

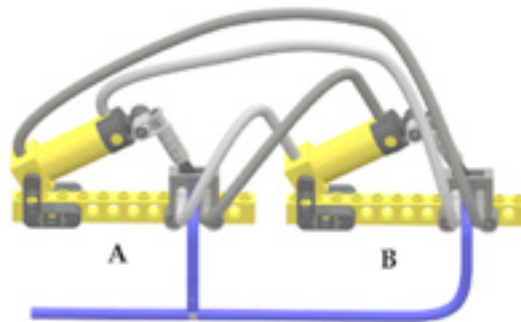
Tutorial: Pneumatic Sequencing (I)

This article describes how to create pneumatic circuits that, over time, create repeated sequences of expansion and contraction.

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Edited by Jetro de Château

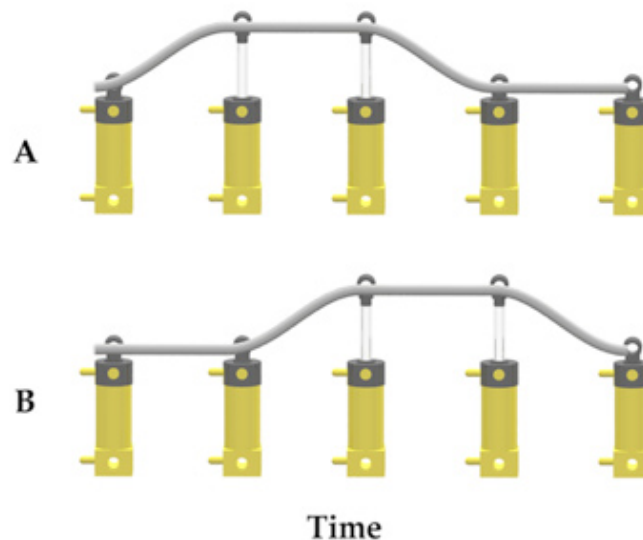
The simplest pneumatic sequencer contains two pistons and two switches hooked together.



Piston A controls switch A. Piston B controls switch B. Piston B is controlled by switch A. Piston A is controlled by switch B. So, piston A controls piston B (via switch A), and piston B controls piston A (via switch B). Switch A makes piston B mimic what piston A is doing, and Switch B makes piston A do the opposite of piston B. The piston/switch pairs feed each other in a thing called a feedback loop. Switch A feeds forward to piston B, and switch B feeds back to piston A. The result is that pistons A and B take turns opening and closing over and over.

As long you keep applying air pressure the pistons keep expanding and contracting in a repeating sequence. You can use this pneumatic sequencer to create your own moving LEGO® creations. If you connect the pistons to a cam mechanism, you can create a pneumatic engine. The pistons go through four distinct states: A contracted/B contracted, A expanded (caused by switch B)/B contracted, A expanded/B expanded (caused by switch A), A contracted (caused by switch B)/B expanded, and A contracted/B contracted (caused by switch A). After this the cycle just repeats.

