Molecules of Structure

Building Blocks for System Dynamics Models

Version 2.0

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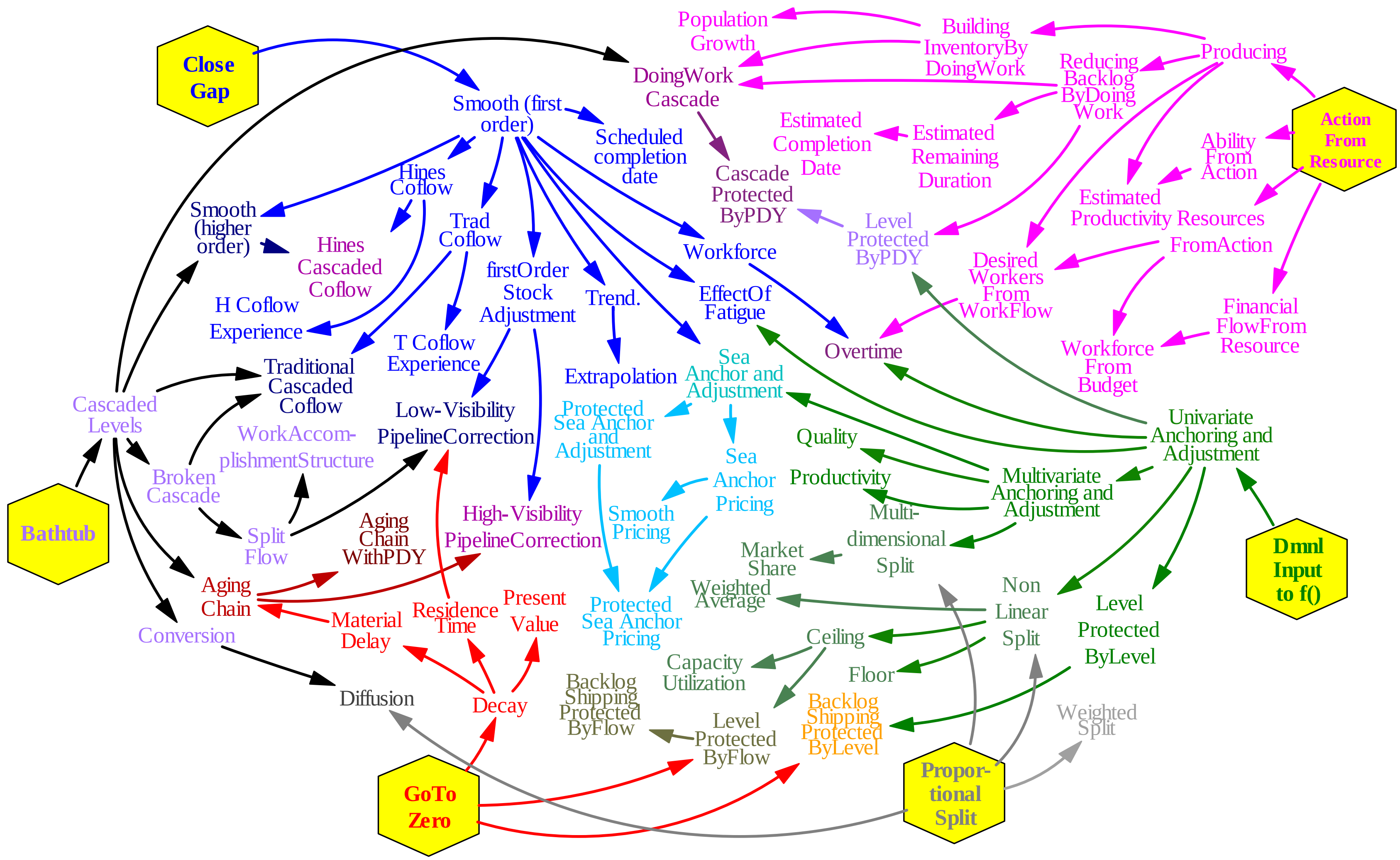
Acknowledgements

Many people have contributed to identifying and collecting the molecules presented here. George Richardson and Jack Pugh described a number of commonly occurring rate equations in their excellent book *Introduction to System Dynamics with Dynamo* (1981, MIT Press). Barry Richmond described a number of common rate structures in his 1985 paper describing STELLA, the first graphical system dynamics modeling environment ("STELLA: Software for Bringing System Dynamics to the Other 98" in *Proceedings of the 1985 International Conference of the System Dynamics Conference*, Keystone Colorado, 1985, pp 706-718). Barry Richmond and Steve Peterson continued to present useful small structures in documentation for STELLA and its sister product ithink. Barry used the term "Atoms of Structure in 1985". Misremembering that paper, I used the term "Molecules" in my own initial attempts to extend and categorize these structures in 1995. Bob Eberlein created a very flexible way of incorporating molecules into Vensim for the 1996 version of the collection. Bob also put the molecules up on the Vensim website which has allowed many, many people to benefit from this common heritage of our field. This current version of the molecules owes a tremendous amount to Jack, George, Barry, Steve, and Bob.

The molecules presented here were invented by many people – and no doubt many of were invented several times independently. Tracing the ancestry of each molecule would be a large task in itself and is one that I haven't undertaken. It would be odd though not to mention at least some of the people who are most responsible for the molecules presented here. To some extent this list is a personal list – molecules tend to get repeated in models without attribution, so some of what I believe to be seminal work no doubt is based on yet earlier work. Still there's no question that many of the molecules first appeared in Jay Forrester's writings beginning with the first published paper and the first published book in system dynamics (Forrester, J. W. (1958). Industrial Dynamics: A Major Breakthrough for Decision Makers. Harvard Business Review, 26(4), 37-66. and Forrester, J.W. (1961). *Industrial Dynamics*. Cambridge, MA: MIT Press). Also important was the market growth model created by Dave Packer working with Jay Forrester (Forrester, J. W. (1968). Market Growth as Influenced by Capital Investment. Industrial Management Rev. (MIT), 9(2), 83-105.). The project model, originally developed by Henry Weil, Ken Cooper, and David Peterson around 1972 contributes a number of important molecules. Jim Lyneis' book contains important structures for corporate models (Lyneis, J. M. (1980). *Corporate Planning and Policy Design*. Cambridge, MA: MIT Press). John Sterman's reworking of the Bass diffusion model into a system dynamics format was important to me personally, though he himself doesn't make much of a to-do about it. Very important for me was the treasure-trove of good structures in the National Model, a model of an industrial economy to which many people contributed including Alan Graham, Peter Senge, John Sterman, Nat Mass, and of course Jay Forrester who was in charge of the project and continues with it today. The publication of that model will be important not only for advancing economic understanding, but also for showing *in situ* countless valuable molecules of system dynamics structure.

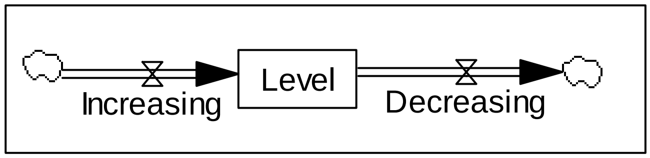

Close Gap
Smooth (first order)
DoingWork Cascade
Population Growth
Building InventoryBy DoingWork
Producing
Reducing Backlog ByDoing Work
Action From Resource
Estimated Completion Date
Estimated Remaining Duration
Scheduled completion date
Cascade Protected ByPDY
Ability From Action
Estimated Productivity Resources
FromAction
Level Protected ByPDY
Desired Workers From WorkFlow
Financial FlowFrom Resource
Workforce From Budget
Workforce
EffectOf Fatigue
Overtime
Hines Coflow
Trad Coflow
Smooth (higher order)
Hines Cascaded Coflow
firstOrder Stock Adjustment
Trend.
H Coflow Experience
T Coflow Experience
Extrapolation
Sea Anchor and Adjustment
Traditional Cascaded Coflow
Low-Visibility PipelineCorrection
Protected Sea Anchor and Adjustment
Sea Anchor Pricing
Quality
Productivity
Univariate Anchoring and Adjustment
Multivariate Anchoring and Adjustment
Cascaded Levels
WorkAccom-plishmentStructure
Broken Cascade
Split Flow
Bathtub
Aging Chain WithPDY
High-Visibility PipelineCorrection
Smooth Pricing
Multi-dimensional Split
Market Share
Dmnl Input to f()
Aging Chain
Residence Time
Present Value
Material Delay
Protected Sea Anchor Pricing
Weighted Average
Non Linear Split
Level Protected ByLevel
Conversion
Ceiling
Capacity Utilization
Floor
Diffusion
Decay
Backlog Shipping Protected ByFlow
Level Protected ByFlow
Backlog Shipping Protected ByLevel
Weighted Split
GoTo Zero
Propor-tional Split

Contents

Bathtub

Immediate Parents: None

Ultimate Parents: None



Used by: Cascaded levels

Problems solved: How to increase and decrease something incrementally.

Equations:

```
Level = INTEG(Increasing-Decreasing,___)
        Units: widgets
Decreasing = ___
        Units: widgets/year
Increasing = ___
        Units: widgets/year
```

Description: A bathtub accumulates the difference between its inflow and its outflow. A physical example is an actual bathtub. The level of water is increased by the inflow from the tap and decreased by the outflow at the drain.

Classic examples: A workforce might be represented as a bathtub whose inflow is hiring and whose outflows is attrition. A final-goods inventory could be a bathtub whose inflow is arrivals of product and whose outflow is unit sales. Factories could be represented as a bathtub whose inflow is construction and whose outflow is physical depreciation. Retained earnings could be represented as a bathtub with revenues as the inflow and outflow of expenses.

Caveats: Often bathtubs represent physical accumulations which should not take on negative values. To prevent negative values, the outflow must be influenced directly by the level. This is termed “first order feedback” (i.e. a feedback loop is created that includes only one level (a feedback loop with two levels would be “second order”). Molecules employing first-order feedback include smooths, decays, and protected levels (e.g. level protected by level and level protected by flow).

Technical notes:

A bathtub is simply an integration of one inflow and one outflow. System dynamics takes an *integral* view of calculus, which is reflected in the form that level equations take in all system dynamics languages (DYNAMO, Vensim, iThink, Powersim, etc.)

$$Level_T = Level_{T_0} + \int_{T_0}^{T} (inflow_t - outflow_t)dt$$

or, in modified DYNAMO notation

$$Level_t = Level_{t-dt} + dt * (inflow_{t-dt} - outflow_{t-dt})$$

The idea is expressed in the *differential* calculus as

$$d\frac{Level_t}{dt} = inflow_t - outflow_t$$

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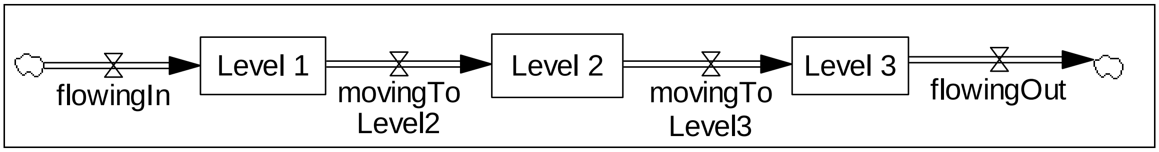
Cascaded levels

(also known as “chain”)



Immediate Parents: Bathtub
Ultimate Patents: Bathtub

Used by: Conversion, Aging chain, Broken cascade, Smooth (higher order), Traditional cascaded coflw, Doing work cascade

Problem solved: How to represent something that accumulates at a number of points instead of just one.

Equations:

```
flowingIn = ____
        Units: material/Month
flowingOut = ____
        Units: material/Month
Level 1 = INTEG(flowingIn-movingToLevel2, ____)
        Units: material
Level 2 = INTEG(movingToLevel2-movingToLevel3, ____)
        Units: material
Level 3 = INTEG(movingToLevel3-flowingOut, ____)
        Units: material
movingToLevel2 = ____
        Units: material/Month
movingToLevel3 = ____
        Units: material/Month
```

Description: A cascade is a set of levels, where one level’s outflow is the inflow to a second level, and the second level’s outflow is the inflow to a third, etc. A cascade can be seen as a structure that divides up an accumulation into “sub-accumulations”. The number of levels in a cascade can be any number greater than two.

Behavior: Because the rates are not defined, behavior is not defined.

Classic examples: Items being manufactured accumulate at many points in the system, perhaps in front of each machine in a production line as well as in finished inventory. Conceptually it is possible to have a chain with a level for each machine. Usually this is too detailed for a system dynamics model; instead we represent material accumulating in a smaller number of levels, perhaps three: manufacturing starts, work in process, and finished inventory.

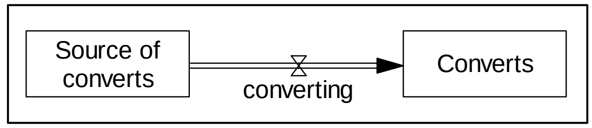
A measles epidemic model might represent people in three stages (levels): susceptible, infected, and recovered. (See Aging Chain molecule)

A workforce might be composed of three stocks: Rookies, Experienced, and Pros. As they are hired, people flow into the rookies level from which they flow in the level of experienced employees. Experienced employees flow into the stock of pros, which is depleted by people retiring. (See Aging Chain molecule).

Caveats: Often the levels represent physical accumulations which should not go negative. See caveats under Level.

