CHAPTER TWO

THE BASICS

(Excerpted from Thinking In Systems, by Dana Meadows)

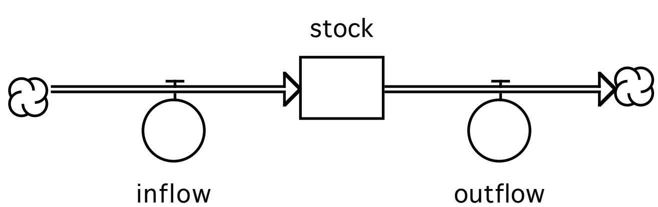
Bathtubs 101

> *Information contained in nature ... allows us a partial reconstruction of the past.... The development of the meanders in a river, the increasing complexity of the earth's crust ..., are information-storing devices in the same manner that genetic systems are.... Storing information means increasing the complexity of the mechanism.*
>
> -- Ramon Margalef[1]

Physical stocks[2] make up the foundation of any system. They are the elements of the system that at any given time you can see, feel, count, and measure. A system stock is just what it sounds like: a store, a quantity of material or information that has built up over time. It may be a population, an inventory, the wood in a tree, the water in a well, the money in a bank. A stock is a physical memory of the history of the system.

Stocks change over time through the actions of flows, usually actual physical flows into or out of a stock -- filling, draining, births, deaths, production, consumption, growth, decay, spending, saving. Stocks, then, are accumulations, or integrals, of flows.

In this book stocks will be illustrated by boxes or rectangles, and flows by pipes leading into or out of the stocks. The small T on each flow signifies a "faucet," indicating that the flow is variable; it can be turned higher or lower, on or off. The circle connected to the T signifies the decision process or rule that turns the faucet. The "clouds" stand for wherever the flows come from and go to. (I'll come back to decision rules and clouds later.)



For example, an underground deposit of minerals is a stock, out of which comes a flow of mined ore. There is no inflow to a mineral deposit, at least not over any time period less than eons.[3]

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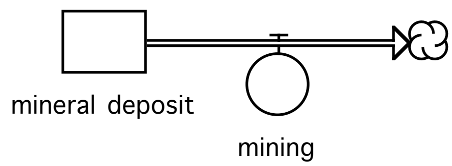
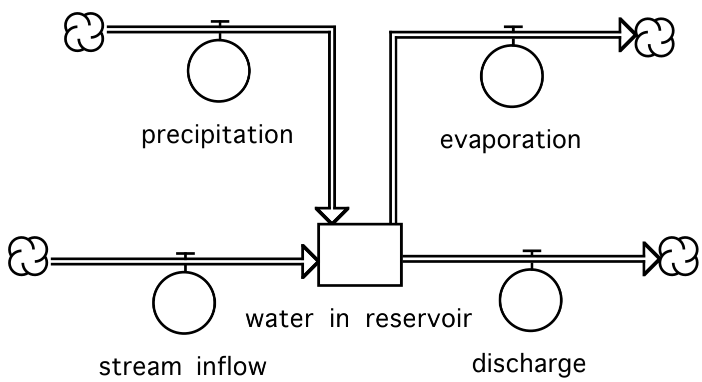
[1] Ramon Margalef, "Perspectives in Ecological Theory," Co-Evolution Quarterly, Summer, 1975, p. 49.

[3] The systems term for physical (and information) stocks is "state variables."

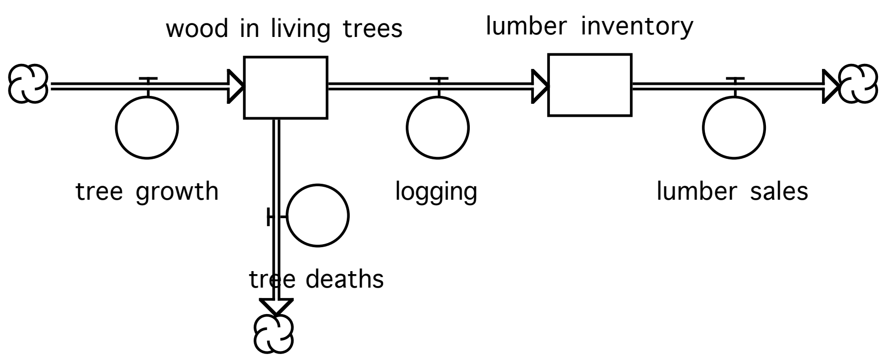
[3] This example brings up an immediate complication. (Systems are always more complicated than they first appear.) On some time scale every stock can be seen as a flow. At bottom, systems



Water in a reservoir behind a dam is a stock, into which flow rain and river, out of which flow evaporation from the reservoir's surface and water discharged through the dam.