The states of the pistons can be drawn graphically like this

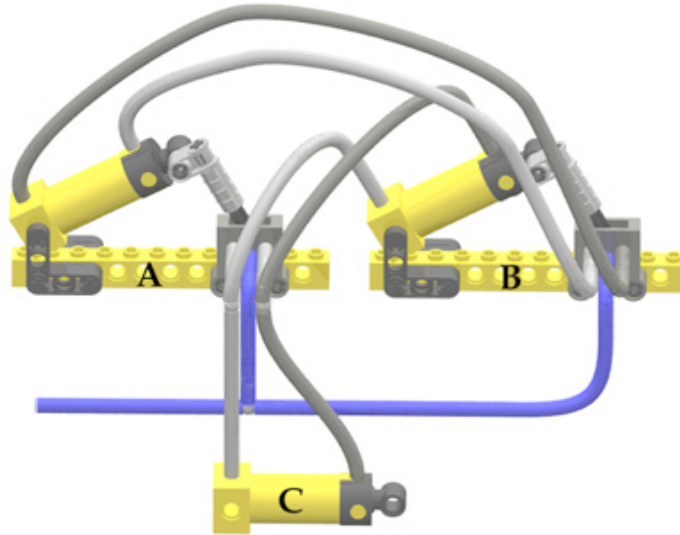


The graph shows the pistons expanded and contracted states over time. The top line of the graph shows piston A over time, and the bottom line of the graph shows piston B over time. The upwardly sloping diagonal lines represent pistons expanding. The horizontal lines represent the pistons in steady state, either expanded or contracted. The downwardly sloping lines represent pistons contracting.

When piston A completes expanding, it makes piston B start to expand. When piston B completes expanding it makes piston A start to contract. When piston A contracts completely it makes piston B start to contract. When piston B contracts completely it makes piston A start to expand, making the cycle repeat.

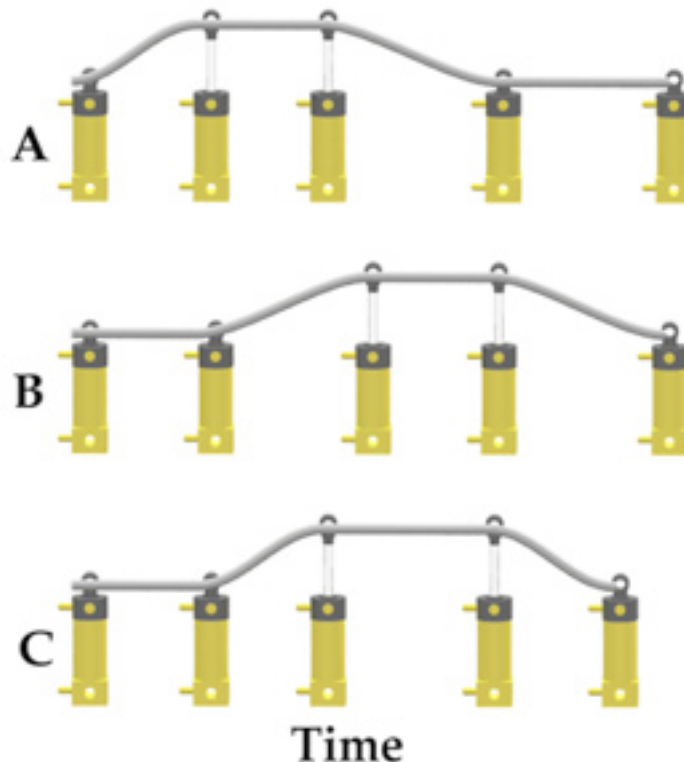
Adding another piston

Let's say we want a second piston that does the same thing as piston B. Using pneumatic T's and more hoses, we can hook up piston C the same way that piston B is hooked up.



If you do it this way, you can see that piston B and piston C don't expand at the same rate. This is because piston B has the load of switch B which slows down the expansion and contraction. Even if we put a switch onto piston C so it has a similar load, piston B and piston C probably wouldn't expand at exactly the same rate due to minor manufacturing differences in the pistons, switches T's and hoses.

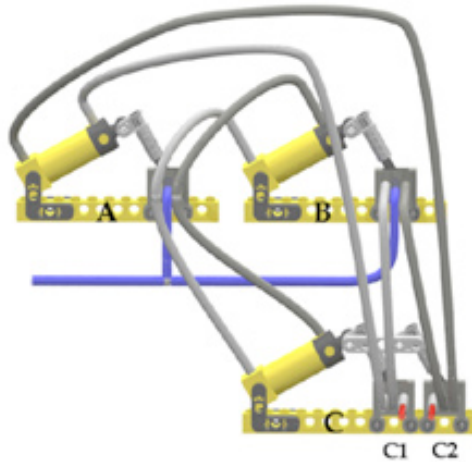
Figure shows the timing diagram for circuit 2.