Technical notes: In nature, there are phenomena which combine the characteristics of both flows and stocks. A river, for example, is both a rate of flow and has volume. In system dynamics modeling we represent the world as consisting of pure flows having no volume; and pure levels having no flow. We view a river as being composed of a chain of “lakes”, each having a volume, connected by flows each being a pure rate: The water accumulates only in the “lakes” not in the flows. A river might be represented as a cascade of two levels: an upstream stock and a downstream stock. This “lumped parameter” view of the world permits the use of integral equations. To represent flows that have volume would require the more complicated mathematics of partial integral (partial differential) equations. Such a view of the world is more difficult to model and more time consuming to simulate.

Conversion



Immediate parents: Cascaded levels
Ultimate parents: Bathtub

Used by: Diffusion

Problem solved: How to represent people changing their status. E.g. from non-believer to believer, from non-customer to customer, from non-infected to infected

Equations:

```
Source of converts = INTEG(-converting, ___)
        Units: people
converting = ___
        Units: people/Year
Converts = INTEG(cnverting, ___)
        Units: people
```

Description: People flow from one category to the other

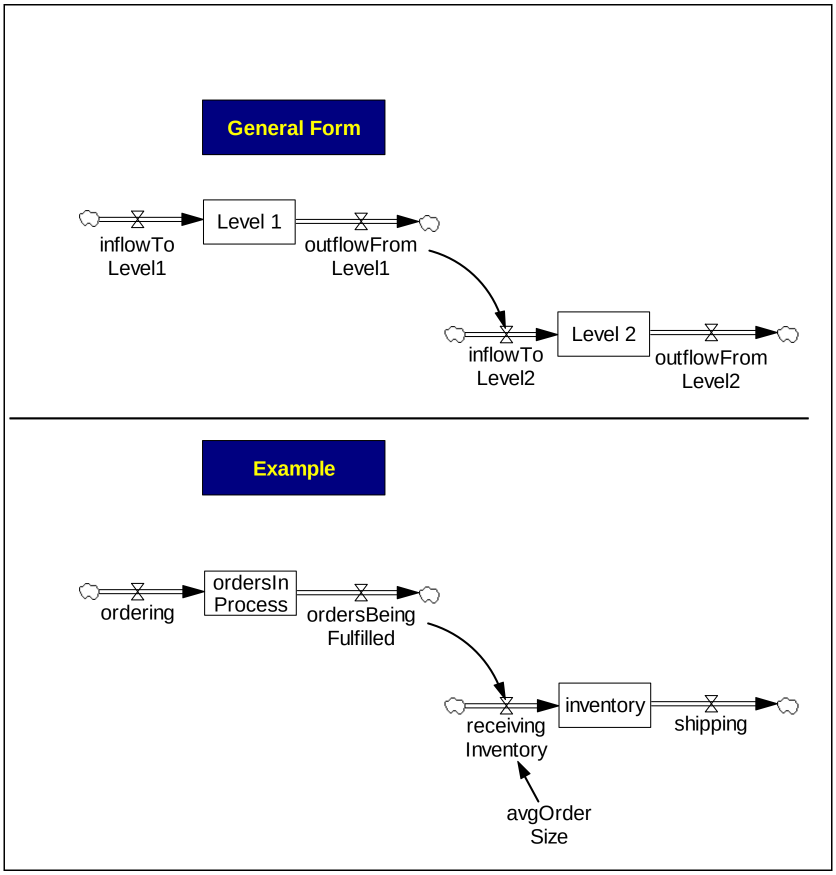
Behavior: Converting is undefined, so behavior is undefined

Classic examples: Used in diffusion models

Caveats: None

Technical notes: None

Broken Cascade



Immediate Parents: Cascaded levels
Ultimate Parents: Bathtub

Used by: Split flow, Traditional cascaded coflow

Problem solved: How to represent a conceptual break in set of cascaded levels. (The conceptual break often, but not always, involves a change of units).

Equations:

General Form	Example
ordersInProcess ordersInProcess = INTEG(orderingrdersBeingFulfilled,__) Units: orders ordering = ___ Units: orders/Month ordersBeingFulfilled = 100 Units: orders/Month inventory= INTEG (receivingInventory-shipping,__) Units: widgets shipping = ___ Units: widgets/Month receivingInventory=ordersBeingFulfilled*avgOrderSize Units: widgets/Month avgOrderSize=_________	Level 1 = INTEG(inflowToLevel1-outflowFromLevel1,___) Units: material inflowToLevel1 = ___ Units: material/Month inflowToLevel2=outflowFromLevel1 Units: material/Month Level 2= INTEG (inflowToLevel2-outflowFromLevel2,___) Units: material outflowFromLevel1 = ___ Units: material/Month outflowFromLevel2 = 100 Units: material/Month

Units: widgets/order	

Description: A broken cascade is a cascade where the outflow of one level, rather than flowing directly into the next level, instead terminates in a cloud. The inflow to the next level is then a function of the prior outflow. If the inflow to the next level is *equal* to the outflow from the prior level (e.g. *receivengInventory = ordersBeingFulfilled*), then the broken cascade is mathematically equivalent to the regular cascade. Often the inflow to the next stock is the outflow from the stock multiplied by a constant that represents a change of units (e.g. *avgOrderSize* in the example above.

Behavior: Behaves like a regular cascade

Classic examples: In modeling a supply chain, there is often a conceptual break from raw materials inventory to work in process. The conceptual break often also involves a change in units.

Caveats: None

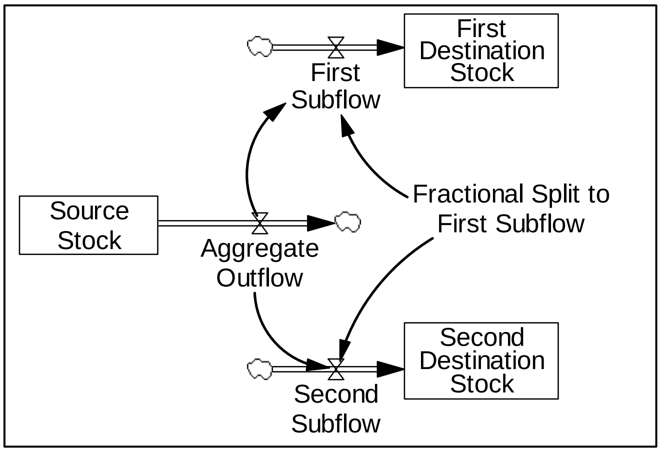
Technical notes: None

Split Flow

Immediate Parents: Broken cascade
Ultimate Parents: Bathtub

Used by: Work accomplishment structure, Low-visibility pipeline correction

Problem solved: How to disaggregate an outflow into sub-flows



Equations:

Source Stock = INTEG(-Aggregate Outflow,____)
Units: Widgets2
Aggregate Outflow = ____
Units: Widgets/Month
First Subflow = Aggregate Outflow*Fractional Split to First Subflow
Units: Widgets/Month
Fractional Split to First Subflow = ____
Units: fraction
First Destination Stock = INTEG(First Subflow,0)
Units: Widgets
Second Subflow = Aggregate Outflow*(1-Fractional Split to First Subflow)
Units: Widgets/Month
Second Destination Stock = INTEG(Second Subflow, ____)
Units: Widgets

Description: This structure splits an outflow into two (or more) subflows into other levels (or into sinks)..

Behavior: Aggregate outflow is undefined, so behavior is undefined.

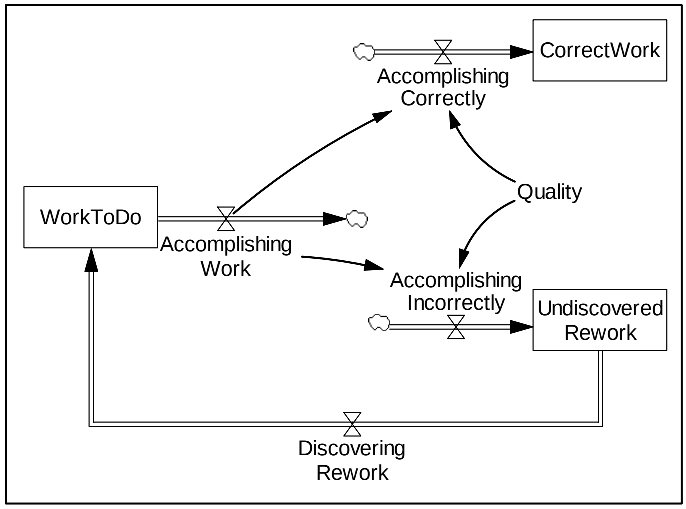
Classic examples: Work Accomplishment Structure

Caveats: None

Technical notes: Traditionally the split outflow is represented with the aggregate flow going into a sink (cloud) and the two sub-flows coming out of sources (clouds). Although not standard, it is possible to draw the pipe splitting in two. The equations remain the same.

Work Accomplishment Structure

Also known as Rework Cycle



Immediate Parents: Split Flow
Ultimate Parents: Bathtub

Used by: None

Problem solved: How to represent rework

Equations:

WorkToDo = INTEG(DiscoveringRework – AccomplishingWork,___)
Units: SquareFeet
DiscoveringRework = ___
Units: SquareFeet/Week
AccomplishingWork = ___
Units: SquareFeet/Week
CorrectWork = INTEG(AccomplishingCorrectly , 0)
Units: SquareFeet
AccomplishingCorrectly = AccomplishingWork * Quality
Units: SquareFeet/Week
Quality = ___
Units: fraction
UndiscoveredRework = INTEG(
AccomplishingIncorrectly - DiscoveringRework ,___)
Units: SquareFeet
AccomplishingIncorrectly = AccomplishingWork * (1 - Quality)
Units: SquareFeet/Week

Description: We begin with some work to do and begin to accomplish it by some process (perhaps by the producing molecule). Some of the work is done correctly, but some is not. Quality is the fractional split. Quality here has a very narrow definition: the fraction of work that is being done correctly. The work that is not done correctly flows into undiscovered rework, where it sits until it is discovered (again by a process not shown). When it is discovered it flows into work to be (re) done.
Note that the stock of undiscovered rework is not knowable by decision makers “inside” the model. The stock is really there, but no-one, except the modeler and god, know how much it holds.
Behavior: Work can make many cycles.

Classic examples: This is the classic project structure. It was originally developed by Pugh-Roberts, which continues to use and develop the structure. The structure is at the heart of Terek Abdel-Hamid's work on software project management. Today it is used by a number of consultants and consulting firms.
Caveats: none
Technical notes: The structure, as shown does not contain the definition of accomplishing work or discovering rework. Typically these flows are formulated using the producing molecule, although discovering rework is sometimes represented as a Go to Zero (i.e. undiscovered rework is represented as a material delay). Quality is usually formulated as an anchoring and adjustment molecule. Often the discovered rework flows into a level that keeps it separate from the original work to do -- this permits one to model a productivity and a quality on rework that are potentially different from productivity and quality on original work.

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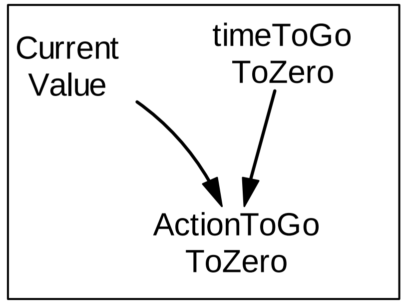
Go To Zero



Immediate Parents: **None**
Ultimate Parents: None

Used by: Decay, Backlog shipping protected by flow, Level protected by flow

Problem solved: How to generate an action (i.e. a flow) that will move a current value (of a stock) to zero over time.

Equations:

```
ActionToGo to zero = CurrentValue/timeToGo to zero
        Units: widgets/Month
CurrentValue = ___
        Units: widgets
timeToGo to zero = ___
        Units: months
```

Description: The action (or rate of flow) that will take a quantity (a stock) to zero over a given time is simply the quantity divided by the given time.

Behavior: No stocks, so no behavior

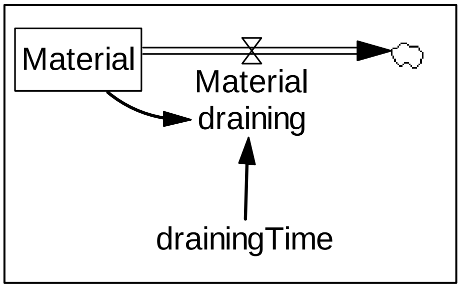
Classic examples: The outflow of a decay or material delay. The *desired shipping* in a Backlog shipping protected by flow molecule.

Caveats: When time "constant" (*timeToGo to zero*) is formulated as a variable, care should be taken to ensure its value can not become zero to avoid a divide-by-zero error.

Technical notes: The intuition behind this formulation is the following: Consider a variable whose current value is *CurrentValue*. The variable will become zero in exactly *timeToGo to zero* months if the variable declines at a constant rate equal to *actionToGo to zero*. Usually, however, the *actionToGo to zero* will not remain constant, because the action itself will change the *currentValue* and/or value of *timeToGo to zero.* Consequently, the variable in question will typically not be zero after *timeToGo to zero* months. Depending on the actual formulation, the *timeToGo to zero* often will have a real world meaning. In the case of a decay, for example, the average time for an aggregate of things (e.g. a group of depreciating machines) to decline to zero is equal to *timeToGo to zero.*

Other molecules that can generate an action (or a flow) include close gap (and its children) and flow from resource (and its children)

Decay



Immediate parents: Go to zero
Ultimate parents: Go to zero

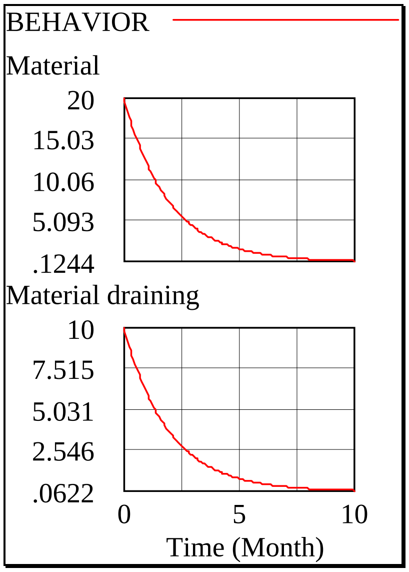
Used by: Present value, Material delay, Residence time

Problem solved: How to empty or drain a stock.

