Introduction to System Dynamics

For Those Interested in its Applications To Church Growth

1 Introduction

Systems dynamics is a methodology to analyse situations that change over time. It is widely used to analyse a range of systems in, for example, business, ecology and social systems as well as engineering. The methodology focuses on the way one quantity can affect others through the flow of physical entities and information. Often such flows come back to the original quantity causing a feedback loop. The behaviour of the system is governed by these feedback loops.

Consider this example of a system with feedback. A person works hard with a certain efficiency to maintain their work load and avoid a backlog. However in the act of working they get stressed, causing them to work less efficiently. Now the backlog of work gets longer and they get more stressed etc. etc. This is a feedback loop and the resulting behaviour of the person and their work load is governed by it. The person will eventually collapse under the strain with a large backlog of work unless there is an intervention. This is the sort of situation that systems dynamics can handle.

There are two important advantages of taking a systems dynamics approach. The inter-relationship of the different elements of the systems can be easily seen in terms of cause and effects. Thus the true cause of the behaviour can be identified. The other advantage is that it possible to investigate which parameters or structures need to be changed in order to improve behaviour. For the person under stress the effects of reducing the workload, or taking exercise to reduce stress, can be investigated with the results on the whole system explored. Exploration is often done with computer software.

Apart from clarity of thinking and analysis, for many people there is another advantage in that the method can be used by people without much mathematical expertise. All situations analysed by systems dynamics can be handled mathematically, but the maths is hard. At least second year university standard. As an alternative systems dynamics can give significant insights without having to use mathematical methods.

Systems dynamics was developed in the 1950’s by J.W. Forrester at MIT who wrote some of the classical text books on the subject, Forrester (1961) being the first. The methodology was also used to analyse the inter-relationships of the world economy and the environment by Forrester and others leading them to press for sustainability rather growth as the goal of countries. This call was taken up by many environmentalists.

Systems dynamics is promoted by its own society, conferences and journal publications. There are a number of books on the subject but some of the best resources are on the internet. As well as documents many systems models can be downloaded and run. The software required to run models is free. However software to construct models requires a payment. A list of references is given at the end of this guide.

2 Dynamic Model Building Blocks

There are a number of different notations in system dynamics. The one presented here is based on the Stella software[1] used in this introduction to simulate the models.

There are only four basic building blocks used in a system dynamics model: Stocks, flows, connectors and converters .

2.1 Stocks

Fundamental to a system are the Stocks, represented by:

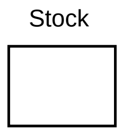

Fig. 2.1a. Symbol to represent a stock.

These represent the basic variables, or quantities that change in a system. For example in a population model one stock may represent the population of a country:

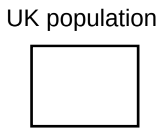

Fig. 2.1b. A stock to represent the UK population.

A stock can be thought of like a water tank, or bath, with its value given by the amount of water it contains. At one time UK population may have 55million, at a later time it may be 60 million. The stock would now contain more "water":

Fig. 2.1c. Two stocks using the "amount of water" to represent the population's value.

For a simple church growth model there would be one stock representing the number of unbelievers and another stock representing the number of believers:

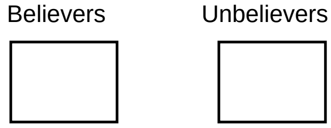

Fig. 2.1d. Stocks representing the number of believers and unbelievers.

[1] Stella is manufactured by High Performance Systems inc. and is distributed in the UK by Cognitus Ltd. Harrogate.

These would be part of the same system at the same time.

2.2 Flows

Just as water can flow in and out of a tank, so quantities can flow in and out of a stock. For the UK population numbers can flow in through births and numbers flow out through death:

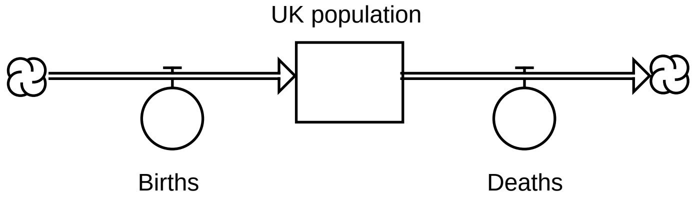

Fig. 2.2a. Flows representing mechanisms for changing the level of a stock.

The circles on the flows act like taps controlling how many go in and come out at any time. This is the rate of the flow. The clouds at the ends of the flows just indicate the outside world. In other words we are not concerned as to where the people come from or go to in this model.

For a church growth model consisting of two stocks, unbelievers and believers, a flow could connect one to another:

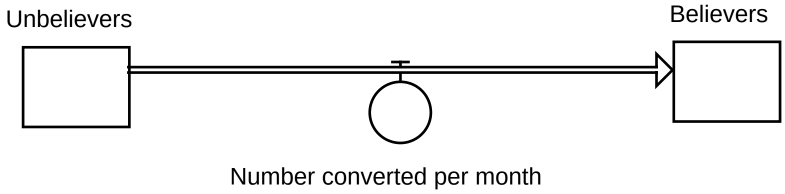

Fig. 2.2b. Unbelievers become believers through conversion.

The flow controls the number converted at any time. None are lost to the outside world in this model as people are either believers or unbelievers.

2.3 Connectors

A flow represents a physical link between stocks. However there are also information or dependency links. For the UK population the more the population the higher the number of births in any given year. Thus the rate of flow into the UK population depends on the population:

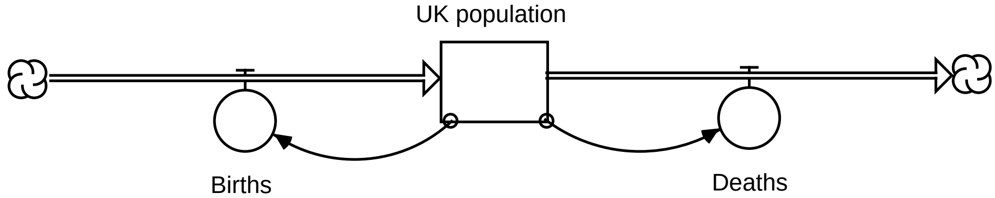

Fig. 2.3a.