Notice that piston C does not behave exactly the same as piston B. If we're trying to use piston B and piston C in a LEGO® model, the two parts controlled by pistons B and C won't behave exactly the same. Clearly adding more pistons to the circuit this way will not have piston B and C behave exactly the same.

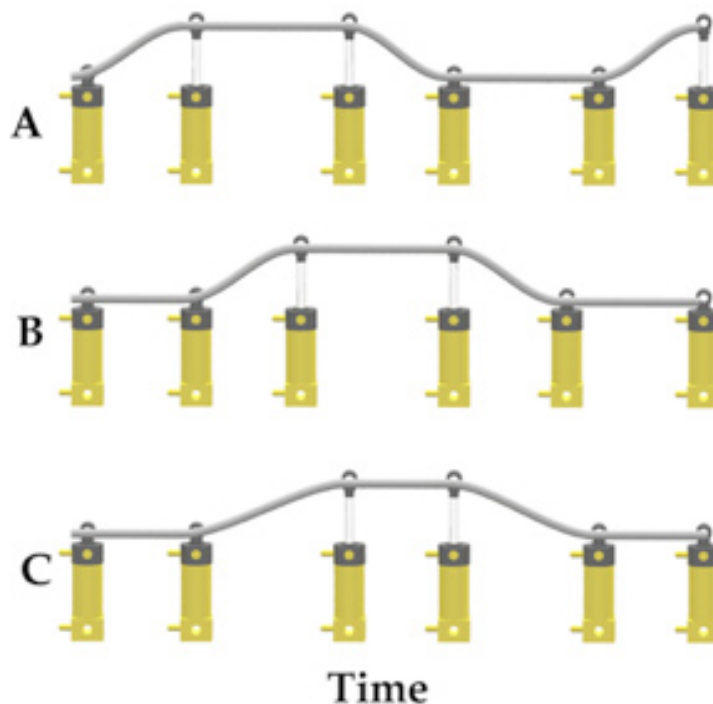
Synchronizing Two Pistons

We cannot make the two pistons expand or contract at exactly the same rate, but we can make sure that both pistons B and C expand completely and contract completely every time through the four step cycle. We do this by adding two switches to piston C as shown in the following circuit.



In circuit 3, we make piston C stay synchronized with piston B by running the each of the outputs of switch B into a switch controlled by piston C (switch C1 and switch C2). The pressure out of switch B's left port (makes piston A contract) goes into switch C1's center port, and then out C1's left port which is hooked to piston A's contract port. Pressure cannot make it through switch B and switch C1 unless piston B and piston C are expanded. Similarly the right port of switch B is hooked to the center port on switch C2, and the right port of switch C2 is hooked to piston A's expand port. In this case pressure cannot make it to piston A's expand port unless both piston B and piston C are contracted. We've now made piston B and C behave the same way, even if they expand or contract at different rates. They are synchronized. Notice that the unused ports of switches C1 and C2 are plugged by small pieces of hose with mini-fig light sabers stuck in them. If we don't plug them, pressure will leak out these ports when pistons B and C are not both expanded or not both contracted.

As you can see from this movie, every time piston B expands completely, so does piston C. Every time piston B contracts completely, so does piston C. Pistons B and C are synchronized.

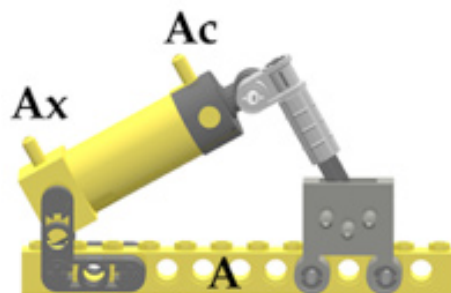


Boolean Algebra

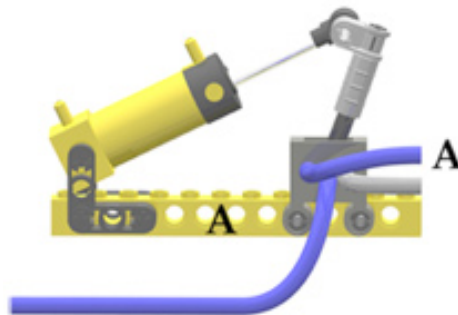
In 1854, a mathematician named George Boole published a paper called "An investigation into the Laws of Thought, on Which are founded the Mathematical Theories of Logic and Probabilities" that described a mathematical way of describing logical statements. Boole's algebra used variables that have value of true and false. He also introduced three new mathematical operators: and, or and not. Over a hundred years later his algebra became the mathematical cornerstone of the digital computer era, using electronic versions of his algebraic functions called gates.