Equations:

```
Material = INTEG(-Material draining, ___ )
        Units: stuff
Material draining = Material / time to drain
        Units: stuff/Year
time to drain = ___
        Units: Year
```

Description: The stock in the decay structure, drains gradually over a period of time determined by the time to drain. The decay can be viewed as a smooth with a goal of zero. As a rule of thumb the stock is emptied in three time constants. The time for the stock to decline by half is termed the half life and is approximately equal to 70% of the time to drain.



Behavior: The decay declines exponentially toward zero. Because the outflow is simply a fraction of the stock, the outflow also declines exponentially toward zero.

Classic examples: Radioactive decay.

Caveats: Sometimes a decay process is better represented more explicitly. For example, one could represent the draining of a finished-goods inventory as a decay. But, the real process involves people purchasing the merchandise. The purpose of the model will determine whether the decay representation is "good enough" or whether a more accurate representation is called for.

Technical notes: The equation for a decay is

$$\text{Material}_t = \text{Material}_0 * e^{-t/\text{smoothingTime}}$$

The half life can be determined from this equation to be: ln(0.5)*timeToDrain. ln(0.5) is approximately 0.7. The outflow from the decay is distributed exponentially. The average residence time of material in the level is equal to the timeToDrain.

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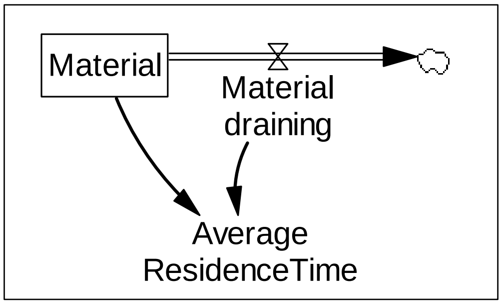
Residence Time

Immediate Parents: Decay
Ultimate parents: Go to zero



Used by: None

Problem solved: How to determine the average residence time of items flowing through a stock.

Equations:

```
AverageResidenceTime = Material/Material draining
        Units: Year
Material = INTEG(-Material draining, ___)
        Units: items
Material draining = ___
        Units: items/Year
```

Description: This is based on the same understanding as that behind the decay; however the inputs and outputs are switched. Here, we know the rate at which material is draining (as well as the stock) and we calculate the average time to drain (i.e. the average residence time).

Behavior: No feedback, so no endogenous dynamic behavior

Classic examples: None

Caveats: None

Technical notes: This is based on Little's Law. In equilibrium the calculation for the average residence time is correct, no matter what process is actually draining the level. To derive the formula for the specific process of a decay provides the intuition. The equation for a decay's outflow is.

$$decayOutflow_t = \frac{Stock_t}{decayTime_t}$$

The above equation says that if we know the values of the *Stock* and the value of the *decayTime*, we can figure out the value of the *decayOutflow*. Now if we already know the value of the *decayOutflow* (as well as the *Stock*'s value) but we don't know the *decayTime*'s value, we can re-arrange the above equation to yield

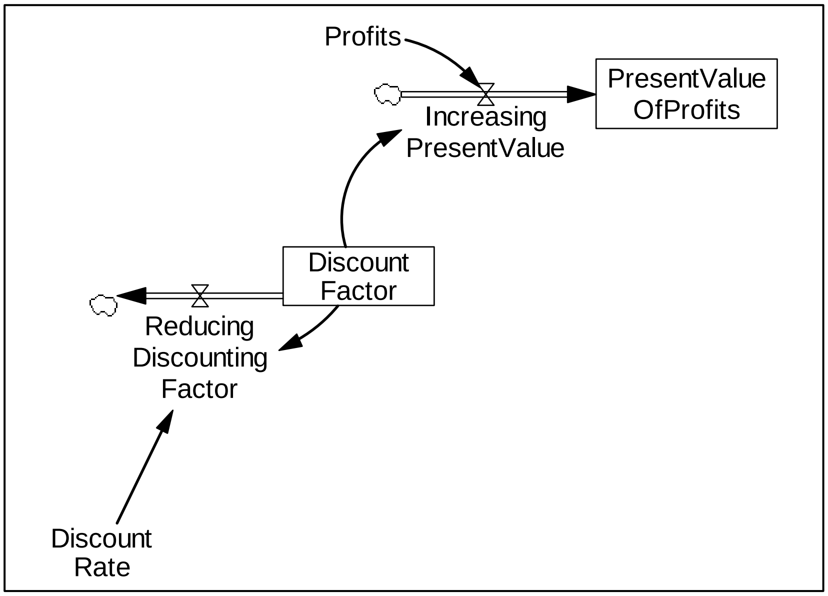
$$decayTime_t = \frac{Stock_t}{decayOutflow_t}.$$

Which is an equation that allows us to figure out the *decayTime* if we know the other two quantities. The equation above is the Residence Time molecule.

Present value

Immediate **parents:** Decay
Ultimate parents: Go to zero
Used by: None

Problem solved: How to calculated the present value of a cash stream.



Equations:

PresentValueOfProfits = INTEG(IncreasingPresentValue, ___)
  Units: $
IncreasingPresentValue = Profits * DiscountingFactor
  Units: $/Year
Profits =
  Units: $/Year
DiscountingFactor = INTEG(- ReducingDiscountingFactor, 1)
  Units: fraction
DiscountRate = ___
  Units: fraction / Year
ReducingDiscountingFactor = DiscountRate * DiscountingFactor
  Units: fraction / Year

Description: The present value of a cash stream (e.g. profits) is simply the accumulation of profits, weighted at each instant by a discounting factor. The discounting factor decays at a rate determined by the discounting factor.

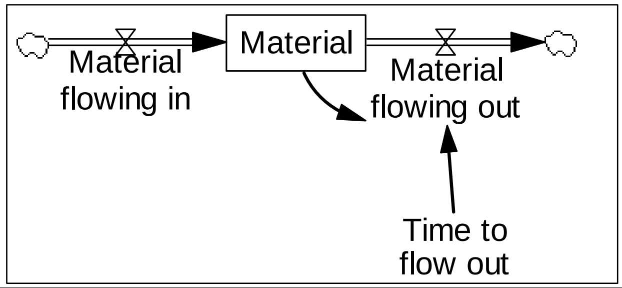
Classic examples: Discounted profits.

Caveats: None.

Technical notes: A discount rate of 0.10 (10%) is equivalent to a time constant of 10 years on the decay structure that represents the discounting factor. (See note on decay molecule).

Material Delay

Immediate parents: Decay
Ultimate parents: Go to zero



Used by: Aging chain

Problem solved: How to delay a flow of material.

Equations:

Material flowing out = Material / Time to flow out
Units: stuff/Year
Time to flow out = ___
Units: Year
Material = INTEG(Material flowing in-Material flowing out, Material flowing in*Time to flow out)
Units: stuff
Material flowing in = ___
Units: stuff/Year

Description: The material delay creates a delayed version of a flow by accumulating the flow into a level and then draining the level over some time constant (timeToFlowOut). The outflow from the level is a delayed version of the inflow. The average time by which material is delayed is equal to the time constant.

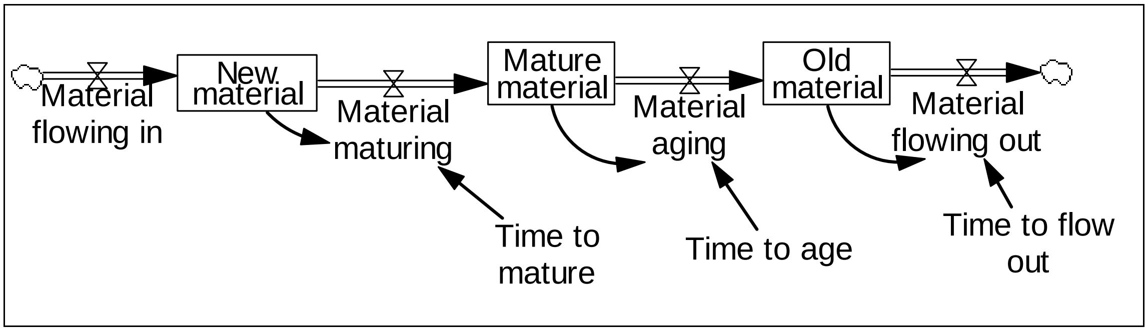
Classic examples: A flow of material is shipped and received after a delay. The stock in this case is the material in transit.

Caveats: None.

Technical notes: The actual delay times for the items that comprise the flow are distributed exponentially with a mean of the time constant. Instead of dividing by a time constant, one can multiply by a fractional decay rate. For example, a 10 year time constant would correspond to a decay rate of 0.10 (10%) per year.

Aging Chain

Also known as *Cascaded Delay*



Immediate parents: Material delay, Cascaded levels
Ultimate parents: Bathtub, Go to zero

Used by: Capacity Ordering, Aging Chain with PDY, Hines Cascaded Coflow, Traditional Cascaded Coflow

Problem solved: How to drain a stock so that the outflow is hump shaped, that is more "normally" distributed. How to create a chain of stocks.

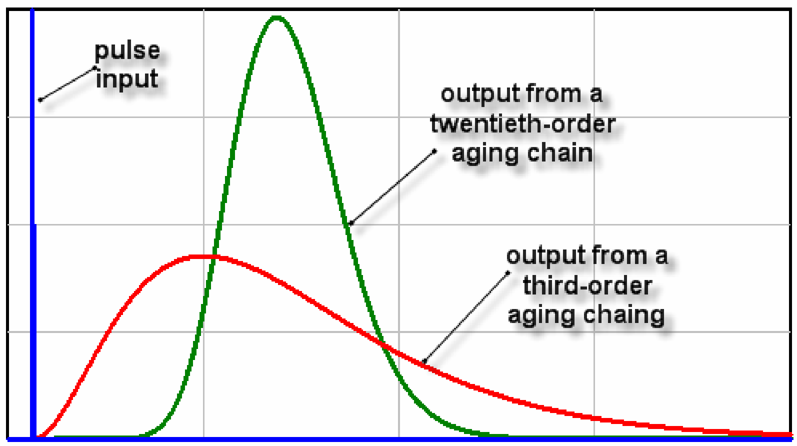
Equations:

```
New material = INTEG(Material flowing in-Material maturing,Material flowing in*Time to mature)
        Units: stuff
Material flowing in = ___
        Units: stuff/Year
Material maturing = New material / Time to mature
        Units: stuff/Year
Time to mature =
        Units: Year
Mature material = INTEG(Material maturing-Material aging, Material maturing*Time to age)
        Units: stuff
Material aging = Mature material/Time to age
        Units: stuff/Year
Time to age = ___
        Units: Year
Old material = INTEG(Material aging-Material flowing out, Material aging*Time to flow out)
        Units: stuff
Material flowing out = Old material/Time to flow out
        Units: stuff/Year
Time to flow out = ___
        Units: years
```

Description: An aging chain is a cascade of material delays. Although, the example above has three stocks (a third-order aging chain), an aging chain can have any number of stocks greater than two. Sometimes only the average time it takes an item to transit the entire chain is known and the time constants associated with each individual flow are not known. In this case, simply set each time constant equal to the overall transit time divided by the number of stocks in the chain. That is the delay for stock i is defined as

$$delay_i = \frac{totalDelay}{numberOfStocksInChain}$$

Behavior: A pulse input into an aging chain will come out with a hump distribution. For an aging chain whose individual-stage time constants are all equal, the more levels in the chain, the more the outflow will be concentrated around the chain's total delay, and the more central the peak will become come. The output of an infinite-order delay will be identical to the input, but offset by the total delay time.



As a rule of thumb, a third-order aging chain is usually sufficient from a dynamic perspective (i.e. more levels in an aging chain will not materially affect the behavior of the system of which the aging chain is a component). An exception to this rule is the case of an "echo", which requires at least a sixth-order aging chain. For example if people buy a large quantity of a hot new product with a five-year product-life, there may be a surge of replacement purchases five years later – that is, there may be a purchasing "echo" with a five-year period.

Classic examples: A production process from production starts to production finishes is often represented as an aging chain. A workforce gaining experience is often represented as an aging chain.