Connectors show that the number of births and deaths depend on total population numbers.

Likewise the higher the population the more people die. Note that the details of the relationship between the rate of births and the population number are hidden in this approach, although it would have to be spelled out mathematically for a simulation to proceed. As we will see in section 4 it is possible to understand the behaviour of the model without the details of this relationship.

For the church growth model the number of converts may depend on how many unbelievers and how many believers there are:

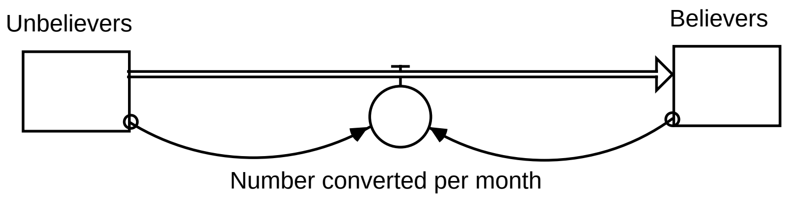

Fig. 2.3b. The number of conversions depends on the numbers of believers and unbelievers.

Essentially the more unbelievers there are the more conversions result in a month.

2.4 Converters

The connector in Fig. 2.3a showed that the number of births depended on the number in the population. In fact the greater the population the more people are born in a given month. The reason why the number of births is higher when the population is higher is because the *birth rate* is constant. The birth rate, the number of people born per person or per family, is a fixed quantity over short periods of time. Fixed quantities are represented by converters.

Different countries would have a different fixed birth rate. Deaths are treated in a similar fashion. This leads to a simple model of a growing or declining, population:

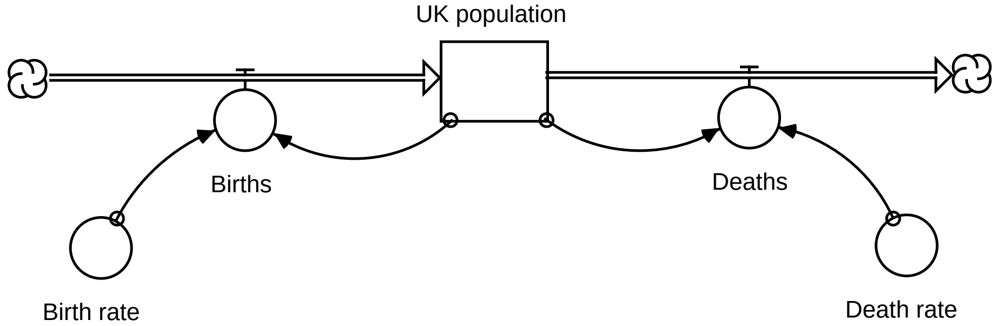

Fig. 2.4a. A model of UK population with births and deaths

Of course the birth and death rates of the UK population are not constant, but they vary due to effects not included in this model. Thus, to a first approximation, they are assumed constant. Such a model should give reasonable predictions over a twenty year period. More importantly it can give predictions indefinitely, <u>given</u> that the rates remain the same. Thus the behaviour of a population with constant birth and death rates can be thoroughly analysed.

Converters can themselves vary because they depend directly or indirectly on stocks. Consider The UK population split up into adults and children. Births produce children whose numbers are depleted by becoming adults (assuming no infant mortality). Adults increase by children growing up but decrease due to deaths. The total number in the population is given by a converter, and is variable as it depends on the number of adults and children:

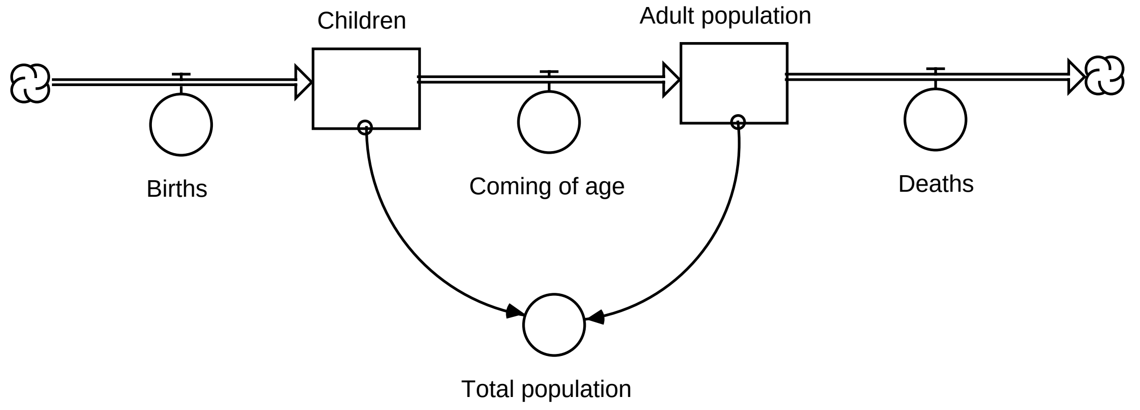

Fig. 2.4b. Converter (total population) derived from other quantities

Thus converters either represent fixed quantities (constants) or represent variable quantities which are derived from other quantities, either stocks or other converters. Unlike stocks they do not represent fundamental variables Stocks change but depend on no other quantities.

2.5 Controllable Converters or Parameters

Some of the converters do not depend on any other converters, flow, or stocks in the model. This are parameters which need to be set before the model is run. Different values for these will give different results to the model

For example in the UK population of figure 2.4a, there are three controllable converters. The birth rate, death rate and the initial value of the UK population. The latter converter is not explicitly drawn on the diagram, although it would need to be present for the simulation of the model to run. Thus the UK population of figure 2.4a is a three parameter model.