Pneumatic pistons are Boolean devices in that they only have two stable states: expanded or contracted. I equate expanded piston as a Boolean true, and contracted piston a Boolean false. The remainder of this description always has a piston controlling a switch. The piston switch pair is typically given a simple name like A, B or C. Some pistons control two switches, and the switch names are the piston name and a single digit suffix (like switch C1 or switch C2).

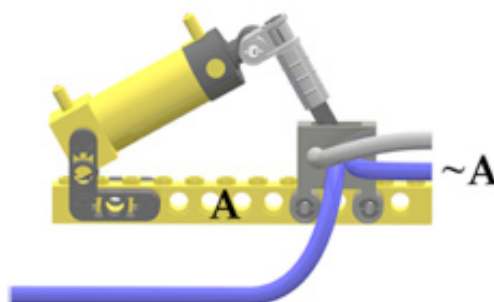
The piston's pressure ports are inputs from some switch. The expand pressure port of a piston is referred to its piston name followed by a lower case x, for expand. For example piston A's expand port is referred to as Ax. The contract pressure port of a piston uses a similar suffix with the value of c, for contract. Piston A's contract port is referred to as Ac.



It is equally important that we have names for the ports of the switch. When the switch handle is flipped to the right, pressure coming in the center port goes out the left port. In all these examples this happens when the controlling piston is expanded. For our examples the port closest to the piston is simply named the piston name. In this example the piston is called A, so the port closest to the piston is also called A.



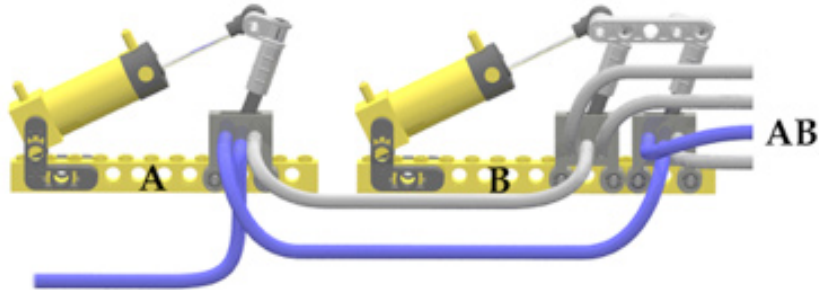
When the switch handle is flipped to the left, pressure going into the center port goes out the right port. In all these examples this happens when the controlling piston is contracted. For our examples the port furthest from the piston is indicated by a tilde (~) followed by the piston name. You can use the word "not" when reading ~. For the example below, the piston is contracted, so pressure is coming out the "not A" port.



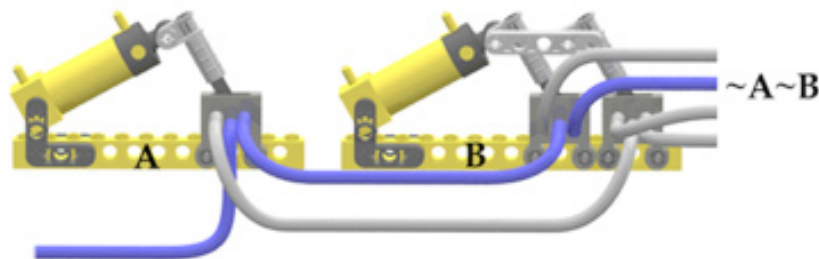
In normal algebra multiplication is very common and variable names are typically single letters. Multiplication is so common that the multiplication operation can be implied by placing two variable names next to each other. So the expression "a x b" can simply be rewritten "ab". In Boolean logic the and function is so common that it can be implied, so "a and b" is often written simply "ab".