Caveats: None

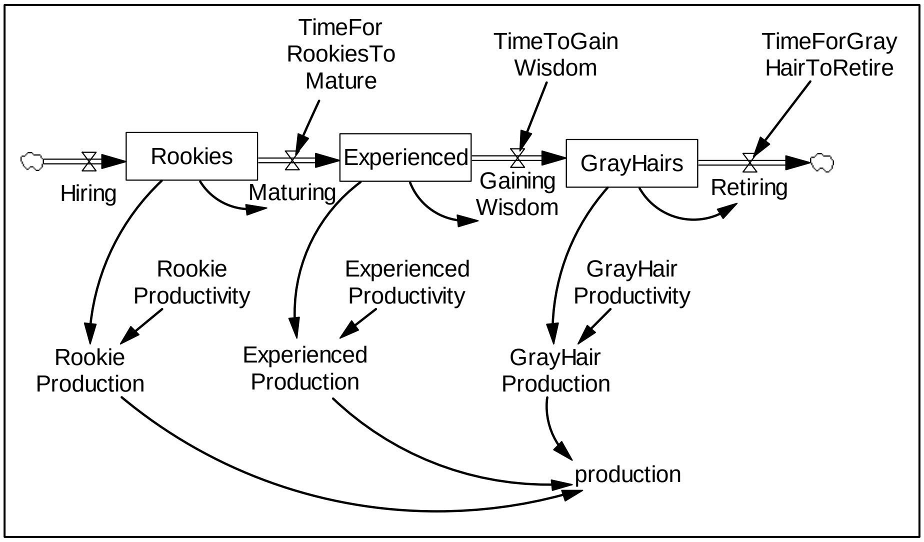
Technical notes: The average residence time in an aging chain is equal to the total delay.

Aging Chain with PDY

Parents: [Aging chain]

Used by: None

Problem solved: How to represent a workforce where people gain experience they become more productive.



Equations:

Production = ExperiencedProduction+GrayHairProduction+RookieProduction
Units: widgets/Year
RookieProduction = Rookies*RookieProductivity
Units: widgets/Year
RookieProductivity = ___
Units: widgets/person/Year
Rookies = INTEG(Hiring - Maturing, Hiring*TimeForRookiesToMature)
Units: people
Hiring = ___
Units: people/Year
Maturing = Rookies / TimeForRookiesToMature
Units: people/Year
TimeForRookiesToMature = ___
Units: years
ExperiencedProduction = Experienced*ExperiencedProductivity
Units: widgets/Year
ExperiencedProductivity= ___
Units: widgets/person/Year
Experienced = INTEG(Maturing - GainingWisdom, Maturing *TimeToGainWisdom)
Units: people
GainingWisdom = Experienced / TimeToGainWisdom
Units: people/Year
TimeToGainWisdom = ___
Units: years
GrayHairProduction = GrayHairs*GrayHairProductivity
Units: widgets/Year
GrayHairProductivity = ___
Units: widgets/person/Year
GrayHairs = INTEG(GainingWisdom - Retiring, GainingWisdom*TimeForGrayHairToRetire)

```
          Units: people
Retiring = GrayHairs / TimeForGrayHairToRetire
          Units: people/Year
TimeForGrayHairToRetire = ___
          Units: Year
```

Description: This is an aging chain of people, where each level also has an (optional) added decay structure to represent attrition. Each category of people has a different productivity. Total production is simply the sum of each category working at its own productivity.

Behavior: See notes for decay and for Cascaded delay or aging chain

Classic examples: A common structure for representing difficulties encountered when a company must grow -- and, hence, expand employment - quickly.

Caveats: Gaining of experience is purely a function of time, rather than a function of doing the work. The latter would be more accurate in most situations, but the structure as formulated is simpler and often good enough. The rule of thumb for DT (see Caveats under Smooth) must be amended because each level has two outflows -- DT should be one fourth to one half of the effective time constant which may be quite short (see technical note).

Technical notes: The outflow from any one level is

Outflow = Level/τ + Level * η

where τ is the time it takes on average to move to the next category and

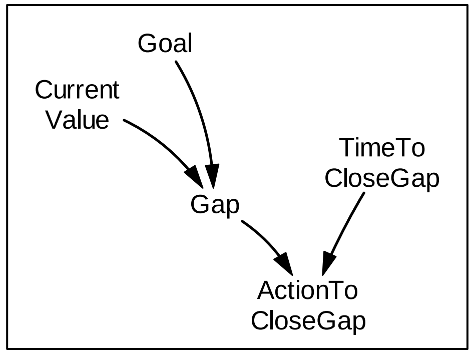
η is the fractional attrition rate for people in the category

Or,

Outflow = Level / (τ/(1 + $\eta\tau$))

So DT needs to be shorter than 1/4 to 1/10 of the effective time constant: (τ/(1 + $\eta\tau$)

Close gap



Immediate parents: None
Ultimate parents: None

Used by: Smooth

Problem solved: How to generate a flow or action to close a gap between a quantity and its desired value

Equations:

```
ActionToCloseGap = Gap/TimeToCloseGap
          Units: widgets/Month
Gap = Goal - Current Value
          Units: widgets
Goal = ___
          Units: widgets
Current Value = ___
          Units: widgets
TimeToCloseGap = ___
          Units: months
```

Description: The action, if it stayed constant, would close the gap in the TimeToCloseGap. Because, the gap will usually be closing via the action (this feedback is not contained in the structure), the gap will not stay constant. If the goal is zero; this structure becomes the action to *eliminate* the current value (see the Decay).

Behavior: No levels, so no endogenous dynamics

Classic examples: Backlog Inventory and Ordering molecule

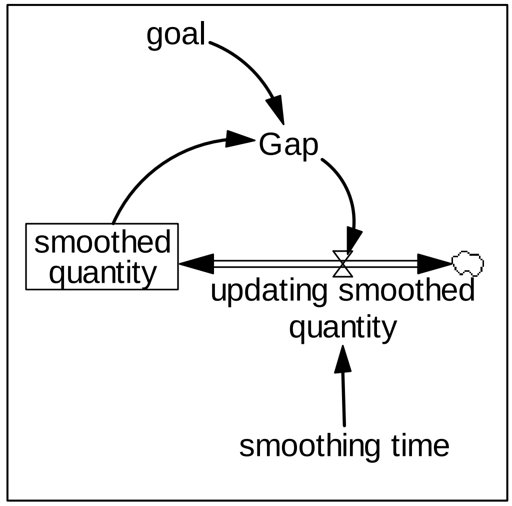
Caveats: None

Technical notes: Other molecules that can generate an action (or a flow) include go to zero (and its children) and flow from resource (and its children).

Smooth (first order)

Immediate parents: Close gap
Ultimate parents: Close gap

Used by: First-order stock adjustment, Hines coflow, Traditional coflow, Trend, Effect of fatigue, Workforce, Scheduled completion date, Sea Anchor and Adjustment



Problem solved: How to have a quantity gradually and smoothly move toward a goal. How to delay information. How to represent a perceived quantity. How to smooth information. How to represent an expectation.

Equations:

smoothed quantity = INTEG(updating smoothed quantity, quantity)
Units: stuff
updating smoothed quantity = Gap / smoothing time
Units: stuff/Year
smoothing time = ___
Units: Year
Gap = quantity - smoothed quantity
Units: stuff
quantity = ___
Units: stuff

Description: A smooth is a level with a specific inflow/outflow formulation. The inflow is formulated as a net rate (i.e. negative values of the "inflow" decrease the level). The rate of change is intended to "close the gap". The gap is the difference between some goal and the smooth itself.

Behavior: The stock adjusts toward the goal exponentially. As illustrated at the right for a step increase in the goal.

The gap between the stock and the goal is closed according to the constant (the smoothing time). Intuitively, the magnitude of the gap would decline to zero over the smoothing time if the net inflow were held constant. In fact, the net inflow changes continuously as the level changes. The rule of thumb is that the gap is almost completely eliminated within three time constants.

If the goal is oscillating the smooth will also oscillate with a lag and with a reduced amplitude. The lag gives rise to the use of a smooth a delay. The reduced amplitude gives rise to using the smooth as means of “smoothing out” random ups and downs in the goal.

Classic examples: The smooth is used in virtually every system dynamics model. A classic example is a cooling cup of coffee. The temperature of the coffee can be represented as the stock; the goal is the temperature of the air surrounding around the cup. The temperature of the coffee gradually adjusts to equal the air temperature. The time constant is determined by the volume of coffee and the insulating properties of the cup. Adaptive expectations are modeled with a smooth. Say one is forming a judgment of how many projects a consultant can sell in a month. If sales have been roughly half a project per month, but in September sales jump to two; we perhaps adjust our expectations upward a bit, but not to two sales per month. If sales stay at around two per month, though we gradually will come to expect that number of sales. A smooth is the structure to capture this.

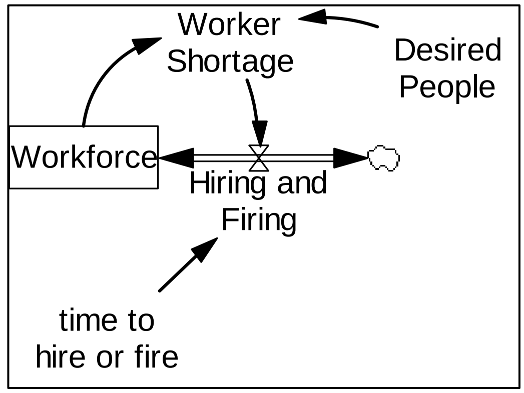
Caveats: When using Euler integration, a large DT (Time Step) can give rise to integration error which will show up as very rapid oscillations of the stock. As a rule of thumb DT should be no larger than 1/4 to 1/10 of the time constant.

Technical notes: If the goal is held constant, the smooth can be expressed mathematically as

$$\text{SmoothedQuantity}_t = \text{Goal} - (\text{Goal} - \text{SmoothedQuantity}_0)e^{-t/\text{smoothingTime}}$$

The “three time constants to close the gap” comes from the above equation. For any number n of time constants the original gap is multiplied by a e^{-n}. In particular in three time constants, the gap is reduced to $e^{-3} \approx 5\%$ of its original size.

Workforce



Immediate parents: Smooth (first order)
Ultimate parents: Close gap

Used by: Overtime

Problem solved: How to represent the number of people working on a project

Equations:

Workforce = INTEG(Hiring and Firing , DesiredPeople)
Units: people
Hiring and Firing = Worker Shortage / time to hire or fire
Units: people/Year
time to hire or fire =
Units: Year
Worker Shortage = DesiredPeople - Workforce
Units: people
DesiredPeople =
Units: people

Description: The workforce is just a smooth of the desired workforce. This means that people will be hired or fired to (gradually) move the actual workforce to the desired level.

Behavior: Obvious

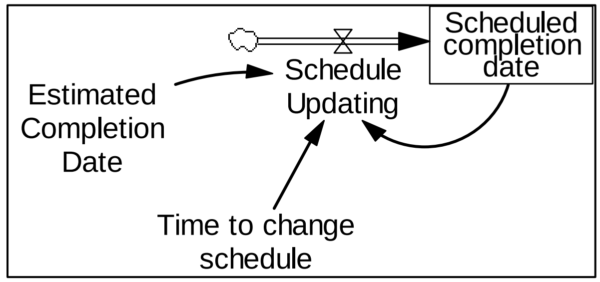
Classic examples: This is often used in models of projects

Caveats: None

Technical notes: Time to hire or fire aggregates a number of lags including: the time for someone to realize that the workforce is not at the correct level, the time to communicate this realization, the time to get authorization for a new workforce level, the time to advertise for workers, the time to interview them, the time to actually bring them on board, and the time to bring them up to speed as fully productive workers.

Note: The essence of this molecule is that the workforce is a smooth of *DesiredPeople.* Although *DesiredPeople* is often formulated as a Desired workforce molecule; there is no requirement that this be the case.. Consequently, this molecule is *not* a child of Desired workforce.

Scheduled Completion Date



Immediate parents: Smooth (first order),
Ultimate parents: Close gap

Used by: None

Problem solved: How to represent the process by which the scheduled completion date is set.

Equations:

```
Scheduled completion date = INTEG( ScheduleUpdating , EstimatedCompletionDate )
        Units: week
ScheduleUpdating =
          ( EstimatedCompletionDate - Scheduled completion date ) / Time to change schedule
        Units: weeks/week
Time to change schedule = ___
        Units: week
EstimatedCompletionDate = ___
        Units: week
```

Description: The scheduled completion date adjusts toward the estimated completion date. The scheduled completion date is simply a smooth of the estimated.

Behavior: Obvious

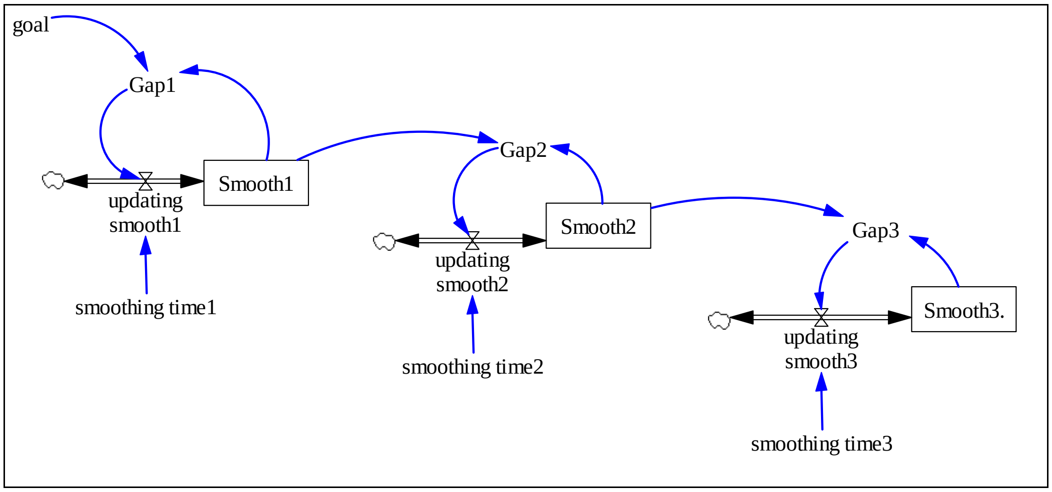
Classic examples: Used in project models

Caveats: None

Technical notes: None

Smooth (higher-order)

Also known as cascaded smooth.