2.6 Dynamic System

The combination of all these building blocks is a the *system*. It is a *dynamic* system because the stocks, rates and converters may change over time. The values of these quantities at any one time are referred to as the *state* of the system.

The dynamic system can be simulated using appropriate software, in this case Stella (also called Ithink). Because the simulation is a model of the real world system it is also called a dynamic model. The model can be investigated by graphing the values of the stocks, flows and converters over time, and by varying the values of the fixed converters and examining the effects.

2.7 Stability

If after a length of time the values of the stocks in the system become constant, i.e. they stop changing, the dynamical system is said to be stable. If a stock has only one flow this will happen when the flow rate becomes zero. Thus in figure 2.2b for believers to stop growing the number converted per month must be zero.

If there is an inflow and an outflow, as in figure2.2a, the inflow must eventually equal the outflow if growth (or decline) is to cease. in this case births must equal deaths. It is possible that this situation can never occur. In this case there will always be change in the stock level.

For more complex situations growth ceases when the sum of all the inflows equals the sum of all the outflows. Like a tank of water for the level to remain constant the total amount of water from all the taps must be equal to the total amount flowing out from the drains.

3 Dynamic Process

The model contains any number of stocks, flows, converters and connectors. As such models can get quite complex, as would be expected in a complex world. To help sift through this complexity it is possible to identify specific fundamental dynamic processes out of which more complex ones are built. These processes include the compounding, draining, and stock adjustment processes, which will be useful in church growth modelling.

3.1 Compounding Process

This is a growth process where the value of the stock reinforces the growth rate, that is the *inflow* is controlled by the stock itself:

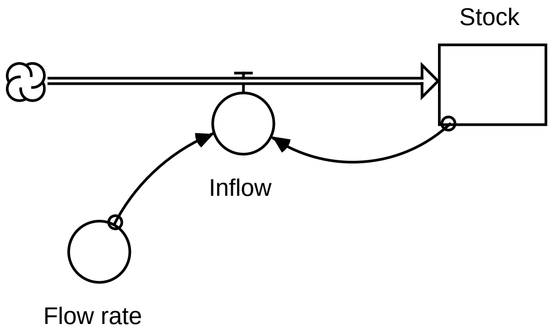

Fig. 3.1a. Compounding process

The inflow is the product of two inputs, the stock and a flow rate, according to the rule:

Inflow = Stock X Flow rate.

(Equation 3.1a)

This is commonly referred to as exponential growth, as its mathematical solution is a growing exponential function. In this case the inflow increases the stock which in turn increases the inflow (opens the tap more). Thus the increases get multiplied or compounded. Note the curve in figure 3.1b gets steeper and steeper. It is a model of the birth process where the birth rate is constant. It is also a model of the compound interest that banks use to calculate interest on savings and loans.

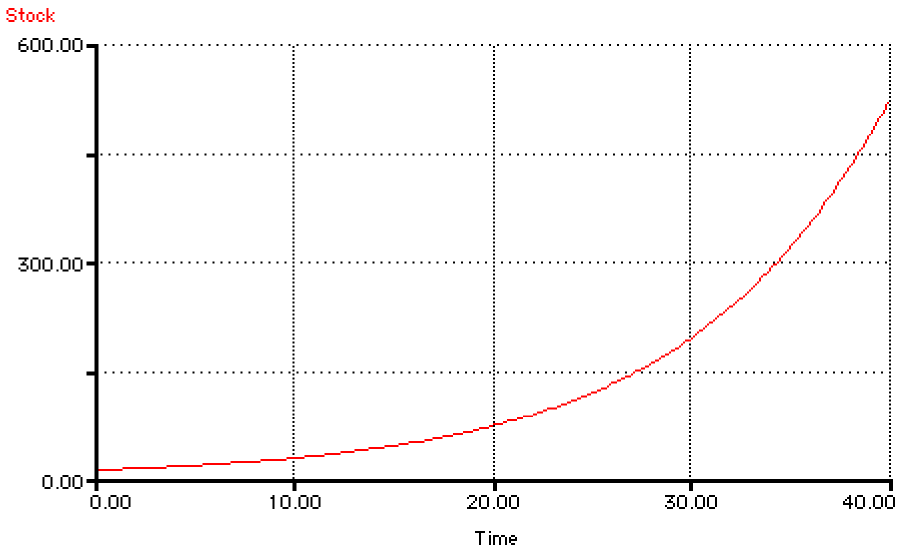

Fig. 3.1b. Exponential growth - result of a compounding process

The only situation where there can be no change in the stock is if the inflow is zero, i.e. the Stock is zero. So for non-zero stock levels there is always growth.

3.2 Draining Process

This is a decay process where the *outflow* is controlled by the stock:

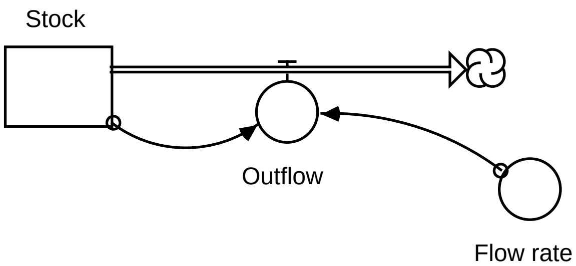

Fig 3.2a. Draining process

The outflow is the product of two inputs, the stock and a flow rate, according to the rule:

outflow = Stock X Flow rate

(Equation 3.2a)

This is commonly referred to as exponential decay, as its mathematical solution is a negative exponential. In this case the outflow decreases in time causing the stock to eventually level at zero. Growth stops when the outflow is zero which only happens when the stock is zero, equation 3.2a. Thus it is a decay targeted to zero. Note the curve in figure 3.2b gets lower but it is slowing down.

It is a model of the death process where the death rate remains constant. It is also a model of radioactive decay, indeed any decay process which has no memory of previous states, often called a Poisson process.