In the example below we combine piston/switch A and piston/switch B to create Boolean and gates. Between the two pistons and the three switches, we get four possible and combinations. When both pistons are expanded, pressure comes the blue hose. Tracing the pressurized ports shows that port A and port B are both pressurized resulting in output pressure AB.

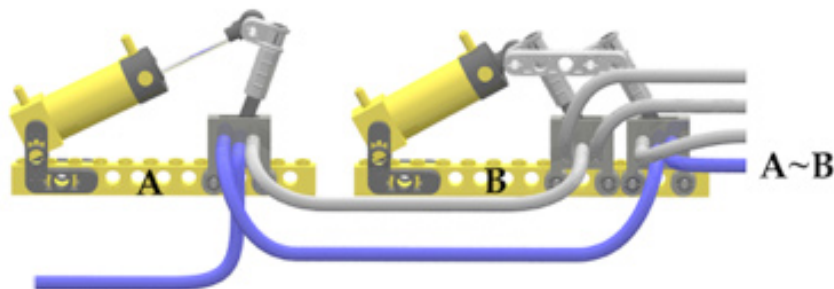
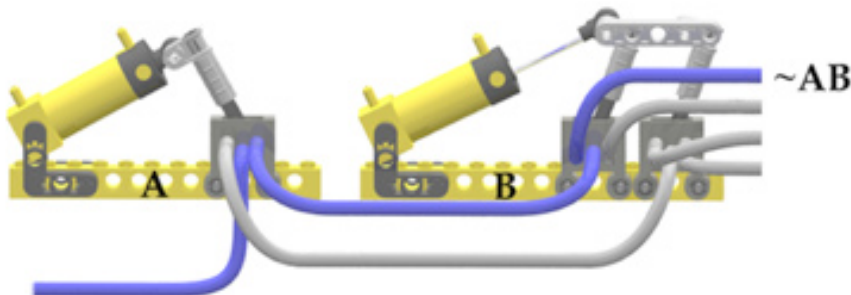
If we contract both pistons, the pressure comes out right hand ports resulting in $\sim A \sim B$ (not A and not B).



This leaves two combinations of one piston expanded and the other contracted.



and



Mathematical Description of Circuits

One of the best things about mathematics is it provides a very concise and succinct way of describing the relationships between things (one of the worst parts of mathematics is that its conciseness and succinctness make it hard to understand :^) We will use

the names we just defined to describe our pneumatic circuits.

Our language needs to describe how switch ports are hooked to pistons. First we'll use an equals sign (=) to mean switch port connected to piston port.

For circuit 1, we can describe the connections from piston/switch A to piston B as:

$Bx = A;$
 $Bc = \sim A;$

The connections between piston/switch B to piston A are backwards so:

$Ax = \sim B;$
 $Ac = B;$

This terse format for circuit description will really help when describing complicated circuits. We can describe circuit 3 like this:

$Ax = \sim B \ \& \ \sim C;$
 $Ac = B \ \& \ C;$
 $Bx = A;$
 $Bc = \sim A;$
 $Cx = A;$
 $Cc = \sim A;$

The description is short and sweet, but easier to write than read for the uninitiated.

Circuit 4

What if we want to have piston C do the opposite as piston B, but at the same time as piston B? Piston B's description remains unchanged:

$Bx = A;$
 $Bc = \sim A;$

Piston C's connections are described:

$Cx = \sim A;$
 $Cc = A;$

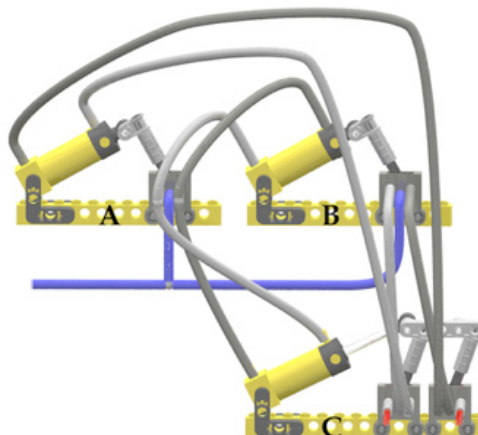
Piston A's connections are different as well. Piston A expands when piston B is contracted and piston C is expanded.