The volume of wood in the living trees in a forest is a stock. Its inflow is the growth of trees. Its outflows are the natural deaths of trees and the harvest by loggers. The logging harvest flows into another stock, an inventory of lumber. Wood flows out of the inventory stock as sales to customers.



If you understand the dynamics (behavior over time) of stocks and flows, you understand a good deal about the behavior of complex systems. And if you have had much experience with a bathtub*[4], you understand the dynamics of stocks and flows.

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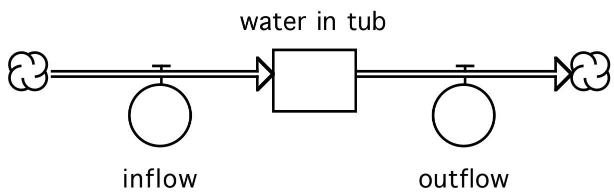
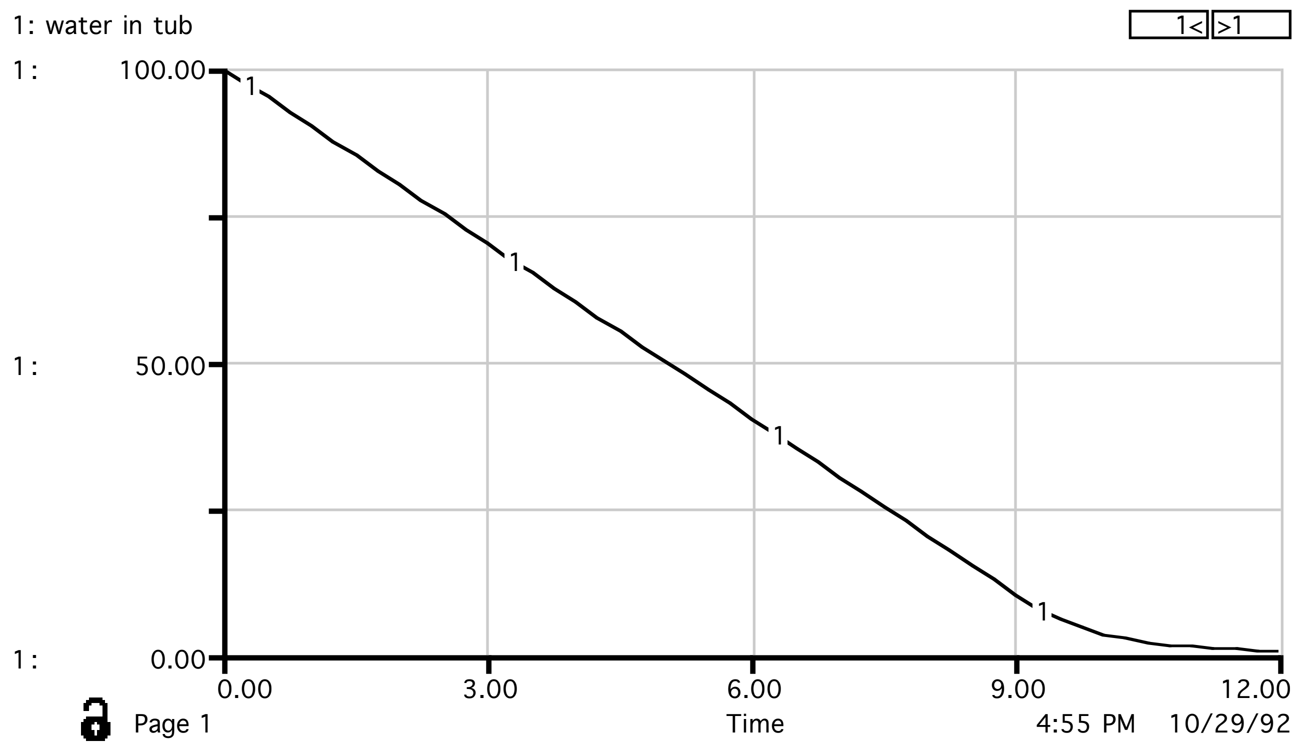
theory sees everything as flow -- it sees the world only as verbs, not as nouns! But for purposes of discussion, if your time-frame is, say, millenia, a mineral deposit is a stock. If your time-frame is minutes, the water in a bathtub is a stock. If your time-frame is decades, a human population is a stock.

