos went on to integrate parts of mathematics into the fields they later persuade. Marshall himself said that he did much of his work early as he "thought much more easily in mathematics at that time than in English.[49]" Marshall, with his background in math, was among the first to bring modeling into the field with his expounding of the supply and demand curves. It was the use of models that Marshall hoped would serves as an engine of inquiry for the moral sciences[50]. So it was that by the 1900s the graph had come to be as a visual display of data and models.

[46] (Morgan & Maas, 2002) p121
[47] (Cook, 2005) p187
[48] (Cook, 2005) p184
[49] (Marshall, 1933) p221
[50] (Cook, 2005) p189

3.3 Conclusion

The original acceptance of graphs was a tough road. Though graphs, statistics and analytical models now stand as a great tool for economists though they were mistrusted at first. With a new tool, it always takes some time to adjust. Graphs have shown themselves to be sound and useful tools in the economic field. It all started with William Playfair in the early 1800s who initiated the use of graphs in economics. Before him they had been used in other field, mainly mathematics, but never for real world data to display trends. William Stanley Jevons was the next one to support the use of graphs and expounded their use. He lived and worked in the 1850s and was the one to work hardest to get them accepted and find new uses that they and statistics had in economics. He was the first to use them in published articles in the field. Then, in the late 1800s and early 1900s, Alfred Marshall furthered their use. He not only promoted their use to display data but began their use as visual models with the supply and demand curves. By the 1950s graphs were used commonly in both forms; visualizing data and mathematical models.

4 System Dynamics

System Dynamics is a new tool being used in the sciences. As an extension of modeling it tries to capture the complexities in a non-linear system. ‘In its purest form, a system dynamics model is a set of assumptions describing a problematic situation.[51]’ The idea is to use a simple visual medium to capturing mental models of the people who know best and are most involved with the problem. The original goal of System Dynamics was to be an intermediate step which was meant to fall ‘between a verbal description and a set of equations[52].’

It has been assumed that readers are familiar with the use and purpose of graphical functions. This familiarity is less likely with System Dynamics so some time will be taken to explain the process of diagramming in System Dynamics.

[51] (Lane, Diagramming Conventions in System Dynamics, 2000) p241
[52] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p5

4.1 Description

System Dynamics is split up between two different types of diagramming. Each of the methods for diagramming has their own strengths and weaknesses. They are generally used at different points of the modeling process to capture different aspects. First is the Causal Loop Diagram (CLD). The CLD is generally used first to capture general aspects of the system. The other type is the Stock-Flow Diagram (SFD). It is the more expanded version of the model.

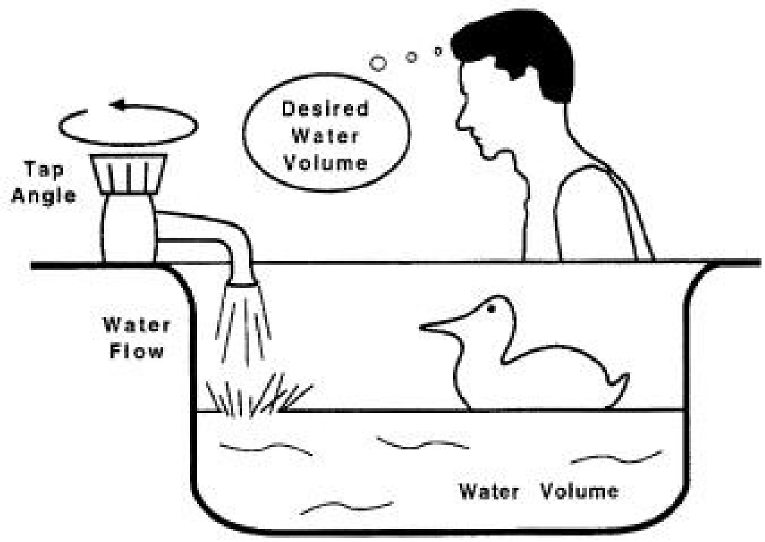


Figure 8: Bathtub Model

To describe each type of diagramming effectively we can use the bathtub model which is the basis of modern System Dynamics diagramming (Figure 8[53]). This model is often used in the description of System Dynamics as it contains all major variable types. These variable types are the stock, flow, and standard variables. Obviously, Water Flow is a flow variable. Flow variables determine the change in the stock variables. In that case we can tell that Water Volume is a stock variable as it gradually accumulates from the faucet. The two remaining variables, Tap Angle and Desired Water Volume, are standard variables. They affect the state of the other variables.