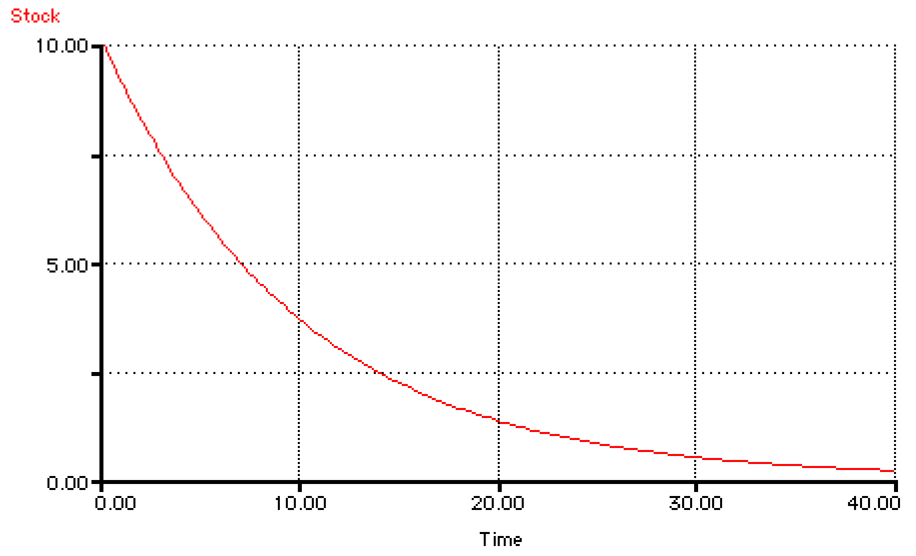

Fig.3.2b. Exponential decay - result of the draining process.

3.3 Stock Adjustment Process

In this process the flow into or out of a stock is adjusted so that the stock can reach a target level:

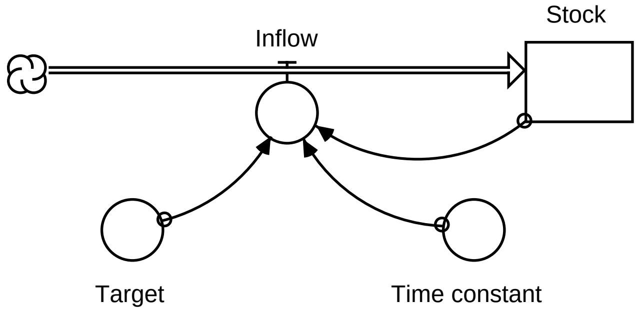

Fig.3.3a. Stock adjustment process

Again this is an exponential limit model, where the stock tends to a fixed target level other than zero. In the example above the inflow decreases according to:

$$\text{Inflow} = \frac{\text{Target} - \text{Stock}}{\text{Time Constant}}$$

(Equation 3.3a)

where it is assumed that the level of the stock starts below the target. It is a model of the recruitment of staff where a target level of staff is required. In figure 3.3b the recruitment slows down the closer the stock (number of staff) gets to the target level. Growth ceases when the inflow is zero, i.e. Stock is equal to the target.

If flow is allowed in both directions it is a model of heat transfer where the stock represents the temperature of a body and the target is the background room temperature. E.g. it would model the temperature of a cold drink in a warmer room. It will warm up until it reaches room temperature slowing down as it gets cooler.

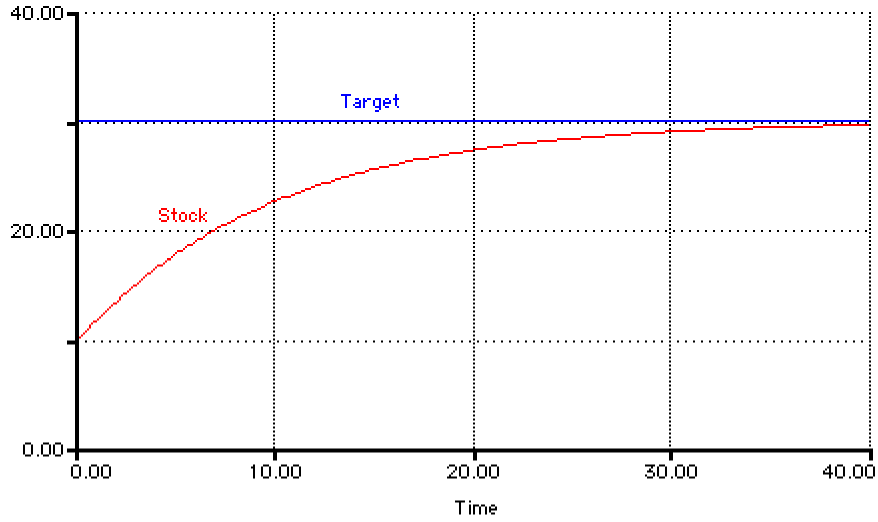

Fig 3.3b. Exponential limit - result of a stock adjustment process.

3.4 Other Processes

There are other fundamental dynamical processes involve two or more stocks. However as these are not relevant to the following church growth models they will not be discussed. The reader is referred to more in-depth treatments of system dynamics (Sterman 2000, Goodman 1989).

4 Causal Loops

4.1 Simple Causal Loop

It is possible to understand the general behaviour of a dynamic system without simulation. Conditions in a system give rise to some action and that action causes the conditions to change. A simple diagram, called a causal loop diagram (figure 4.1a) summarises this connection.