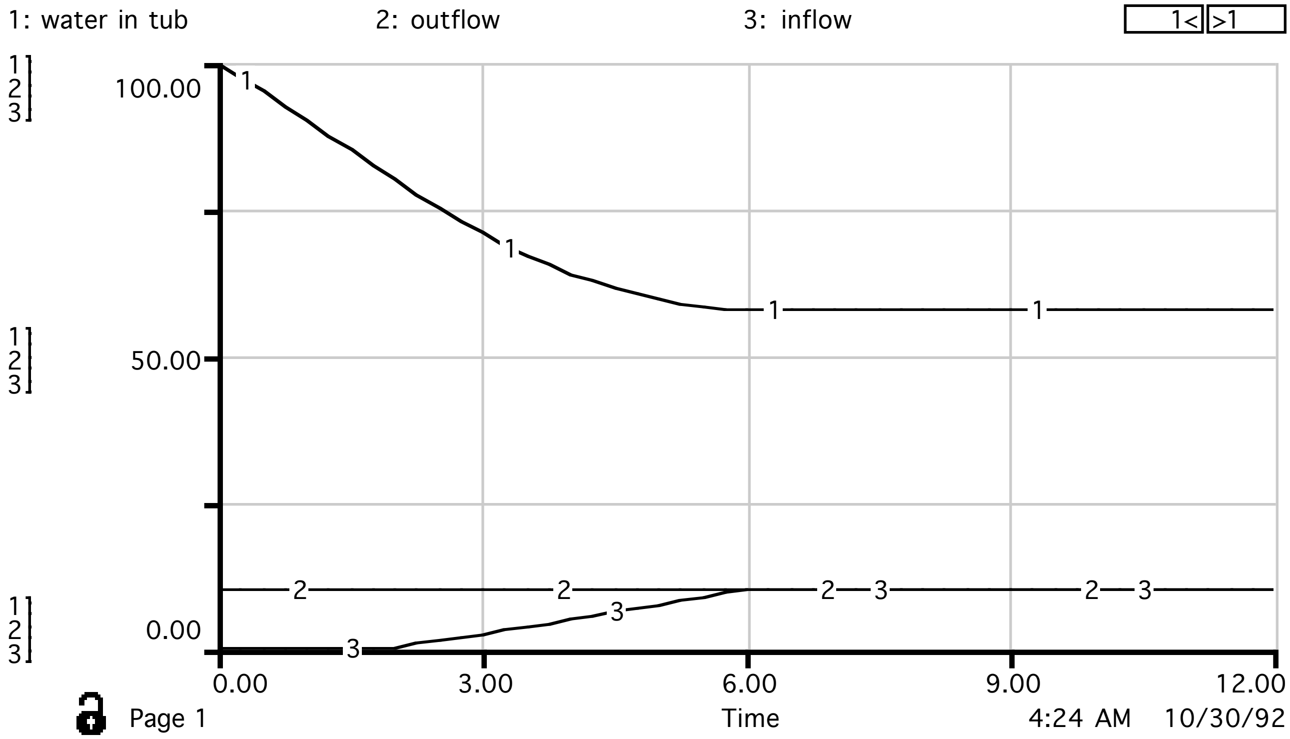
[4] Starred words like this one indicate the titles of models on the computer disk, which you can run, change, and test.