[53] (Lane, Diagramming Conventions in System Dynamics, 2000) p242

4.1.1 Causal Loop Diagrams

The goal of a CLD is to get a broad representation of the feedback structures of the system[54]. Basically, this means that the main focus when looking to create a CLD is to look at the various feedbacks that occur.

Let us look at the bathtub model using the CLD (Figure 9). As we can see below, each variable is listed and then connected to each other variable they affect with an arrow. There are also pluses or minuses assigned to each arrow depending on what type of relationship there is between the two variables. The basic way of determining the relation between the two variables is by the reactions they trigger. If the independent variable goes up, what happens to the dependent variable? If the reaction is in the same direction, the link polarity is positive (+). If the reaction is in the opposite direction, the link polarity is negative (-). If the Tap Angle increases, the Water Flow increases. The link polarities in turn lead to the loop polarity.

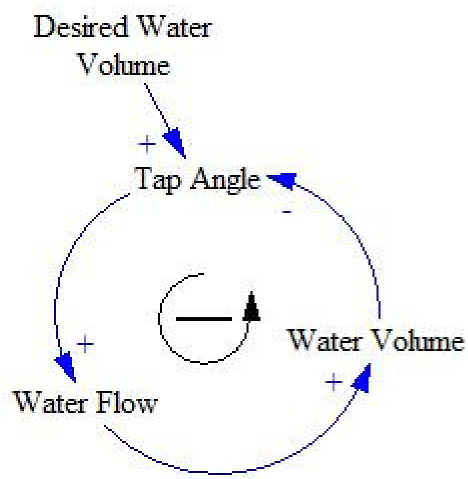


Figure 9: CLD of the Bathtub Model

The loop polarity is in fact a good indicator of a models behavior. To find the loop polarity each link of the loop is multiplied together. Simplified, this means that if the number of negative links is even the loop is positive. A positive loop is one which causes exponential growth or decay. If the number of negative links is odd however the loop is negative and it would act as a balancing loop, adjusting to some level. In the case of the bathtub model, it has a single loop which is negative. It is easy to see that Water Volume would try to adjust to the level of Desired Water Volume. A well labeled model should also help indicate the behavior.

[54] (Lane, Diagramming Conventions in System Dynamics, 2000) p242

The real strengths of the CLD lies in initial conceptualization or post model explanation. The CLD its self does not support any equations and thus is good when used deductively early in the process. That simplicity of the CLD is what makes it so useful for this[55]. It uses few symbols which makes easy for non-professionals to pick up when building models in conjunction with people who have never used System Dynamics before. The process of making the CLD can also offer some quick wins. Just seeing the problem and the feedback loops drawn in a simple and easy to read way can offer these important insights. All these aspects means the CLD is very good for rapid prototyping early on in the modeling process[56].

A CLD is also strong when used inductively. This strength lies in using it after the fact to distil important aspects of a model. Returning to the simple CLD means much of the clutter of the SFD is removed. This means it is easier to connect the simulated behavior to the structure which caused it[57]. This focus on feedback instead of equations and specific properties means that the over arching structure can be viewed and decisions can be made about changes.

This same simplicity which is the CLDs strength is also its weakness[58]. The simplicity which makes CLDs great for first time modelers make it much harder once you want to delve deeper. One of the major flaws is that there are no distinctions between the different variable and link types. This is specifically tough when determining what affect flows have on stocks. As we can see in Figure 5, it would seem that when Water Flow decreased, Water Level would decrease which is obvious to see in this case as not being true[59]. With a reduced Water Flow, the Water Level would just increase more slowly. In a more complex model, however, it might not be as obvious.

[55] (Lane, Diagramming Conventions in System Dynamics, 2000) p243
[56] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p12
[57] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p12
[58] (Lane, Diagramming Conventions in System Dynamics, 2000) p244
[59] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p13

Another difficulty with CLDs comes when trying to infer the models behavior. Being able to conceptualize decision points without simulation is tough. It has to do with determining loop dominance. Without solid equations and variable values, you can only guess which loops will be dominant. This only becomes a factor when models are more complex and with multiple loops. The point of making a model is that the behavior of the system cannot simple be inferred so in having to infer its behavior, the strength of the model is largely diminished[60].