Immediate Parents: Smooth (first order), Cascaded levels
Ultimate Parents: Close gap, Bathtub

Used by: Hines cascaded coflow

Problem solved: How to create a "smooth" where the adjustment toward the goal starts out slowly, gains speed, and then slows for the final approach. How to model a situation where people are slow to initially perceive a change, but ultimate do catch on completely.

Equations:

```
Smooth1 = INTEG( updating smooth1 , goal )
          Units: stuff
updating smooth1 = Gap1 / smoothing time1
          Units: stuff/Year
smoothing time1 = ___
          Units: Year
Gap1 = goal - Smooth1
          Units: stuff
goal = ___
          Units: stuff
Smooth2 = INTEG( updating smooth2 , Smooth1 )
          Units: stuff
updating smooth2 = Gap2 / smoothing time2
          Units: stuff/Year
smoothing time2 = ___
          Units: Year
Gap2 = Smooth1 - Smooth2
          Units: stuff
"Smooth3." = INTEG( updating smooth3 , Smooth2 )
          Units: stuff
```

```
updating smooth3 = Gap3 / smoothing time3
        Units: stuff/Year
smoothing time3 = 2
        Units: Year
Gap3 = Smooth2 - "Smooth3."
        Units: stuff
```

Description: A higher order smooth is a cascade of two or more smooths where each smooth becomes the goal of the immediately following smooth. The stock of final smooth is often considered the “output” variable -- that is the variable that’s ultimately adjusting toward the goal. The usual case is to have the same delay at each stage of the smooth. That is if k is a constant

$$lag_i = k \;\; \forall\, i = 1...Order$$

where

Order is the order of the delay

i is any particular stage in the cascade

k is the lag for each individual stage

and where

either the aggregateLag (or the average lag) is defined as

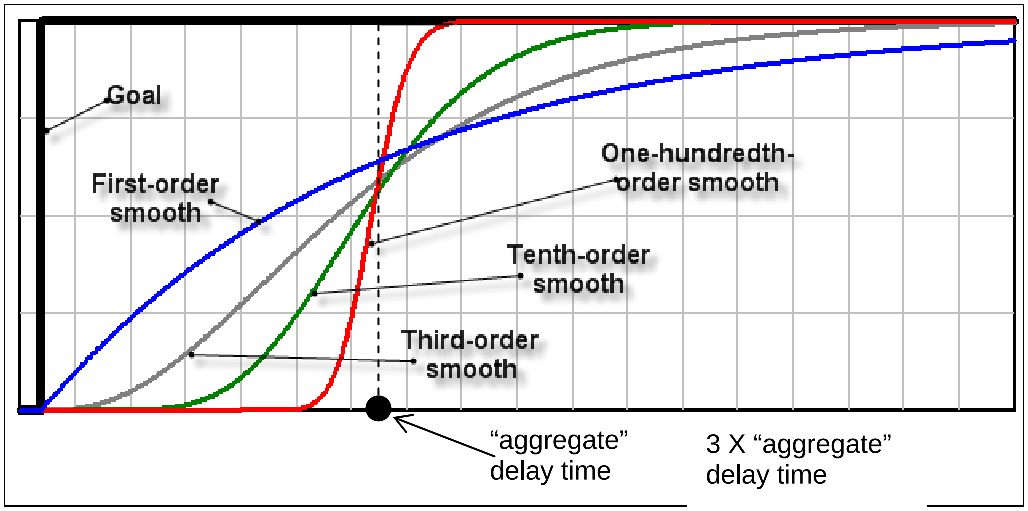
$$aggregateLag = \sum_{i=1}^{i=Order} k = Order * k$$

or else k is defined as

$$k = \frac{aggregateLag}{O}$$

For example in the usual case where the individual lags are all the same, if the aggregate lag is, say, thirty weeks, then the lag for each stage will be $\frac{30\text{ weeks}}{3} = 10\text{ weeks}$.

Behavior: In the case were the individual-stage lags are all the same, the adjustment will become more sudden and more concentrated at the point of the aggregate lag. *All* of the adjustment would happen at the aggregate lag in the case of an *infinite*-order smooth. (Note in such a case the aggregate lag is a finite real number and each individual-stage lag is an infinitesimal, intuitively $k = \frac{Order}{\infty}$ which is an infinitesimal. The infinite-order smooth’s response to a step is another step offset from the original by the overall (or aggregate) lag.



Classic examples: Third order smooths are fairly common. Second-order smooths very rare, as are smooths with order higher than 3.

Caveats: If you create the delays by dividing an overall delay by the number of smooths in the cascade, be watchful of integration error. Remember, the solution interval ("dt" or "time step") should be one-quarter to one-tenth as large as the smallest time constant. The time constant on a higher-order smooth is not the overall delay, but rather the delays on the individual smooths making up the cascade. This consideration holds even when using the built in 3rd order smooth functions provided by most SD simulation modeling environments. These built in functions typically take a parameter for the overall delay. Keep in mind that internally the software converts this overall delay into three individual delays, each one third the size of the time "constant" parameter.

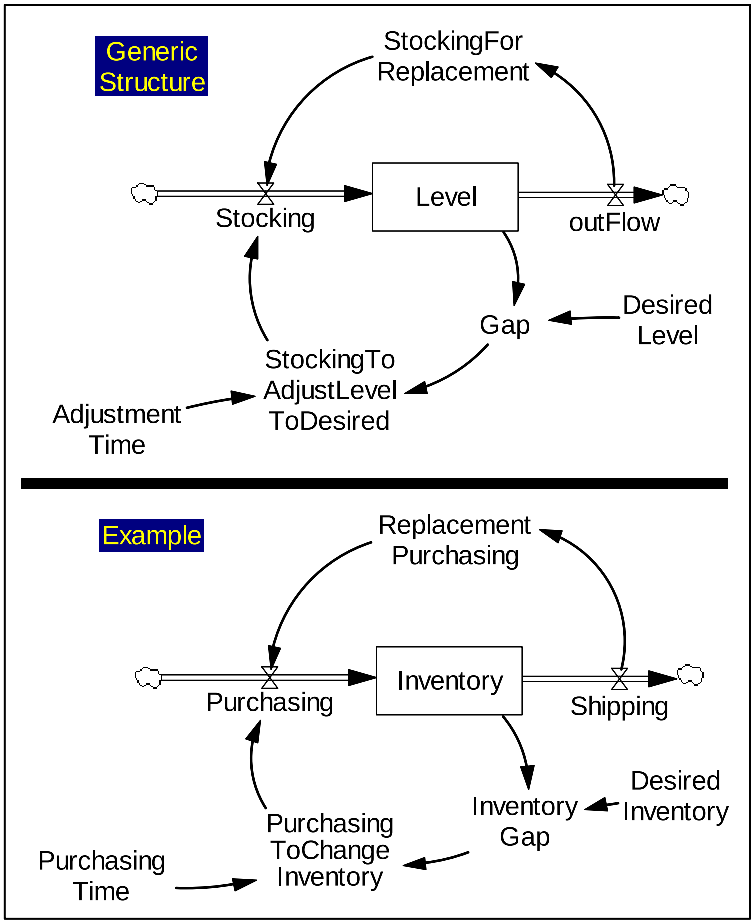
Technical notes: If you take an aggregate view of the a higher-order smooth, the "aggregate delay" is equal to the average delay. For example, if you use a third order smooth with overall delay of 3 month (implying individual stage delays are each each equal to one month) to represent how buyers gradually adjust their perception of a price, the *average* buyer will adjust his perceptions completely in 3 months – of course some buyers will adjust more quickly and others less quickly than the average.

First-order stock adjustment

Immediate parents:
Smooth (first order)
Ultimate parents:
Close gap

Used by: Low-visibility pipeline correction, High-visibility pipeline correction

Problem solved: How to purchase in order to maintain a stock at a desired level



Equations:

Level = INTEG(Stocking - outFlow , DesiredLevel)
Units: widgets
outFlow = ___
Units: widgets/Year
DesiredLevel = ___
Units: widgets
Stocking = StockingToAdjustLevelToDesired + StockingForReplacement
Units: widgets/Year
StockingForReplacement = outFlow
Units: widgets/Year
StockingToAdjustLevelToDesired = Gap / AdjustmentTime
Units: widgets/Year
Gap = DesiredLevel - Level
Units: widgets
AdjustmentTime = ___
Units: years

Description: The key component of the first order stock adjustment molecule is the *stocking* decision. The *stocking* decision can be thought of as having two parts. First, one "orders" what ever is being used up (this is *StockingForReplacement)*. This portion of the decision will keep inventories at their *current* levels. The second component of the decision is to "order" a bit more or a bit less to move the *Level* to its desired value. This decision is done in a "goal-gap" way. Structurally this molecule is a smooth with a piece added on to take care of an extra outflow from the level.

Behavior: This structure will smoothly move the actual inventory to the desired level. If the outflow were zero, this structure would be equivalent to a smooth. If the replacement part of the decision can be made immediately (as shown above) without a perception delay, the structure will behave like a smooth no matter what the outflow is.

Classic examples: A very common structure.

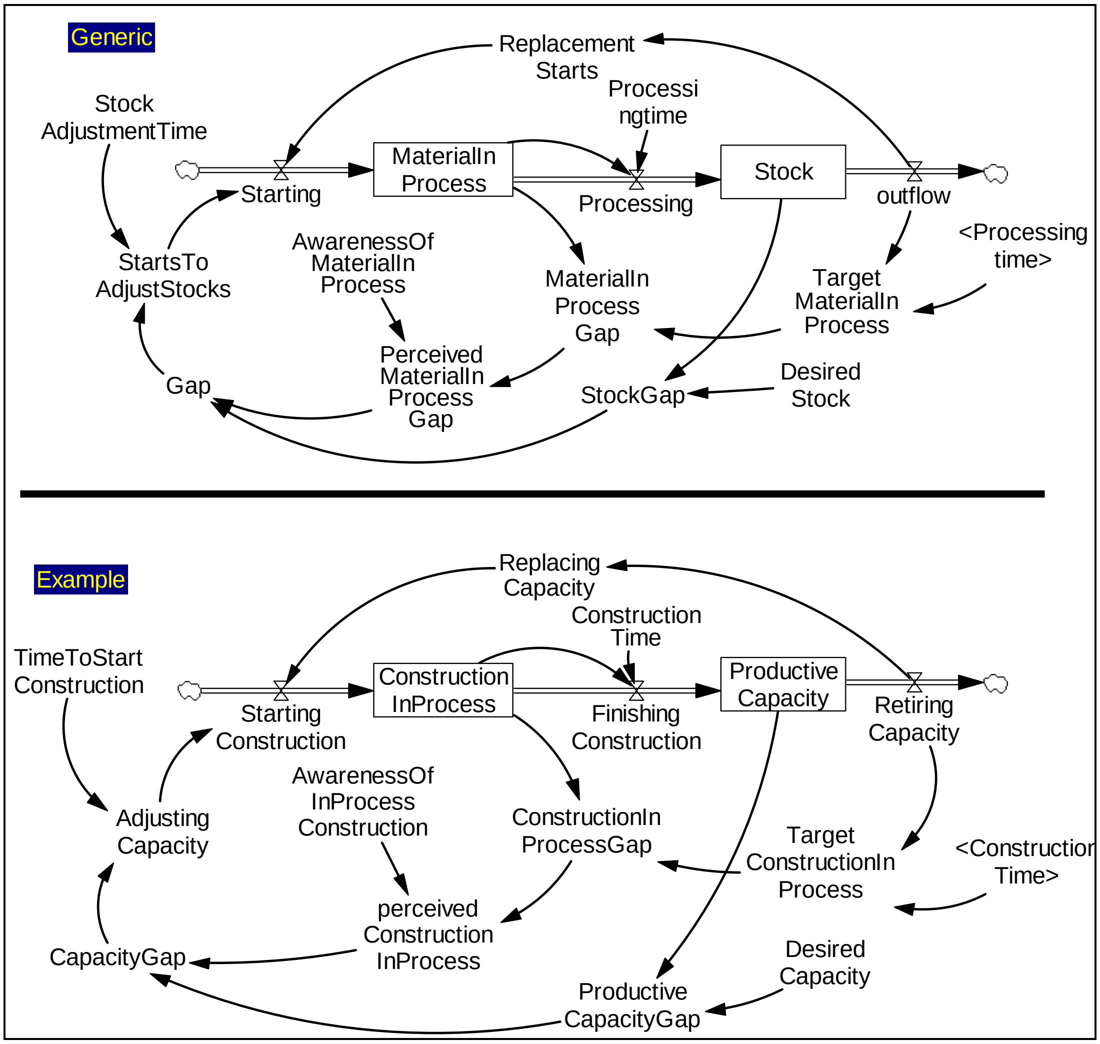
Caveats: In many cases there the *stocking* flow should not go negative (e.g. if the inflow is actually a manufacturing process, one cannot "unmanufactured" what has already been placed in the level). In this case, the modeler should modify the inflow so that it cannot go negative.

This structure assumes that stocking can be made with no delay (i.e. the inflow is from off the shelf, immediately available, products). If there is a delay (e.g. the things being ordered need to be custom-made), then it may be important to consider the supply pipeline. For this see the Capacity Ordering molecule.

In some situations one may want to recognize a perception lag between the outflow and the knowledge of how much should be replaced. In this case, *StockingForReplacement* will should be modeled as a smooth (or perhaps an extrapolation) of the outflow.