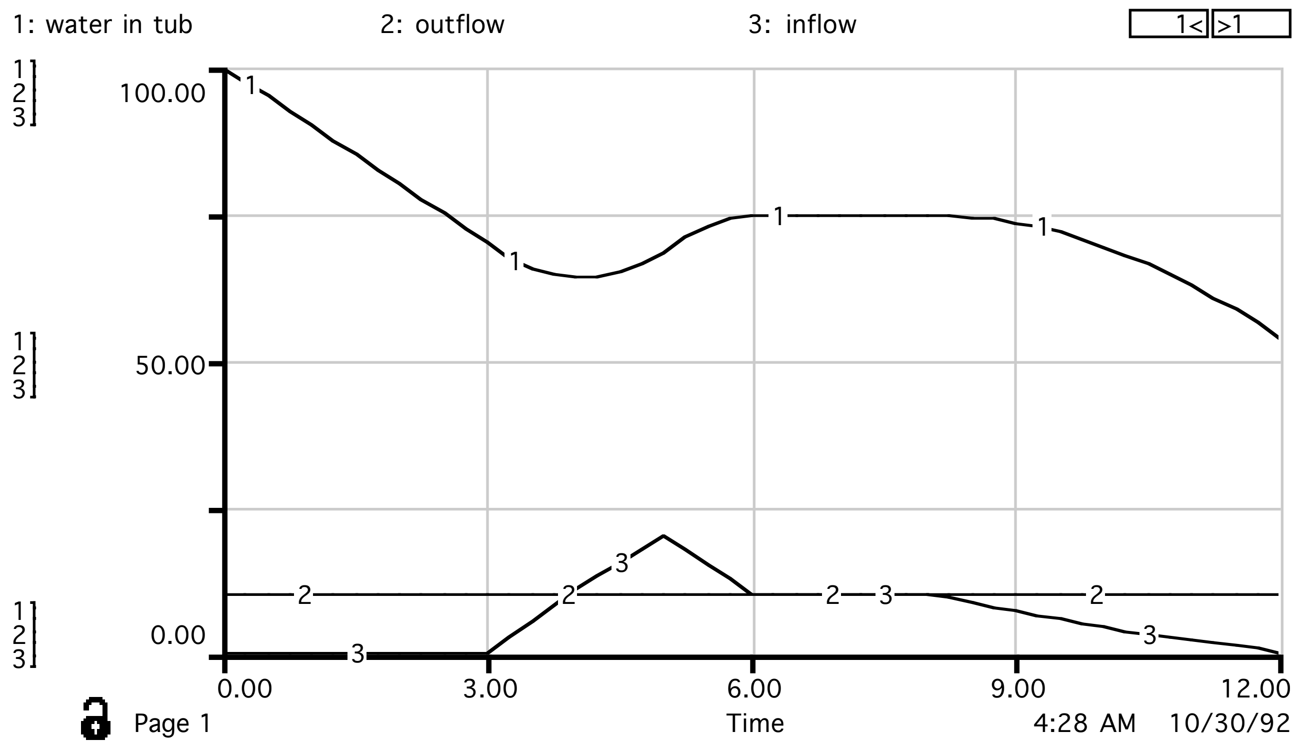
Imagine a bathtub filled with water, with its drain plugged up and its faucets turned off -- an unchanging, undynamic, boring system. Now mentally pull the plug. The water runs out, of course. The level of water in the tub goes down at a constant rate until the tub is empty.



Now start again with a full imaginary tub and again open the drain, but this time when the tub is about half empty turn on the inflow faucet so the rate of water flowing in is just equal to that flowing out. What happens? The amount of water in the tub stays constant at whatever level it had reached when the inflow became equal to the outflow. It is in a state of <u>dynamic equilibrium</u> -- its level does not change, though water is continuously flowing through it.



Imagine turning the inflow on somewhat harder while keeping the outflow constant. The level of water in the tub slowly rises. If you then turn the inflow faucet down again, the water will stop rising. Turn it down some more, and the water level will slowly fall.



The bathtub is a very simple system with just one stock, one inflow, and one outflow. You know all its dynamic possibilities. From it you can deduce several important principles that extend to more complicated systems:

As long as the sum of inflows exceeds the sum of outflows, the stock level will rise.
As long as the sum of outflows exceeds the sum of inflows, the stock level will fall.
If the sum of outflows equals the sum of inflows, the stock level will not change -- it will be held in dynamic equilibrium at whatever level it happened to be when the two flows become equal.