Another issue arises due to all of the variable and nuances not being included in the CLD. Each connection in a model affects the polarity of a loop and when some are left out or not explicitly clear, there can be polarity errors[61]. These polarity errors further compound the problems with inferring behavior from the CLD and can lead to an incorrect assumption about the system.

4.1.2 Stock-Flow Diagrams

A SFD is a more detailed depiction of the structure of a system[62]. The goal is to fully expand all the aspects of a system to make the inclusion of equations easier.

Let's take a look at a SFD of the Bathtub Model to explore SFDs further (Figure 10). Once again each variable is connected with an arrow but now, there are multiple types of arrows. There's the standard arrow which are the same as those used in CLD but there's also a new arrow used for depicting a flow. These are used in conjunction with the symbol for stocks which is the new

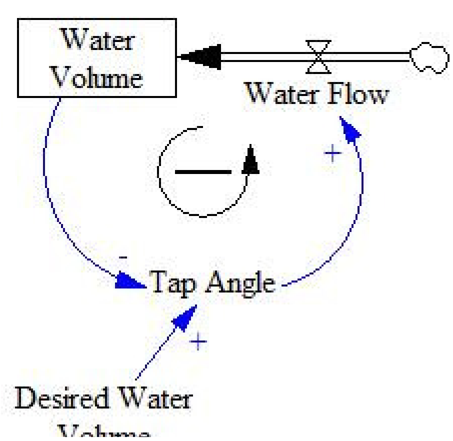


Figure 10: SFD of the Bathtub Model

[60] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p13
[61] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p13
[62] (Lane, Diagramming Conventions in System Dynamics, 2000) p243

type of variable symbol.

There is much strength to the SFD. Much of it stem from the fact that the SFD is more detailed. This gives more information about the underlying model that was lacking in the CLD. As mentioned previously, both the link and variable type are specified[63]. These distinguish important characteristics of these variables. Stocks are variables which store something, such as the bathtub stores water. This can be concrete, such as water or money, or something abstract, like happiness. Flows go along with stocks and are the connections that affect the level of the stock. They increase or decrease the stock based on the variables which affect them.

With the expanded representation of the variables and links, a SFD allows for a more thorough and accurate model. This precision means that the polarity of each link can be determined more confidently. The accuracy also allows a greater focus on measurable values. This is good considering the next step is to begin including equations in the model[64]. In the visual software packages available for System Dynamics at this time, a SFD is required to begin integrating equations.

Due to the fact that SFDs are so detailed, it makes it much better for inferring behaviors of the model. This becomes especially apparent when the model would produce counter intuitive behavior. The model used here is very simple, containing only a single stock and flow but models can become complex very quickly. Once complexity begins to get greater, it is good to have any aid in mental simulation[65].

These aspects of the SFD that lend an advantage are once again what cause its weaknesses. With the added clutter of differing symbols, the basic structure of the loops can be obscured. One of the major reasons for this is due to the symbol for a flow. When a flow is

[63] (Lane, Diagramming Conventions in System Dynamics, 2000) p244
[64] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p14
[65] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p15

decreasing the stock it is attached to the arrow points away from the stock. This means there is still an interaction between the stock and the flow but due to the direction of the arrow, to see the loop effectively, you have to look along it backwards[66].

4.1.3 Conclusion

There are also issues that arise for both types of System Dynamics diagramming. First of these is related to the bathtub metaphor. The current graphical representation and method of System Dynamics is tied closely to the bathtub metaphor. This may not be the best method to explain it however. Another problem with the metaphor used is that it may cause System Dynamics users to focus too much on the tangible details. One of the strengths of System Dynamics is that it is able to work with intangible, 'soft' variables. To be distracted from this would negate a major aspect of System Dynamics.

Another is that as a purely diagramming convention, there is no way to discern loop dominance. This is much more evident with a more complex diagram. Discerning loop dominance is very important as each loop can lead to vary different behavior and figuring out which behavior occurs is the purpose of a model. The introduction of equations can assist in this. Even with the equations time must be taken to discern which loop is dominant given the behavior of the model because only the behavior is given and not which loop is dominant specifically. With equations it is also tricky because input variables can often have a very large effect over the behavior and dominance of loops so care must be taken. These points which so greatly control behavior can often be quit important in their own right as they can be the best place to affect the changes desired in the system.