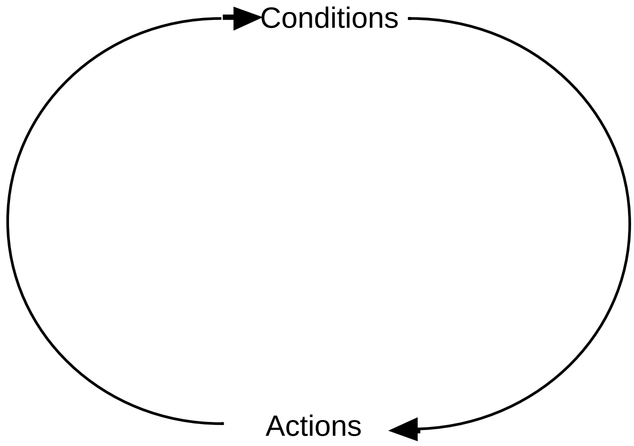

Fig.4.1a. Simple causal loop diagram

The causal changes may be due to the *physical flow* of some quantity, or they may be due to *information links*. For example in the above stock adjustment model the recruitment rate causes staff numbers (the conditions) to increase. This is a physical link. However as the staff numbers get close to the target the recruitment rate (action) is reduced. This is a policy decision, a deliberate action, an example of an information link.

All systems models can be analysed with causal loop diagrams. The causal loops show the fundamental structure of a system, without being burdened by the details. Often, if a system is not behaving as it should, the solution is easier to see at the causal loop level than at the modelling level. Often it is a change of structure that is required such as an extra loop or the removal of a loop.

It is also possible to start the modelling process off at the causal loop level, and only move to the dynamic model once the structure is understood. This is particularly useful when the system contains "soft" variables, i.e. ones that are not easily quantified such as emotion, stress, desire etc. Population modelling usually only contains "hard" variables based on population number - which are easily quantified. Thus the alternative approach of constructing the dynamical model first and then analysing it with causal loop diagrams will be taken.

Starting with the dynamic model, rather than the causal loop, will also avoid one of the common pitfalls of causal loop diagrams - the failure to distinguish between information links (connectors) and rate-to-level links (flows), as described by Richardson 1997. There is also a failure to distinguish between stocks (the system variables) and converters (the derived quantities. The type of link and the type of quantity effects the dynamics of the system and, following a number of authors, this paper will preserve that distinction in the causal loop diagram.

Some of the basic dynamical processes can be analysed with causal loops. The two fundamental loops are the reinforcing loop and the balancing loop. All complex systems are a combination of these two loops.

4.2 Reinforcing Loop

The reinforcing loop is the fundamental process of growth. If the increase in conditions leads to an increase in the actions, and an increase in the actions leads to an increase in the conditions then, the effect traced all the way around the loop, causes further increase in the conditions. Because of this accumulated increase it is often called positive feedback.

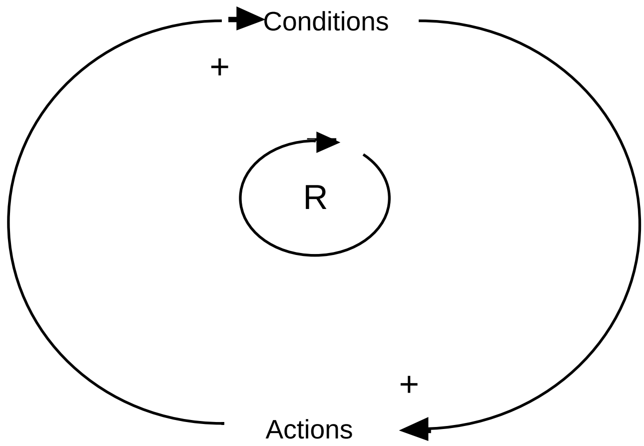

Fig.4.2a. Reinforcing loop due to quantities reinforcing each other.

The compounding process is an example of a reinforcing loop:

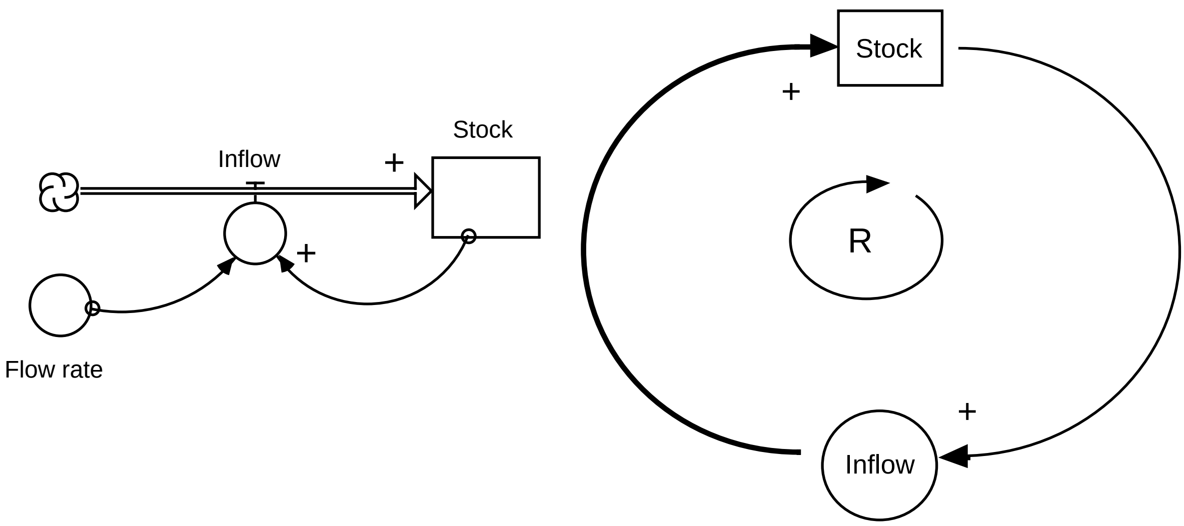

Fig.4.2b. Compounding process as an example of a reinforcing loop

The thin line is an information link due to the connector from the stock to the inflow. The thick line is a rate-to-level link due to the physical flow into the stock from the inflow.

The flow rate is a constant and not part of the loop.

The plus sign refers to a positive effect of one quantity on the next. A positive effect in an <u>information link</u> can be seen by saying either of:

An <u>increase</u> in *quantity 1* produces an <u>increase</u> in *quantity 2*
An <u>decrease</u> in *quantity 1* produces a <u>decrease</u> in *quantity 2*.