These conclusions are obvious when it comes to bathtubs, but not so obvious when the subject changes to larger tubs of water, or money.

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<u>The Great Mud Flats and the National Debt</u>

If present trends continue, the southwestern United States will face severe water shortages at the end of this century. At the same time the Great Lakes* on the border of the United States and Canada hold about 20% of the world's entire supply of fresh water (a stock of 14,000 cubic kilometers). It has been suggested that Great Lakes water could be transported to the southwest to alleviate water scarcities.

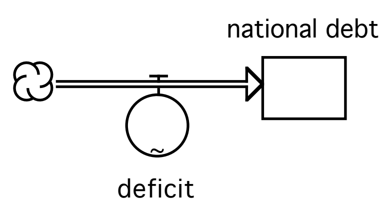
Aside from the enormous cost of pumping water such great distances, a more fundamental flaw in this scheme comes from a confusion about stocks and flows.

The Great Lakes represent an immense stock of water. However, the flow of water through them is relatively small. The outlet of the Great Lakes -- the St. Lawrence River at the end of Lake Ontario -- has a mean annual flow of 210 cubic kilometers per year. This quantity is the maximum that could be diverted out of the Great Lakes without lowering them.

If more than 210 cubic kilometers per year were sent southward, North America would slowly become famous for the Great Mud Flats, and eventually the Great Holes. The sustainable water resource of the Great Lakes is not the stock, but the flow.[5]

* * *

In 1992 the national debt* of the United States was approximately $4 trillion ($4,000,000,000,000). The deficit that year, which is the difference between the amount of money the government took in and the amount it spent, was about $300 billion ($300,000,000,000). There are two ways a government can spend more than it earns. One is to print money, which is inflationary and therefore frowned upon. The other is to borrow; that is, to increase the debt. The deficit, therefore, is the annual inflow to the debt. (At the rate of $300 billion a year, the debt is increasing by $821 million a day, or roughly half a million dollars a minute.)



This formulation may seem a bit strange, because the debt is a negative stock of money, the accumulation of what the nation owes. It is a financial hole, and the deficit is the borrowing that digs the hole deeper. But negative stocks and flows behave the same way as positive ones.

If the deficit continues at the rate of $300 billion a year the debt will continue to grow steadily. After ten more years it will reach $7 trillion and will still be growing. If the deficit is gradually reduced after 1995 so that it reaches zero by the year 2000, the debt will rise to $5.5 trillion and then stay there (requiring constant payments of interest, but interest is a feedback concept that we'll come to in a minute.) The only way to reduce a debt is not just to stop running a deficit, but to run a surplus.

For some reason, politicians never talk about running a surplus.
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[5] Stephen Chapra of Texas A&M University first suggested this example to me. The water statistics come from UNESCO, World Water Balance and Water Resources of the Earth, Paris, 1978, p. 536.

The human mind seems to focus more easily on stocks than on flows, as the Great Lakes story suggests. It also focuses on inflows more easily than on outflows. Therefore it sometimes misses seeing that you can fill a bathtub not only by increasing the inflow rate, but also by decreasing the outflow rate. Everyone understands that you can prolong the life of an oil-based economy by discovering new oil deposits. It seems to be harder to understand that the same result can be achieved by burning less oil. A breakthrough in energy efficiency is equivalent in systems terms to the discovery of a new oil field (except, importantly, that different people profit from it).

Similarly a company can build up a larger workforce by more hiring, or it can do the same thing and save training costs by reducing the rates of quitting and firing. The economic output of a nation can be boosted by investment to build up a larger stock of factories and machines. It can also be boosted, often more cheaply, by decreasing the rate at which factories and machines wear out, break down, or are discarded.

> A stock can be increased by decreasing its outflow rate as well as by increasing its inflow rate. There's more than one way to fill a bathtub!