There is a flaw common to all models that must be kept in mind. This is that no model is ever complete. The complexity and detail that can be reached with System Dynamics may cause

[66] (Lane, Diagramming Conventions in System Dynamics, 2000) p244

people to lose sight of this but it is an important detail to keep in mind. The world is an extremely complex system and no model could hope to catch all the nuances.

4.2 History

System Dynamics was founded by a man named Jay Wright Forrester. Forrester was born on a farm in Nebraska. He later went on the work on digital computers; leading to some of the most fundamental breakthroughs and the invention of magnetic core memory. He was working at MIT when he began his work in creating the field of System Dynamics on the back of an envelope[67]. Forrester initially worked in electrical engineering but switched to studying a wide range of systems when he moved to the Sloan School of Management in the 1950s[68]. The transition may seem odd but Forrester viewed System Dynamics was derived as an engineer's approach to social science. The first published use of System Dynamics was in Forrester's book *Industrial Dynamics* (1961)[69]. From his flow diagrams, the SFD was born.

This was the first use of what was to become System Dynamics. His later works were more controversial and well know. He wrote *Urban Dynamics* in 1969 which created some of the most heated controversy. He stated that low-income housing was what was causing the urban issues in the Unites States. This angered many people but when Forrester actually got the chance to explain it, people were convinced. He was told to his face that "you're not dealing with the urban problem.[70]" His suggestions were put into action in St Louis to great effect.

One of his later works which upset economists was his National Model. This was his first model working primarily with economics systems. His work supported the idea of an economic long wave or Kondratiev cycle and had an explanation of the feedback look which caused both it and a short term business cycle. The long wave is caused by an overinvestment in capital and the

[67] (Forrester, 1995) p4
[68] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p4
[69] (Lane, The Emergence and Use of Diagramming in System Dynamics: A Critical Account, 2008) p7
[70] (Forrester, 1995) p8

excessive debt associated with that investment. The short wave was related to the same thing but with consumer durables[71].

The CLD specifically wasn't invented until 1968 when an early form was used inductively; utilize the feedback loops in a model to explain the behavior of simulation. This early work was only used after loop dominance had already been established by simulation[72]. It took some time for people to realize that the CLD could easily be used before a SFD to find out important information as well as making it easier for non-professionals to assist in the modeling process.

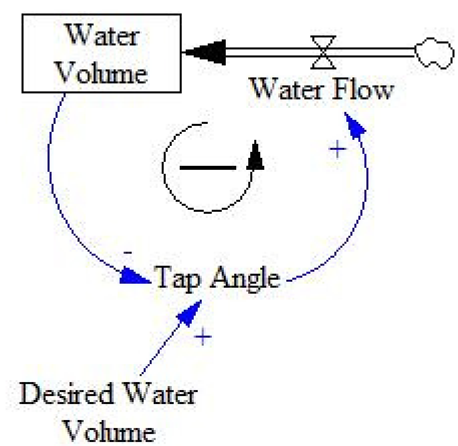
[71] (Forrester, 1995) p10

[72] (Lane, Diagramming Conventions in System Dynamics, 2000) p242

4.3 Analysis

In trying to draw a parallel between the two forms of visual information display, graphs and system dynamics, we must come up with a common set of criteria to judge them by. Since the main aspect of the two forms is that they are visual, this is what must be analyzed. Graphs, being the older of the two, have been analyzed previously and can lend some aspects to the analysis of the visual elements.

There are three essential aspects of visual representations of data: simplicity, aesthetics, and data-density. The skill with which these are implemented determines their usefulness. By analyzing these three characteristics within System Dynamics it is possible to see the value of using it for data analysis and presentation. Let's use the SFD of the bathtub model to analyze the general diagramming conventions in System Dynamics.



Before an analysis can be made the data portrayed through System Dynamics must be clarified. It is not the same as with a graph. System Dynamics diagramming represent relationships between various variables. These interactions and connection of variables are the essence of mental models which is what System Dynamics is trying to capture. Graphs can help to figure out which relationships may be important for further testing within the framework on System Dynamics. With an idea of what System Dynamics has as data, let's return to the analysis.

Simplicity in visual representation is important because it reveals the critical information. One measure of the clean simplicity of visual representations is data-ink[73]. The idea of data-ink is to measure what faction of the total ink used for a chart is actually used for representing the data. As well as maximizing the data-ink ratio, within reason of course, removing redundant data ink improves the clarity of the chart.