$Ax = \sim BC;$

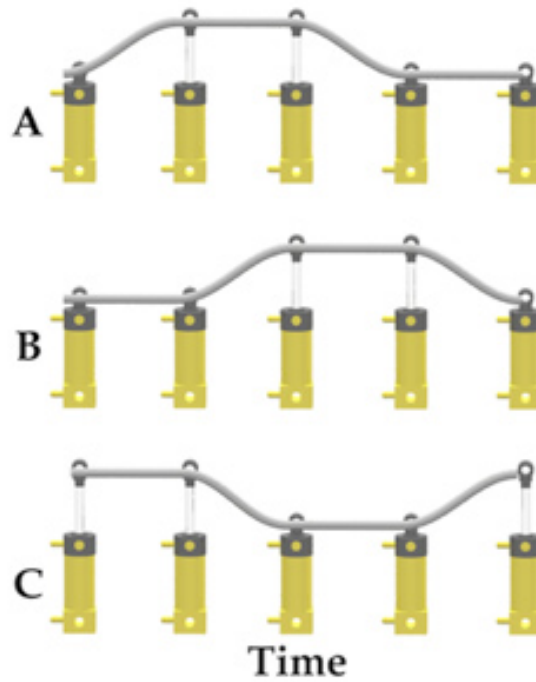
Piston A contracts when B is expanded and C is contracted.

$Ac = B\sim C;$

Here is an image of circuit 4.



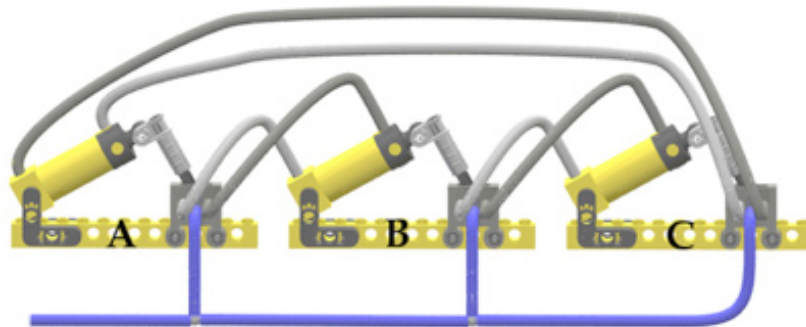
Here is graph of circuit 4's behavior over time.



Circuits 1, 2 3 and 4 all have four steps in their repeating sequence. With three pistons, we can make longer sequences.

Three Pistons Three Switches

With three pistons and three switches, we can make a six step sequencer:

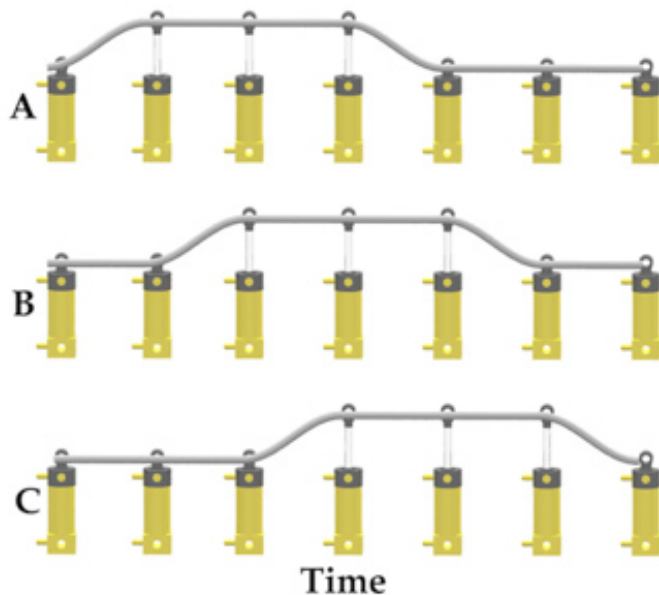


Its mathematical description is:

- $Ax = \sim C$
- $Ac = C$
- $Bx = A$
- $Bc = \sim A$
- $Cx = B$
- $Cc = \sim B$

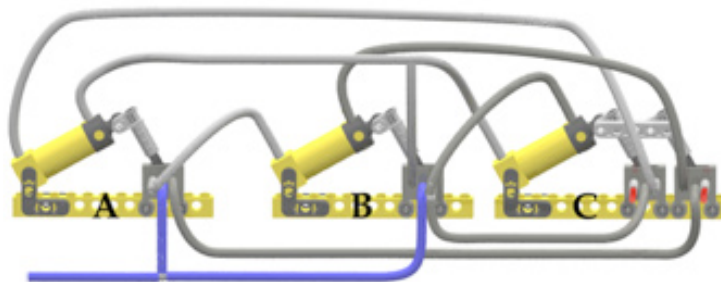
Figure its behavior over time:

This circuit has a total of 6 steps. This circuit would be good for a three piston pneumatic engine.



Three Pistons Four Switches

With three pistons and four switches, we can make a sequencer that has five steps:



The formulas describing circuit 6 are:

$$Ax = \sim B \sim C$$

$$Ac = B$$

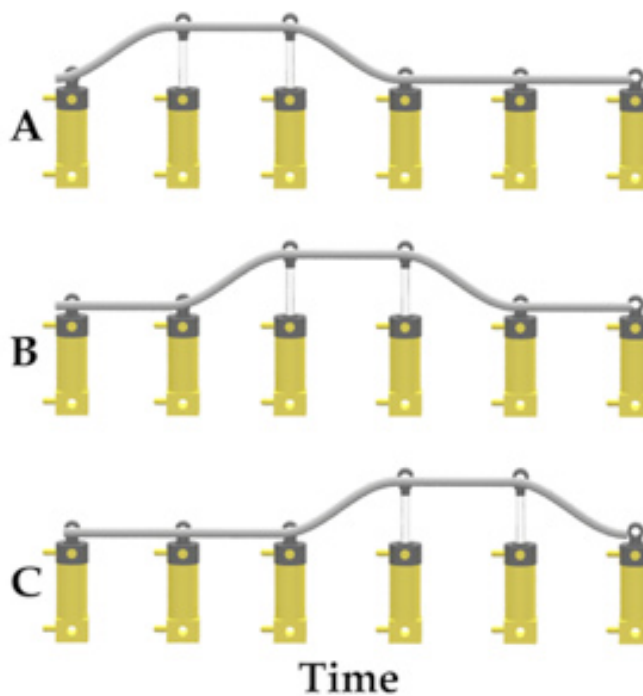
$$Bx = A$$

$$Bc = \sim AC$$

$$Cx = B$$

$$Cc = \sim B$$

The waveform:



This waveform looks a lot like the waveform for circuit 5, but circuit 5 has the pistons expanded half the time. In circuit 6, the pistons are expanded two of the five steps in the cycle.

Practical applications

So far we have seen some theory and maybe you have rebuilt the circuits to see their behavior for yourself. But what is their practical application? I will show you a practical application in the second part of this tutorial, but in the meantime you can have a look at the inchworm (especially 1 and 4) in my Brickshelf gallery which use the principle explained in this part of the tutorial.

Kevin Clague on Brickshelf: <http://www.brickshelf.com/cgi-bin/gallery.cgi?m=kclague>

Inchworm 1: <http://www.brickshelf.com/cgi-bin/gallery.cgi?f=48796>

Inchworm 4: <http://www.brickshelf.com/cgi-bin/gallery.cgi?f=291660>

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