For example an increase in the stock gives an increase in the inflow - thus its effect is positive or reinforcing.

A positive effect in a <u>physical flow</u> can be seen by saying:

An <u>increase</u> in *quantity 1* produces a <u>faster</u> increase in *quantity 2*.

For example an increase in the inflow (opening the tap wider) will cause the stock to rise *faster*. The stock will always rise unless the inflow is zero.

Because each increases the other the net result back on the variable is positive, as it is reinforcing itself. It is thus called a <u>reinforcing loop</u> or, in more engineering terms, positive feedback. The birth process mentioned in sections 2.3 and 2.4 is a reinforcing loop. An increase in the population increases the number of births. This likewise causes a faster increase in the population.

It is also possible to have a link with a negative change, called an opposing link. If a loop has two opposing links it is also a reinforcing loop as the two negatives also make a positive:

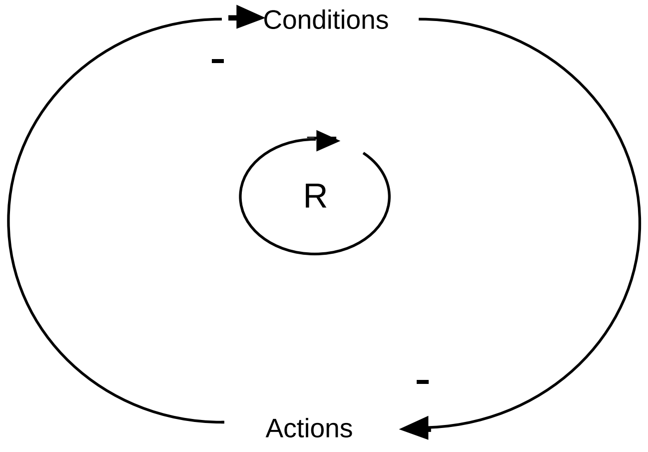

Fig.4.2c. Reinforcing loop due to two opposing links

A negative link means that an increase in the conditions reduces the actions and a reduction in the actions increases the conditions. Thus the net effect back on the conditions is positive or reinforcing. However many items there are in a causal loop diagram, if there are an even number of opposing links then the overall loop will be reinforcing.

Reinforcing loops indicate instability. The feedback between a microphone and an amplifier, which results in a squeal that gets louder, is an example of a reinforcing loop.

4.3 Balancing Loops

In a balancing loop the net effect of all the changes around the loop back on the original variable is negative. It is thus called negative feedback. For example:

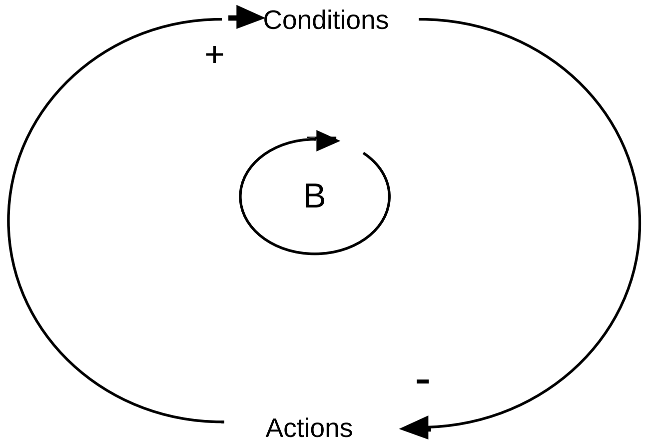

Fig. 4.3a. Balancing loop

Increasing the conditions leads to the actions being decreased. its decrease in actions causes the conditions to decrease. Thus the net effect of increasing the conditions is to bring it back down. The net effect is a balancing one.

The stock adjustment process is an example of a balancing loop. The inflow increases the stock. However, as the stock increases, and gets closer to the target, the inflow decreases:

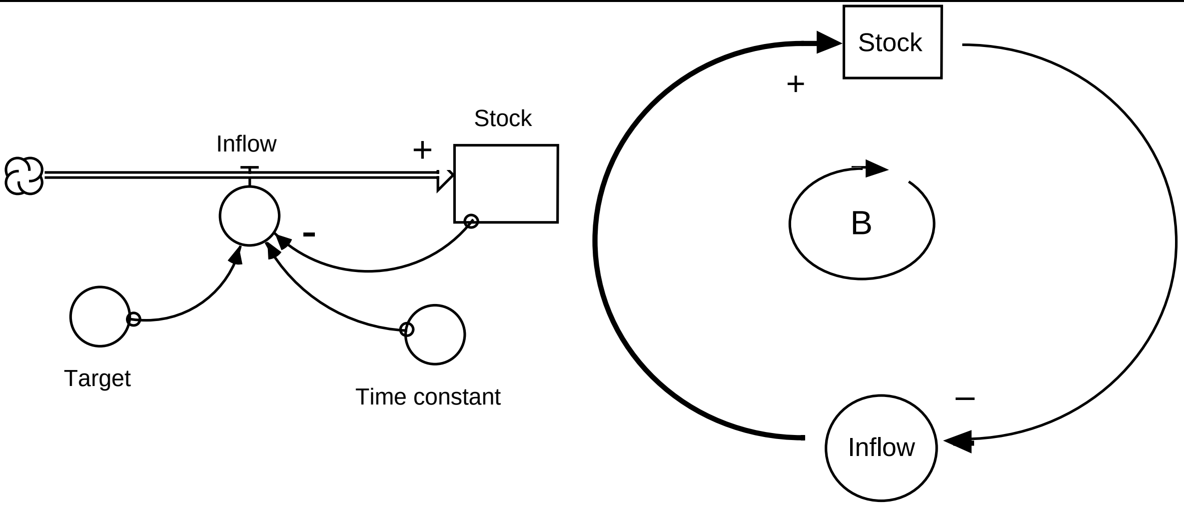

Fig. 4.3b. Stock adjustment process as an example of a balancing loop

A negative sign on an <u>information link</u> can be seen by saying:

An <u>increase</u> in *quantity 1* produces a <u>decrease</u> in *quantity 2*.