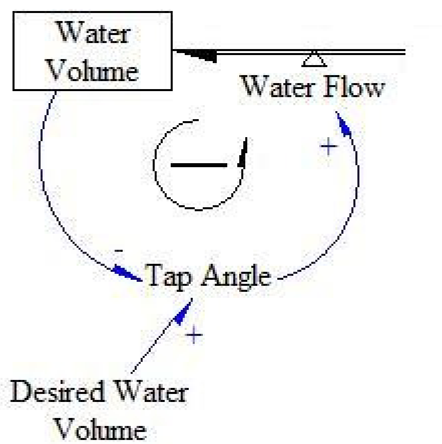


Figure 11: Simplified SFD of the Bathtub

If we take a look at the SFD we can see that the representation of the data is very simple. In fact, the data-ink ratio approaches 1 which would be the ideal. There is however a certain amount of redundant data-ink that can be removed to a small effect (Figure 11). This adds a certain amount of cleanness to the curves but does not fundamentally alter the diagram.

Another significant factor in representations of data is how appealing the visual is. For that reason aesthetics is important to analyze. The effective integration of words, drawing and numbers can greatly improve the effectiveness of a chart[74]. It is also important to keep an accessible complexity of detail as well as having a narrative of the data.

That is where System Dynamics truly shines. What System Dynamics does is a narrative of a problem with the goal of finding the point at which the least amount of effort will give the greatest, and most permanent, result. The complexity, however, is something which can be debated. The fundamentals are very simple, there are only two types of variables and links, but these simple building blocks can produce very complicated systems. The complexity also sky rockets once equations are involved.

[73] (Tufte E. R., 1983) p105
[74] (Tufte E. R., 1983) p177

Other important aspects of aesthetics are avoiding content free decoration. This has already been looked at with the data-ink ratio. Other facets are the use of color-blink friendly colors and use of appealing shapes. The most notable of these is the Golden Rectangle[75].

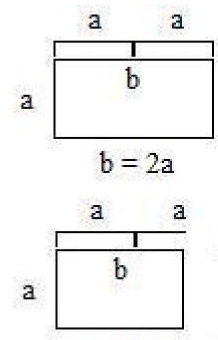


Figure 12: Golden Rectangle adjustment

As we have already seen, the links in System Dynamics are often colored in blue while the colors to be avoided for the color-blind are red and green[76] so that has already been addressed. The use of rectangles for stocks is a perfect opportunity to add aesthetics. The current default ration in one software package is approximately two to one while the ratio of the Golden Rectangle is one to one and a half (Figure 12).

With the eyes ability to detect large amounts of information in small spaces, data density is important to take advantage of the true strength of a visual medium. Graphics are quite easy to shrink and with a greater density of data the chart can facilitate and encourage the eye to compare different parts of data. Representing multiple variables will also increase the images data density and value.

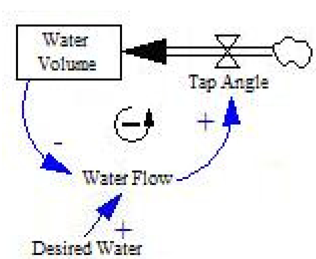


Figure 13: Compacted SFD of the Bathtub Model

This is one of System Dynamics weakest points. The inclusion of labeling of the variables is required but limits the data-density possible in its diagrams. Once diagrams get too compact, they become cluttered which is not a good alternative. In more complex models however System Dynamics is heavily multivariate. With multiple stocks being affected by a plethora of variables the interactions represented get very complex. This complexity shows large amounts of data in a small area, especially with many feedback loops.

[75] (Tufte E. R., 1983) p189
[76] (Tufte E. R., 1983) p183

As we can see, System Dynamics is a fundamentally sound visual portrayal of complex systems. The information is presented in a simply way with good aesthetics. With a few changes the diagram can be improved but only superficially which, as a visual medium, is something that should always be striven for[77].

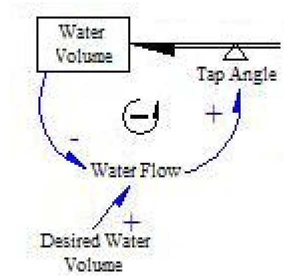


Figure 14: Improved SFD of the Bathtub Model

System Dynamics is a different way of viewing the social sciences than the standard method. Traditionally social science has been a search for generalizations in specific situations. System Dynamics, on the other hand, is the search for causal relationships and the feedback that these connections cause. It is a much more policy driven approach to social science, much like that which Tufte promoted.