You can turn the drain or faucet of a bathtub -- the flows -- on or off abruptly. But you can't change the level of water -- the stock -- quickly. Water can't drain out instantly, even if you open the drain all the way. The tub can't fill up immediately, even with the inflow faucet on full blast. <u>A stock takes time to change, because flows take time to flow.</u> That's a vital point, a key to understanding why systems behave as they do. <u>Stocks change slowly.</u> They act as delays, lags, buffers, ballasts, sources of momentum in a system. Stocks respond to change, even sudden change, only by gradual filling or emptying.

> Stocks change only slowly, never suddenly, even if the rates flowing into or out of them change suddenly. Therefore stocks act as delays in systems.

People often underestimate the inherent momentum of a stock. It takes a long time for populations to grow or stop growing, for wood to accumulate in a forest, for a dam to fill up, for a mine to be depleted. An economy cannot build up a large stock of functioning factories and highways and electric plants overnight, even if a lot of money is available. Once an economy has a lot of oil-burning furnaces and automobile engines, it cannot change quickly to furnaces and engines that burn a different fuel, even if the price of oil suddenly changes. It has taken decades to accumulate the stratospheric pollutants that destroy the earth's ozone* layer; it will take decades for those pollutants to be removed.

Slow stock changes set the pace of the dynamics of systems. Economic development cannot proceed faster than the rate at which factories and machines can be constructed and the rate at which human beings can be educated to run them. Forests can't grow overnight. Once contaminants have accumulated in groundwater, they can only be washed out at the rate of turnover of the groundwater, which may take decades or even centuries.

The time lags that come from slowly changing stocks can cause problems in systems, but they can also be sources of stability. Soil that has accumulated over centuries rarely erodes all at once. A population that has learned many skills doesn't forget them immediately. You can pump groundwater faster than the rate it recharges for a long time before the water table is depleted. The time lags imposed by stocks allow room to maneuver, to experiment, and to revise policies that aren't working.

If you have a sense of the rates of change of stocks, you don't expect things to happen faster than they can happen. You don't give up too soon. You can use the opportunities presented by a system's momentum to guide it toward a good outcome -- much as a judo expert uses the momentum of an opponent to achieve his or her own goals.

There is one more important principle about the role of stocks in systems, a principle that will lead us directly to the concept of feedback:

> The presence of stocks allows flows to be independent, decoupled, and dependable.

It would be hard to run an oil company, if gasoline had to be produced at the refinery at exactly the rate the cars are burning it. Managing a store would be impossibly hectic if merchandise deliveries had to come in the back door just as customers placed orders at the front counter. It isn't feasible to harvest a forest at the precise rate at which the trees are growing. Gasoline in storage tanks, inventories in shops, wood in the forest, all are stocks that permit life to proceed with some certainty, continuity, and predictability, even though flows vary.

Human beings have invented hundreds of mechanisms to decouple and stabilize flows by maintaining stocks. Here are some examples:

- Dams, so residents and farmers downriver don't have to adjust their lives to a river's varying flow, especially its droughts and floods,

- Banks, so you don't have to earn money at exactly the rate you spend it,

- Inventories of products along a chain from distributors to wholesalers to retailers, so production can proceed smoothly though customer demand varies, and so customer demand can always be filled even though production rates vary.

Most individual and institutional decisions are designed to regulate stocks. If inventories rise too high, then prices are cut or advertising budgets are increased, so that sales will go up and inventories will fall again. If the stock of food in your kitchen gets low, you go to the store. As the stock of growing grain rises or fails to rise in the fields, farmers decide whether to apply water or pesticide, grain companies decide how many barges to book for the harvest, speculators bid on commodity markets, cattle growers build up or cut down their herds. Water levels in reservoirs cause all sorts of corrective actions if they rise too high or fall too low. The same can be said for the stock of money in your wallet, the oil reserves owned by an oil company, the pile of woodchips feeding a paper mill, the concentration of pollutants in a lake.

People monitor stocks constantly and make decisions and take actions designed to keep them at acceptable levels. Those decisions add up to the ebbs and flows, successes and problems, of socioeconomic systems. Systems thinkers see the world as a collection of stocks and mechanisms for regulating stocks by manipulating flows.

That means they see the world as a collection of feedback processes.