Technical notes: None

High-Visibility Pipeline Correction



Immediate parents: Aging chain, First-order stock adjustment
Ultimate parents: Close gap, Bathtub, Go to zero

Used by: None

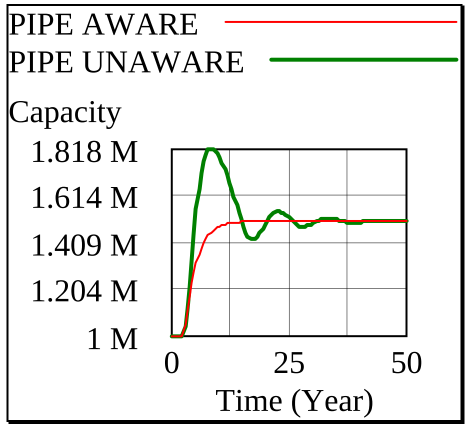
Problem solved: How to adjust a stock to its desired value, items taking account of what is in the pipeline

Equations:

PerceivedMaterialInProcessGap = MaterialInProcessGap * awarenessOfMaterialInProcess
    Units:
MaterialInProcessGap = TargetMaterialInProcess - MaterialInProcess
    Units: stuff
outflow = ___
    Units: stuff/Year
AwarenessOfMaterialInProcess = ___ {must be between zero and one}

```
        Units: fraction
DesiredStock = ___
        Units: stuff
Stock = INTEG( Processing - outflow , DesiredStock )
        Units: stuff
StockGap = DesiredStock - Stock
        Units: stuff
Processing = MaterialInProcess / Processingtime
        Units: stuff/Year
Processingtime = ___
        Units: years
Gap = StockGap + PerceivedMaterialInProcessGap
        Units: stuff
MaterialInProcess = INTEG( Starting - Processing , TargetMaterialInProcess)
        Units: stuff
ReplacementStarts = outflow
        Units: stuff/Year
Starting = max ( 0, StartsToAdjustStocks + ReplacementStarts )
        Units: stuff/Year
StartsToAdjustStocks = Gap / StockAdjustmentTime
        Units: stuff/Year
StockAdjustmentTime = ___
        Units: Year
TargetMaterialInProcess = outflow * Processingtime
        Units: stuff
```

Description: Based on the First-order stock adjustment structure, this molecule adds the idea that creating material is a time consuming process. As in the *first-order* molecule, this one also represents the need to replace what is being used (or sold) and also adjusts the stock toward a desired level. This molecule takes account not only of what is ultimately needed in the final stock, but also what is needed in the "pipe line". Put differently, this molecule keeps track not only of what is on hand in the final stock, but also of what it has been started but has not yet been completed. The representation shown above provides a single level for in-process material, which – when combined with the final stock – results in a second-order aging chain. However, the in-process stock can easily be disaggregated simply by adding stocks to the aging chain – for example, for a production-distribution system one could have stocks of raw materials, in-process inventory, finished inventory, inventory-at-the-warehouse arranged in a fourth-order aging chain.



Behavior: Failing to keep track of what is in process (i.e. failing to keep track of the "pipeline", means that the decision for *starting* will over order -- it will keep ordering the same item until it is received; rather than realizing the order has been placed even though it hasn't shown up yet. This is the main mistake that people make in playing the Beer Game. The variable *awarenessOfMaterialInProcess* can be set anywhere between zero and 1 to represent partial awareness of the pipeline. Failing to include replacement demand will result in steady state error.

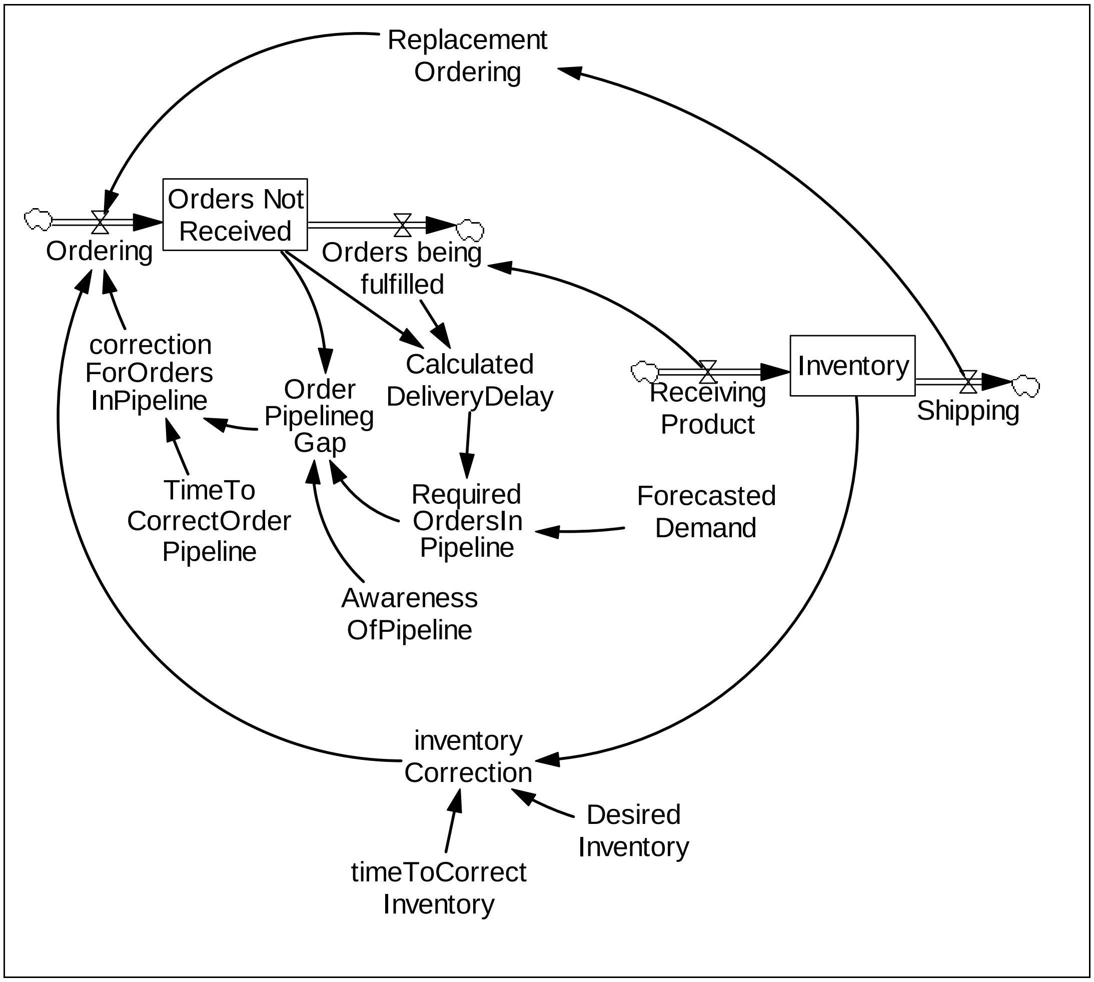
Classic examples: Structures like this are found in Forester's Industrial Dynamics model to represent a production-distribution system (supply chain) and in the System Dynamics National Model to represent an economy-wide aggregate structure leading from raw-materials to company's final inventories and, ultimately, to consumer's stocks. The structure is also used to represent construction processes for, say, office buildings or factories.

Caveats: The process of moving material from in-process to the final stage in this molecule only takes time. It does not take productivity or people. In some instances this is relatively accurate. In many instances, such as manufacturing, this is not accurate. However, the structure is still used in many such situations by the best modelers in the field, because it is simple and good enough in the sense that the dynamics of interest are not obscured.

In cases where "capacity" represents final inventory, *desired inventory* (i.e. "desired capacity" in the diagram) should respond to demand. If it doesn't, the structure is at the mercy of a positive loop involving the effect of stockouts on shipments (not shown), shipments (i.e. "retiring capacity") and ordering (i.e. "replacing capacity" and "adjusting capacity").

Technical notes: This molecule provides a more detailed (and more specific) representation of the pipeline than the closely related Low-visibility pipeline correction molecule. This molecule is more appropriate when the decision maker has visibility of the process that "creates" the inflow into the final stock.

Low-visibility Pipeline Correction



Immediate parents: First-order stock adjustment, Split flow, Residence time
Ultimate parents: Close gap, Bathtub

Used by: None

Problem solved: How to adjust a stock to its desired value, taking into account what is in the pipeline in a situation where the decision maker does not have explicit visibility of the pipeline itself.

Equations:

Ordering = max (0, correctionForOrdersInPipeline + ReplacementOrdering + inventoryCorrection
Units: cases/quarter
ReplacementOrdering = Shipping
Units: cases/quarter
Shipping = ___
Units: cases/quarter
inventoryCorrection = (DesiredInventory - Inventory) / timeToCorrectInventory
Units: cases/quarter

timeToCorrectInventory = ___
Units: quarter
DesiredInventory = ___
Units: cases
Inventory = INTEG(Receiving Product - Shipping , DesiredInventory)
Units: cases
Receiving Product = ___
Units: cases/quarter
correctionForOrdersInPipeline = OrderPipelinegGap / TimeToCorrectOrderPipeline
Units: cases/quarter
TimeToCorrectOrderPipeline = ___
Units: quarter
OrderPipelinegGap = (RequiredOrdersInPipeline - Orders Not Received) * AwarenessOfPipeline
Units: cases
AwarenessOfPipeline = ___ *(usually a number between between 0 and 1)*
Units: fraction
Orders Not Received = INTEG(Ordering - Orders being fulfilled , ___)
Units: cases
Orders being fulfilled = Receiving Product
Units: cases/quarter
RequiredOrdersInPipeline = ForecastedDemand * CalculatedDeliveryDelay
Units: cases
CalculatedDeliveryDelay = Orders Not Received / Orders being fulfilled
Units: quarters
ForecastedDemand = ____
Units: cases/quarter

Description: As in the First-order stock adjustment molecule, ordering has two components: replacing whatever is (expected to be) sold, and adjusting inventory. This formulation also recognizes a hidden component of inventory: Inventory that is on the way (or has been ordered), but has not yet been received. In steady state, this inventory-on-the-way will be non-zero. In fact, if the ordering rate is constant, this inventory-on-the-way will be equal to the ordering rate multiplied by the time it takes to receive orders. In other words, the inventory on the way will be the entire stream of orders that have been placed, but not received.

This structure represents a great deal of what is present at each stage of the beer game. The mistake that most beer-game players make is that they do not keep track of orders not received - they do not take account of the pipeline. In this structure this is represented by setting the Pipeline Recognition Factor to a small number. The result will be oscillations caused by placing the “same” order more than once.

Behavior: No relevant behavior because the process of incoming orders (and shipping) is not specified in this molecule.

Classic examples: This molecule is commonly used.

Caveats: None

Technical notes: This molecule does not specify how an order is "processed" by a supplier. The closely related High-visibility pipeline correction molecule may be more appropriate if the decision maker has explicit knowledge of the process used to create the material.

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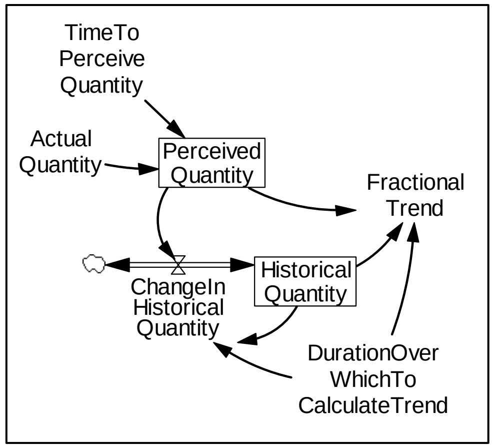


Trend

Immediate parents: Smooth (first order)
Ultimate parents: Close gap

Used by: Extrapolation

Equations:

FractionalTrend = (PerceivedQuantity - HistoricalQuantity) /
(HistoricalQuantity * DurationOverWhichToCalculateTrend)
Units: fraction/year
PerceivedQuantity = SMOOTH(ActualQuantity, TimeToPerceiveQuantity)
Units: Quantity units
ActualQuantity = ___
Units: Quantity units
TimeToPerceiveQuantity = ___
Units: year
HistoricalQuantity = INTEG(ChangeInHistoricalQuantity, PerceivedQuantity)
Units: Quantity units
ChangeInHistoricalQuantity = (PerceivedQuantity - HistoricalQuantity) /
DurationOverWhichToCalculateTrend
Units: Quantity units / year
DurationOverWhichToCalculateTrend = ___
Units: years

Description: The basic idea is very intuitive if one regards the historical quantity as an observation made at a point in the past and the perceived quantity as the current observation. The difference between the two is the absolute growth or decline. Dividing this quantity by the past observation gives the fractional growth or decline over the period separating the two observations. Dividing by the time between the two observations give growth fraction per time unit. The perceived quantity is a smooth of the actual quantity and the historical quantity is a further smooth of the perceived quantity; the time between these two smooths is the time constant on the historical quantity.

Behavior: The structure will eventually converge to the actual fractional growth rate of an exponentially growing quantity.

Classic examples: Often used to calculate the rate at which sales or demand is increasing.