[77] (Tufte E. R., 1983) p105

5 Comparison

The development time so far for System Dynamics is short, but already similarities can be seen between its initial inception and growth and that of the beginning of the use of Graphs in Economics. Those who founded these two different methods were surprisingly similar people in their manner and disposition. Their methods both also required a change in the view of what study was to be done. In the case of System Dynamics, it's true that Economists have been using model for some time but they have all been models of equilibrium which, in real life with incredible complex systems with delays, inaccuracies, and sometimes missing feedback, equilibrium is not likely.

5.1 Founders

Both of these men, William Playfair and Jay Forrester, began as engineers to only later take of the social sciences and economics. Playfair started by apprenticing under many famous engineers who are now identified as being groundbreaking innovators. The first of these was Andrew Meikle who developed the threshing machine which is credited with being one of the key inventions of the British Agricultural Revolution as well as other useful developments. After working with Meikle, Playfair went to be a draftsman for James Watt. Working under Watt, Playfair participated in studies of the steam engine as Watt was developing it. These charts and graphs that were made during study shaped Playfair's view of science and caused it to be much easier for him to take that step in the case of Economics.

This is initial study in the use of some method in one field which, when applied to a different field, yields new and beneficial results can be seen in the case of Forrester. He started out life on a ranch in Nebraska and randomly decided to go into engineering. He apparently excelled at it as he joined MIT as a research assistant and worked with Gordon S. Brown. Brown was a pioneer in feedback control systems. This time focusing on feedbacks and control derived from them, much like Playfair and Watt's studies, ended up affection Forrester later in life when he started thinking about social systems. As we can see from the CLD, System Dynamics focuses on feedbacks and their interactions to reveal the behavior and focal point to control change.

Both of these men also faced much controversy in developing their visual tools. With the initial introduction of their work, doubt was shed on their possible results. With Playfair this was in the form of distrust for the visual medium. The Economists of the time doubted that anything could really be shown with any sort of graph as the senses in general were mistrusted. As discussed previously this was due in part to philosophers such as Descartes.

In the case of Forrester there was doubt about the system he portrayed. Take for example the controversy previously discussed about his Urban Dynamics model. In that specific situation there were people involved who already had a previously established mental model and held it quite firmly. This is, however, a general trend in System Dynamics. This resistance to changes in mental models is the reason that group model building is being developed and used. Being able to integrate people into the discovery process makes it simple to convince them of something as they participated in its finding.

5.2 View Change

Previously in this paper much space has been dedicated to the discussion of the shift in view of the economic discipline. This shift was a transition from a view of economics as a branch of history to a science. This was very important as it changed the economist's view of history from independent events to possible points of data to be analyzed and used to determine trends and the like.

To have to use of System Dynamics proliferate through the economic discipline another change may be required. Currently, economics is a study of situations with redemptory models created to try and explain them. These models tend to focus on the idea of equilibriums in a system. This is not an accurate view of complex systems. As mentioned before there are waves such as the Kondratiev cycle which break this idealistic view of markets. It is more or less the same issue that has cropped up in other sciences such as those natural sciences which study ecosystems. It has been found that nature does not develop equilibriums and have a beautiful balance which man enters and disrupts. Nature is constantly changing and is by no means a stagnant entity which existed before man interfered. It is much the same way with markets as they are simply human ecosystems with traded goods instead of nutrients.

With this new information about dynamics and the inherent lack of equilibriums in complex systems, a shift can be made away from the academic study inherent in many sciences to a new order which we can call a policy discipline. This new shift would build upon the old one which brought economics to the point of science from history. The shift reflects the idea that it would be focused less on the simple collection of information, cataloging, and attempted explanation. The new focus would be upon causes, effects, and the focal points at which change can be affected. Economists as policy setters have created for themselves a social obligation for improvement of the market and as such, the study and practice of economics and should be geared towards this obligation. As we have seen with the recent mortgage, economies are systems which are complexly interwoven and whose effects are profound and wide reaching.