In this case an increase in the stock causes the inflow to decrease. This was the process behind the staff recruitment model. An increase in staff (stock) leads to the recruitment rate (inflow) to decrease as target levels are nearer to being achieved.

It is also possible to have a negative link on a physical flow. This happens when the flow is an outflow. Reducing the stock through an outflow is a negative effect. The draining process is a an example of such a balancing loop:

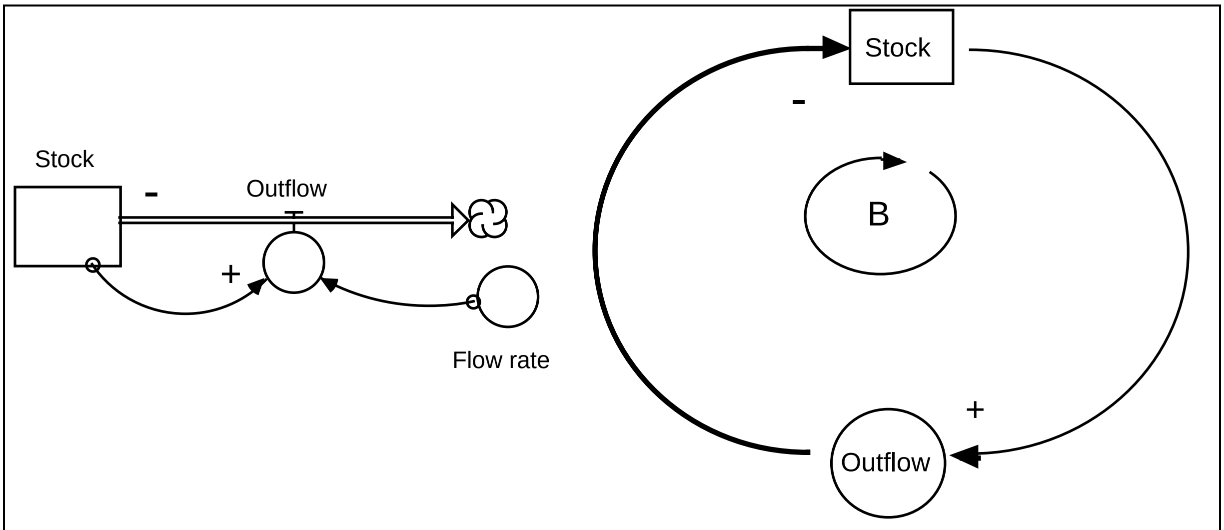

Fig. 2.3g. Draining process as an example of a balancing loop

A negative sign on a physical flow can be seen by saying:

An increase in *quantity 1* produces a faster decrease in *quantity 2*.

A more helpful way of saying this would be:

An decrease in *quantity 1* produces a slower decrease in *quantity 2*.

Thus decreasing the stock causes the outflow to decrease, the positive link. However the decrease in the outflow causes the stock to decrease slower, the negative link. The net effect is negative as the outflow slows down with decreasing stock. In this case it balances out to zero.

The death process in a population is a balancing loop. Balancing loops have a target. In the case of death the target is zero, but others are possible.

However many variables there are in a loop, if there are an odd number of negative changes, then it will be a balancing loop. Balancing loops indicate stability.

4.4 Loops In Complex Systems

The behaviour of a more complex system can be understood by combining together different balancing and reinforcing loops. As an example consider the logistic model of population growth. One example of this process is where a population grows in a fixed environment. Initially, when numbers are small and space is plentiful, the process is the compounding one reinforcing loop) - as the population increases the number of births, with a fixed growth rate, increases. However as the fraction of space taken by the population goes up the number of births decreases (balancing loop). This balancing loop becomes dominant and stability is achieved with the population being the maximum the space can support.

The dynamical model for this process is:

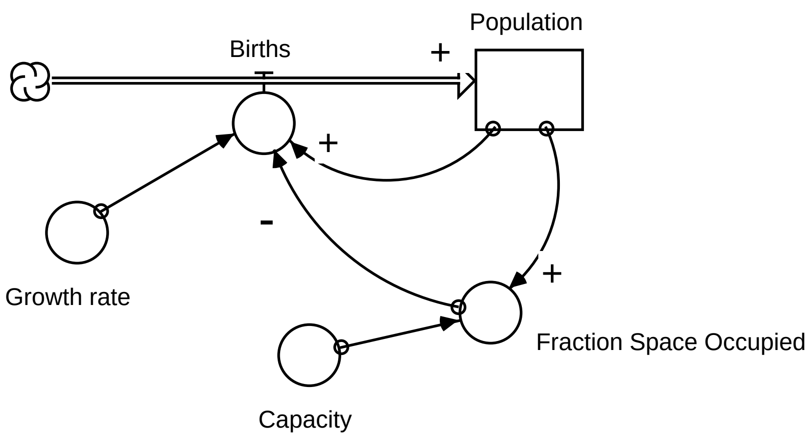

Fig. 4.4a. Logistic process - growth limited due to lack of space

This gives the S-shaped result for the population stock typical of logistic behaviour:

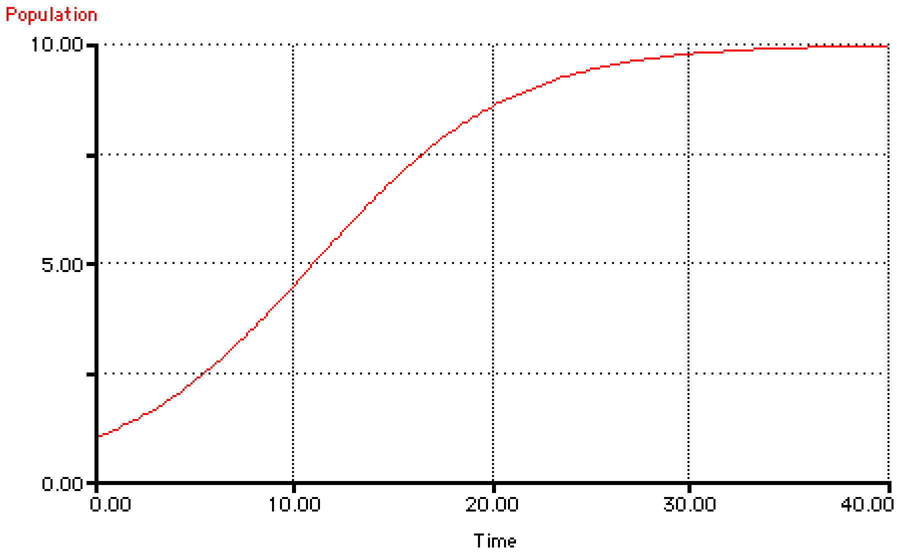

Fig.4.4b. Graph of logistic process showing population reaching capacity.

The causal loop for this model shows the two loops:

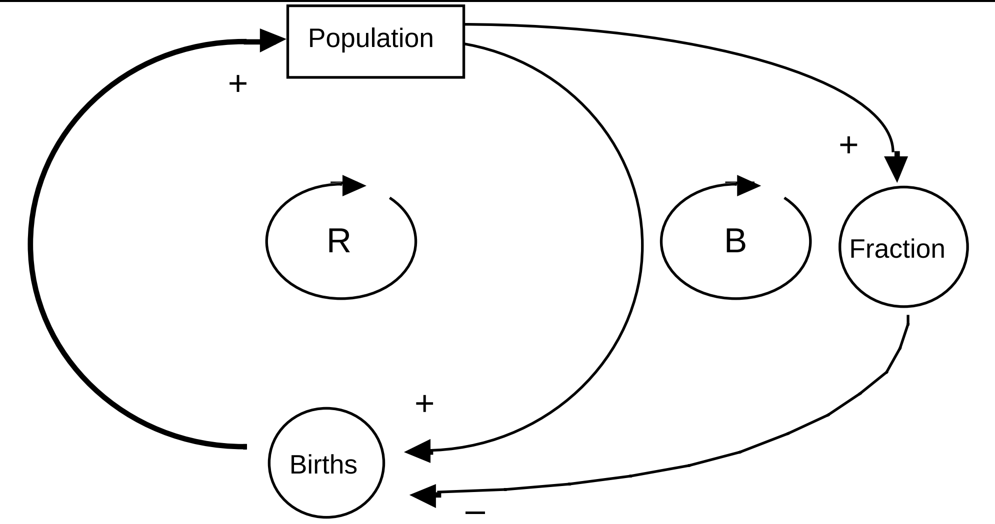

Fig.4.4c. Causal loop diagram of the logistic model - shifting loop dominance.

The population is affected by two loops, one direct through births, and the other indirect through the fraction of space taken up by the population. The direct link is a reinforcing loop and gives growth, or "success". The balancing loop places limits on that growth. Thus this scenario is often called "limits to success", or “limits to growth”. It is an example of shifting loop dominance as first the reinforcing loop dominates and then the balancing loop dominates.

Note it is not clear from the above diagrams *how* and *when* the shift from one loop to another takes place. At this point more detailed modelling of the nature of the relationships is required. This would require mathematics.

Again determining the exact limit to the growth would require some mathematics. However some qualitative understanding can be gained by setting the only inflow, “Births”, equal to zero. The only converter that can do this is “Fraction Space Occupied”. Thus the limit is achieved when the fraction of space occupied by the population is at its maximum.

Other complex systems are modelled in similar ways. In fact there have been attempts to describe all systems in terms of a fixed number of archetypes. (Anderson & Kim 1998). There are very few truly different dynamical systems. However only the limits to growth one is relevant to the church growth models

5 References

5.1 Books

Anderson D.H and Kim V. (1998), System Archetype Basics: From Story to Structure, Pegasus Communications Inc., Mass. USA.

Forrester J.W. (1961), *Industrial Dynamics*, reprinted by Pegasus Communications, Mass, USA.

Goodman M.R. (1989), *Study Notes in System Dynamics*, Pegasus Communications, Mass, USA.

Sterman J.D. (2000), *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Peagasus Communications, Mass, USA

5.2 Papers

Richardson G.P. (1997), Problems in causal loop diagrams revisited, System Dynamics Review 13 (3) , 247-252.

5.3 Internet Sites

Road Maps: A substantial introduction to system dynamics and related articles http://sysdyn.mit.edu/road-maps/home.html

System Dynamics in Education. The home page of the system dynamics group at MIT of which road maps is a part. http://sysdyn.mit.edu/

Peagasus Communications: Specialists in system dynamics books and other media. Mainly aimed at the business community. http://www.pegasuscom.com/index.html

The System Dynamics Society: Professional society for those who use systems dynamics. Many links to other related web sites. http://www.albany.edu/cpr/sds

System Dynamics Resource Page. http://www.public.asu.edu/~kirkwood/sysdyn/SDRes.htm

5.4 Software

Stella / Ithink. Goes by the name Stella in the education field and Ithink in the business community. It is the same piece of software. Easy to use. A demo version is available which enables models to be run.

Manufactured by High Performance Systems http://www.hps-inc.com/

Distributed in the UK by Cognitus Ltd http://www.cognitus.co.uk/

Vensim. Probably the most sophisticated of the different system dynamics software. Has academic and professional versions. A demo version of the software is available which will save small models.

Manufactured by Ventana Systems Inc. http://www.vensim.com

Powersim. Aimed at the business community. http://www.powersim.com