Caveats: None

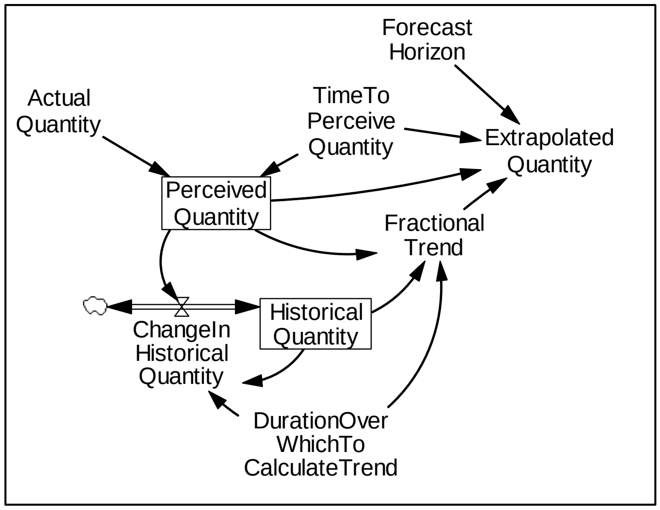
Technical notes: The perception lag on the perceived quantity is often conceptually necessary. On a technical level, however, smoothing actual conditions prevents the fractional trend from changing abruptly.

(Continued on next page...)

Extrapolation

Immediate parents: Trend
Ultimate parents: Close gap

Used by: None



Equations:

```
ExtrapolatedQuantity = PerceivedQuantity *
          (1 + FractionalTrend * (TimeToPerceiveQuantity + ForecastHorizon) )
        Units: Quantity units
ForecastHorizon =
        Units: year
FractionalTrend = (PerceivedQuantity - HistoricalQuantity) /
              (HistoricalQuantity * DurationOverWhichToCalculateTrend)
        Units: fraction/year
PerceivedQuantity = SMOOTH(ActualQuantity, TimeToPerceiveQuantity)
        Units: Quantity units
ActualQuantity =
        Units: Quantity units
TimeToPerceiveQuantity =
        Units: year
HistoricalQuantity = INTEG(ChangeInHistoricalQuantity, PerceivedQuantity)
        Units: Quantity units
ChangeInHistoricalQuantity = (PerceivedQuantity - HistoricalQuantity) /
                                     DurationOverWhichToCalculateTrend
        Units: Quantity units / year
DurationOverWhichToCalculateTrend =
        Units: years
```

Description: The extrapolation works on the fractional trend which is the output of a Trend Molecule. The extrapolation is simply the current observation (the perceived quantity) multiplied by a factor representing how much it will grow by the end of the forecast horizon. This factor is the fractional trend multiplied by the forecast horizon and by the time it takes to perceive current conditions. Using the time to perceive current conditions extrapolates from the observation, which is necessarily lagged, to the current time. Then, using the forecast horizon extrapolates from the current time to the time of the forecast horizon. However, this degree of exactness is unknown in the literature and unlikely to characterize actual trend extrapolations.

Behavior: The extrapolated forecast will be accurate for an exponentially growing quantity.

Classic examples: Extrapolations are often used to decide how much to order (or to begin construction of) in order to have the proper number of orders arriving (amount of construction coming on line) at the point in the future when we can expect our order to be filled..

Caveats: Extrapolation within an otherwise oscillatory system often will make the system more oscillatory. Note: this may be realistic.

Technical notes: What is used in the molecule is a linear extrapolation. It is roughly correct. The precise forecast would use linear extrapolation to bring the perception lag “forward” and then use continuous compounding up to the forecast horizon.

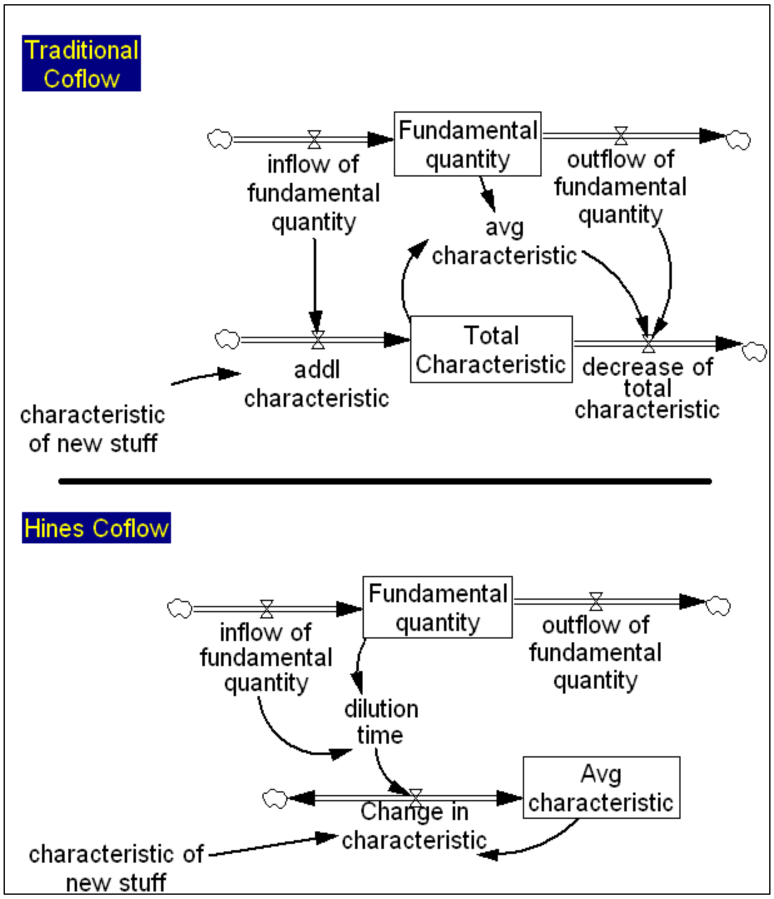
Coflow

There are two equivalent ways of representing a coflow. The *Traditional coflow* and the *Hines coflow*

Immediate parents: Smooth(first order)
Ultimate parents: Close gap

Used by: Cascaded Coflow, Coflow with Experience

Problem solved: How to keep track of a characteristic of a stock.



Equations:

Traditional Coflow

avg characteristic =Characteristic/ Fundamental quantity
Units: characteristic units/widget
Fundamental quantity =
INTEG(inflow of fundamental quantity-outflow of fundamental quantity, ___)
Units: widgets
inflow of fundamental quantity = ___
Units: widgets/Year
outflow of fundamental quantity = ___
Units: widgets/Year
Characteristic = INTEG(addl characteristic-decrease of characteristic,
Fundamental quantity*characteristic of new stuff)
Units: characteristic units
addl characteristic = inflow of fundamental quantity*characteristic of new stuff
Units: characteristic units/Year
characteristic of new stuff = ___
Units: characteristic units/widget
decrease of characteristic = outflow of fundamental quantity*avg characteristic
Units: characteristic units/Year

<u>Hines Coflow</u>

Avg characteristic = INTEG(Change in characteristic,characteristic of new stuff,___)
    Units: characteristic units/widget
Change in characteristic = (characteristic of new stuff-Avg characteristic)/dilution time
    Units: characteristic units/widget/Year
characteristic of new stuff =___
    Units: characteristic units/widget
dilution time = Fundamental quantity/inflow of fundamental quantity
    Units: Year
Fundamental quantity =
        INTEG(inflow of fundamental quantity-outflow of fundamental quantity, ___)
    Units: widgets
inflow of fundamental quantity = ___
    Units: widgets/Year
outflow of fundamental quantity = ___
    Units: widgets/Year

Description: The Hines coflow makes clearer the relationship of coflow to smooth or Goal-Gap formulations. The traditional coflow makes clearer why it is called a "coflow". The Hines Coflow makes clear that the characteristic is a smooth with a variable time "constant". The dilution time determines how quickly the current characteristic will change to or be diluted by the new characteristic. The traditional coflow shows that the flows of the characteristic are linked to the flows of the fundamental quantity.

Behavior: To anticipate the behavior think of how the smooth operates.

Classic examples: A firm continually borrows money at different interest rates. The amount borrowed is the fundamental quantity. The average interest rate is the average quantity. A business continually hires people with different skill levels. The number of people is the fundamental quantity. Average amount of skill is the average characteristic.

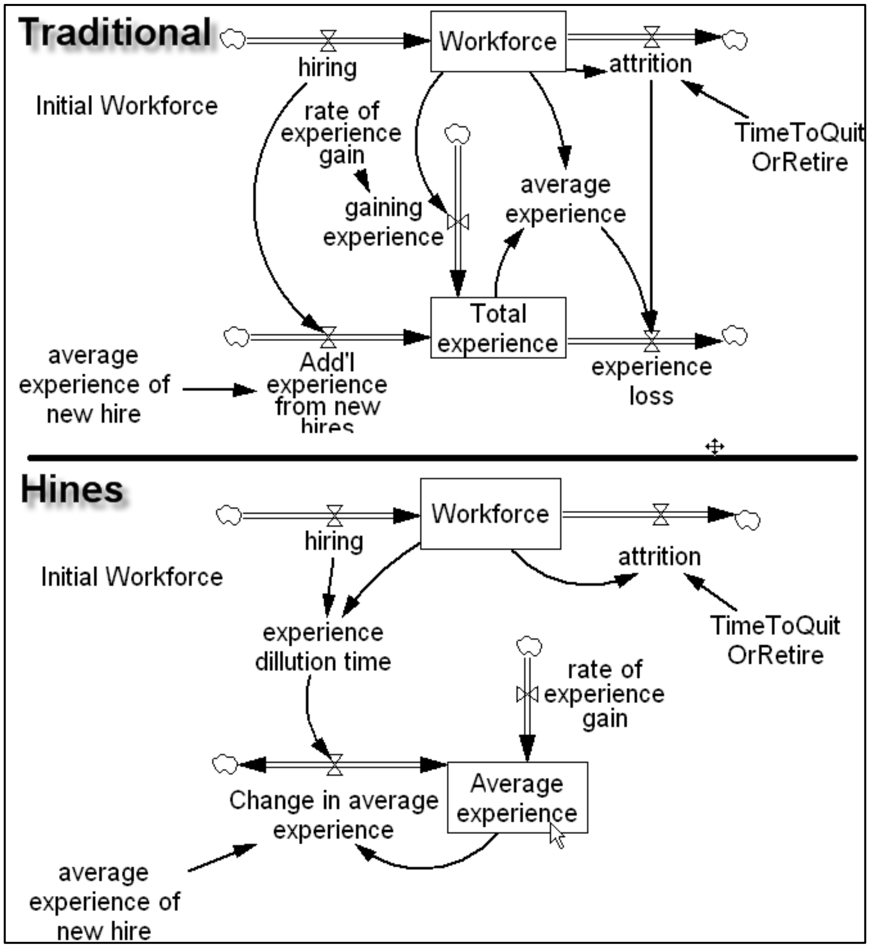
Caveats: The outflow of the fundamental quantity has the average characteristic. In some situations this is accurate. In many situations it is accurate enough. For situations where it is not good enough, see the cascaded coflow. In the Hines coflow be careful of having the dilution time be too small relative to DT. This can happen if the fundamental quantity is (close to) zero. Be careful of divide by zero errors: In the *Hines coflow* a divide by divide-by-zero will occur if the *inflow of the fundamental quantity* equals zero; in the *Traditional coflow* the divide by zero problem will occur if the *fundamental quantity* equals zero.

Technical notes: None

Coflow with Experience

There are two equivalent versions, the Traditional and the Hines.

Immediate parents: Coflow
Ultimate parents: Close gap
Used by: None



Problem solved: How to represent a workforce in which new people have less experience, and where everyone gains experience with time

Equations:

Traditional Coflow

average experience = Total experience / Workforce
Units: Years/person
Workforce = INTEG(hiring - attrition , Initial Workforce)
Units: People
hiring = ___
Units: People/Year
attrition = Workforce / TimeToQuitOrRetire
Units: People/Year
Initial Workforce = INITIAL(hiring * TimeToQuitOrRetire)
Units: People
TimeToQuitOrRetire = ___
Units: Year
Total experience = INTEG(Add'l experience from new hires + gaining experience
- experience loss , Workforce * (average experience of new hire
+ rate of experience gain * Workforce / attrition))
Units: Year

```
experience loss = attrition * average experience
        Units: dmnl
Add'l experience from new hires = average experience of new hire * hiring
        Units: dmnl
average experience of new hire = ___
        Units: Years/person
gaining experience = Workforce * rate of experience gain
        Units: dmnl
rate of experience gain = 1
        Units: Years/(Year*person)
```

```
Hines Coflow

Average experience =
           INTEG(Change in average experience + rate of experience gain,
             average experience of new hire + Workforce / attrition)
        Units: Years
rate of experience gain = 1
        Units: Years/Year
Change in average experience =
            (average experience on new hire - Average experience) / experience dilution time
        Units: fraction
average experience on new hire =  ___
        Units: Years
experience dilution time = Workforce/hiring
        Units: Year
hiring =  ___
        Units: People/Year
Workforce = INTEG(hiring-attrition,  hiring*TimeToQuitOrRetire)
        Units: People
attrition = Workforce/TimeToQuitOrRetire
        Units: People/Year
TimeToQuitOrRetire = ____
        Units: Year
```

Description: This formulation modifies the regular coflow by adding a steady accumulation of experience as time goes by. Experience can be used as an input to an effect on productivity or quality.

Behavior: Left to the reader.