The idea of cycles is not something that economic theory currently budgets for. The most famous of the economic visual models, the supply and demand curve displays this well. In these curves there is no area through which they cycle but a single point to which the market should converge. This is what currently conflicts so harshly with the current view of economics. If the view of economics were to change, however, System Dynamics could become an invaluable tool in the study of a policy discipline.

6 Conclusion

System Dynamics does seem to serve well as a visual representation of data. The exact visual representation may vary but the methods are strong. Both the CLD and the SFD have their strengths and weaknesses as any model does. It works out that where CLDs begin to show their weaknesses is just when SFDs begin to shine. In this way the two methods complement each other extremely well to produce the overall strength of System Dynamics.

With graphs as an example, we can see that new tools take some time to become accepted and integrated. System Dynamics does seem to show its use and beg to be included in the tools used to analyze the economic sciences. So why isn't System Dynamics in use? One hypothesis may be that causality, which is what the link in System Dynamics portrays, is not acceptable in economics. This may be true to a certain extent as the possible experimentation and discovery with System Dynamics is unprecedented in the age before digital computer. The simpler graphical models do portray a certain amount of causality though which suggests this may not be the main case. The supply and demand curves portray causality between the quantity and price of a certain item.

Another reason may be that System Dynamics can provide little value or is anti-economics in some way. The lack of value can likely be thrown out relatively quickly. As we can see from Forrester's early work, System Dynamics can provide much information and illuminate vary complex problems and systems. Forrester's work, while showing System Dynamics uses, can clarify were the issue lies with economics. Both his National Model and World Model were quite controversial and upset many economists[78]. These models went against the idea of classical economics which stated that markets would take care of themselves and seek out the

[78] (Radzicki, 2007)

most advantageous equilibrium. This tendency for System Dynamics models to conflict with the standard models in economics seems to be the main reason for the lack of proliferation of System Dynamics in the field of economics. These models, in what cases there is data to compare them to have been correct which may indicate that in may be time for another shift in the view of economics. As it stands, economics and System Dynamics are not compatible but System Dynamics has so much to offer economics. The potential for dynamic learning environments that can cover the span of decades in a couple of minutes and allow people to learn by trial and error without any real-world consequences is incredible.

It is empowering to think of being on the edge of a revolution but reform is much harder[79]. The task of integrating the old and the new is not easy but it has been managed before in integrating graphical representations of data into economics and we can hope to accomplish it again in introducing graphical models. Mathematical models are nothing new, as we can see in the case of supply and demand curves, but the introduction of a whole new diagramming convention may take some time.

[79] (Grady, 2006) p260

Timeline

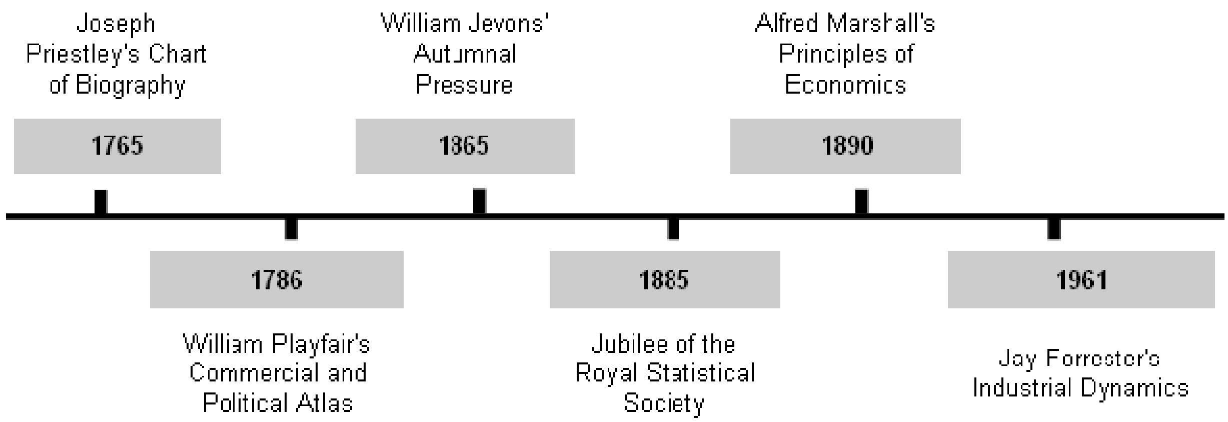


Figure 15: Timeline of Graphical Innovators

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