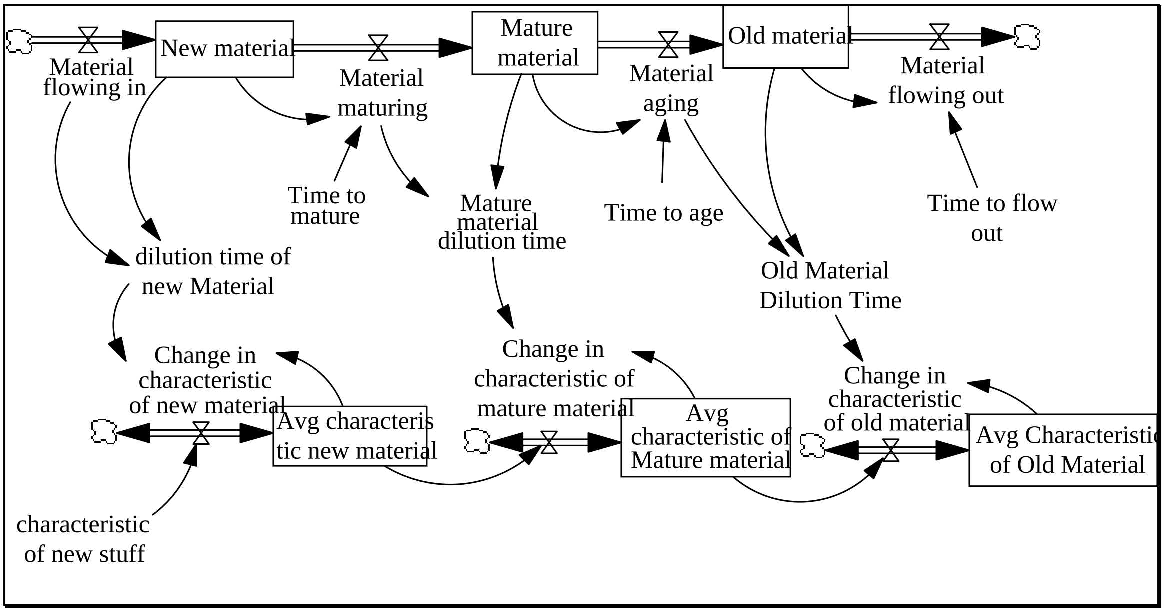
Classic examples: None

Caveats: None

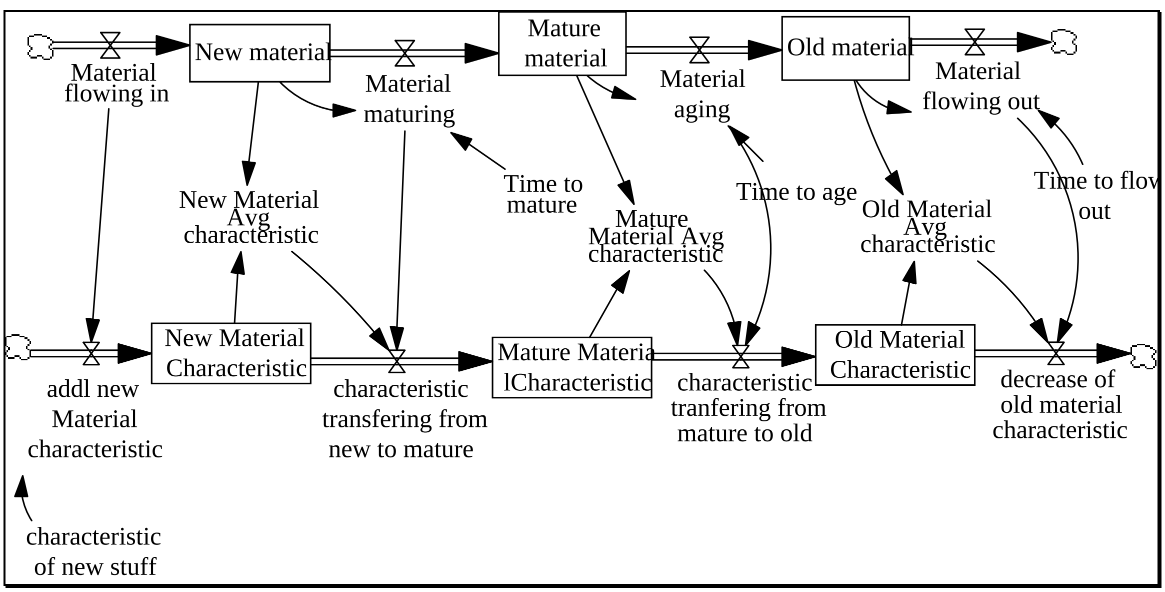
Technical notes: None

Cascaded Coflow

Hines Cascaded Coflow



Traditional Cascaded Coflow



Immediate parents Aging chain
Traditional: Traditional coflow, Broken cascade, Cascaded levels
Hines: Hines coflow, Smooth (higher order)
Ultimate parents: Close gap, Bathtub, Go to zero

Used by: None

Problem solved: How to represent a characteristic of a fundamental quantity where the outflow from the fundamental quantity is *older* than the average.

Equations:

```
Traditional Cascaded Coflow Equations

Change in characteristic of old material =
      ( Avg characteristic of Mature material- Avg Characteristic of Old Material ) /
        old Material Dilution Time
         Units: characteristic units/(widget*Year)
Avg characteristic of Mature material = INTEG(
       Change in characteristic of mature material, Avg characteristic new material )
         Units: characteristic units/widget
Avg Characteristic of Old Material = INTEG(
       Change in characteristic of old material, Avg characteristic of Mature material )
         Units: characteristic units/widget
Change in characteristic of mature material =
       ( Avg characteristic new material- Avg characteristic of Mature material ) /
           Mature material dilution time
         Units: characteristic units/(widget*Year)
Old Material Dilution Time = Old material / Material aging
         Units: Year
dilution time of new Material = New material / Material flowing in
         Units: Year
Mature material dilution time = Mature material / Material maturing
         Units: Year
Avg characteristic new material = INTEG(
        Change in characteristic of new material, characteristic of new stuff )
Units: characteristic units/widget
Change in characteristic of new material =
        ( characteristic of new stuff - Avg characteristic new material ) / dilution time of new Material
         Units: characteristic units/(widget*Year)
characteristic of new stuff = ___
         Units: characteristic units/widget
Material aging = Mature material / Time to age
         Units: stuff/Year
Material flowing in = ___
         Units: stuff/Year
Material flowing out = Old material / Time to flow out
         Units: stuff/Year
Material maturing = New material / Time to mature
         Units: stuff/Year
Mature material = INTEG(Material maturing - Material aging , Material maturing * Time to age )
         Units: stuff
New material = INTEG(
        Material flowing in - Material maturing , Material flowing in * Time to mature )
         Units: stuff
```

Old material = INTEG(Material aging - Material flowing out , Material aging * Time to flow out)
Units: stuff
Time to age = ___
Units: Year
Time to flow out = ___
Units: years
Time to mature = ___
Units: Year

Hines Cascaded Coflow Equations

Avg characteristic new material = INTEG(
Change in characteristic of new material, characteristic of new stuff)
Units: characteristic units/widget
Change in characteristic of new material = (
characteristic of new stuff - Avg characteristic new material)/dilution time of new Material
Units: characteristic units/widget/Year
characteristic of new stuff = ___
Units: characteristic units/widget
dilution time of new Material = New material/Material flowing in
Units: Year
Avg characteristic of Mature material = INTEG(
Change in characteristic of mature material,Avg characteristic new material)
Units: characteristic units/widget
Change in characteristic of mature material =
(Avg characteristic new material -Avg characteristic of Mature material)/
Mature material dilution time
Units: characteristic units/widget/Year
Mature material dilution time = Mature material/Material maturing
Units: Year
Avg Characteristic of Old Material = INTEG(
Change in characteristic of old material,Avg characteristic of Mature material)
Units: characteristic units/widget
Change in characteristic of old material =
(Avg characteristic of Mature material - Avg Characteristic of Old Material)/
Old Material Dilution Time
Units: characteristic units/widget/Year
Old Material Dilution Time = Old material/Material aging
Units: Year
New material = INTEG(Material flowing in-Material maturing,Material flowing in*Time to mature)
Units: stuff
Material flowing in = ___
Units: stuff/Year
Material maturing = New material / Time to mature
Units: stuff/Year
Time to mature = ___

```
        Units: Year
Mature material =INTEG(Material maturing-Material aging,Material maturing*Time to age)
        Units: stuff
Material aging = Mature material/Time to age
        Units: stuff/Year
Time to age = ____
        Units: Year
Old material = INTEG(Material aging-Material flowing out,Material aging*Time to flow out)
        Units: stuff
Material flowing out = Old material/Time to flow out
        Units: stuff/Year
Time to flow out = ___
        Units: years
```

Description: In the Hines coflow, each average characteristic is a "coflow-smooth" whose goal is the prior "coflow-smooth". In the traditional coflow, the outflow of one coflow-level flows into the next. The two formulations are mathematically the same.

Behavior: Obvious.

Classic examples: None

Caveats: None

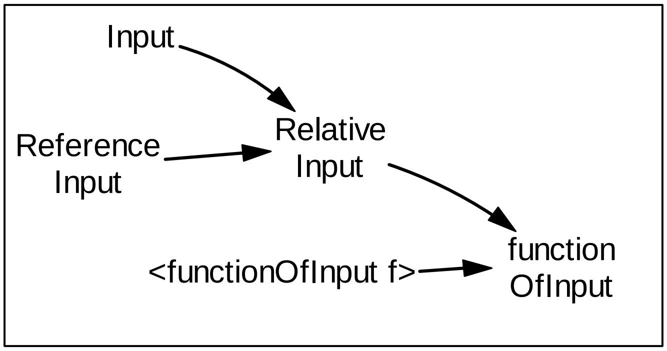
Technical notes: None

Dimensionless Input To Function

Immediate parents: None
Ultimate parents: None

Used by: Univariate anchoring and adjustment

Problem solved: How to create a table function (also known as lookup function) that is easy to parameterize.



Equations:

functionOfInput = functionOfInput f(Relative Input)
Units: output units
functionOfInput f = [table (or "lookup") function]
Units: output units
Relative Input = Input/Reference Input
Units: dimensionless
Input = ___
Units: Input units
Reference Input = ___
Units: Input units

Description: The key here is that the input to the table function is measured relative to a reference. It is usually easier for people to judge what value the function should produce for an input that is some factor of a reference, than to judge the value of the function for a raw input. The most important exception is a domain-expert who may find it easier to parameterize the function in terms of raw inputs.

The reference input is often, but not always, a constant.

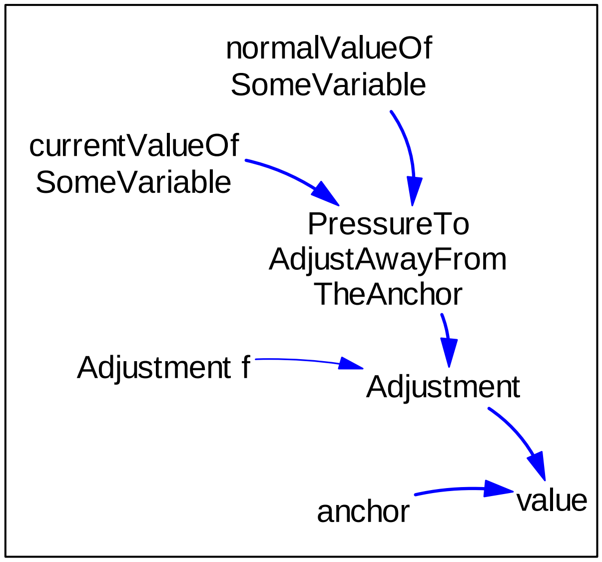
Behavior: No stocks, so no endogenous behavior.

Classic examples: Effect of inventory on sales.

Caveats: Although this molecule makes it easier for a modular who is not intimately familiar with the substantive area being modeled; this molecule can make it more difficult for the client who is extremely familiar with the subject. People with tremendous experience in a subject area may find it easier to parameter a function when the input is a raw, dimensioned quantity.

Technical notes: An added benefit of this structure is that it can be reparameterized for tuning or sensitivity testing by changing the value of the reference input (if the reference input is a constant). If the function takes raw values, the only way to reparameterize is to change (i.e. "redraw") the function.

Univariate Anchoring and Adjustment



Immediate parents: Dimensionless input to function
Ultimate parents: Dimensionless input to function

Used by: Multivariate anchoring and adjustment, Nonlinear split, Level protected by level, Effect of fatigue, overtime, Level protected by pdy

Problem solved: How to model the human process of judging an "appropriate" value (e.g. actual value or ideal value) of some constant or variable. How to create a user-defined function whose equilibrium value is easy to change.

Equations:

value = Adjustment * anchor
Units: valueUnits
anchor = ___
Units: valueUnits
Adjustment = Adjustment f (PressureToAdjustAwayFromTheAnchor)
Units: dmnl
Adjustment f ( ) = *A user defined function that contains the point (1,1)*
Units: dmnl
PressureToAdjustAwayFromTheAnchor =
currentValueOfSomeVariable / normalValueOfSomeVariable
Units: fraction
currentValueOfSomeVariable = ___
Units: unitsOfSomeVariable
normalValueOfSomeVariable = ___
Units: unitsOfSomeVariable

Description: Anchoring and Adjustment is a common judgmental strategy (Hogarth). Rather than finding a new quantity by solving a problem from scratch, people often will simply take a known quantity (the anchor) and adjust it to account for new factors or pressures. For example I don't know the distance from London to Hamburg. So, I might start with the distance from London to Berlin (the anchor), which I happen to know. Because I know that Hamburg is closer to London than Berlin, I'll "adjust" the value downward by " a bit" say 20%. The structure above represents this process: A normal (or maximum or minimum) value – the "anchor" -- is multiplied ("adjusted") by the effect (or pressure) of some piece of information. The effect has a neutral values of 1.

Behavior: No stocks, so no dynamics.

Classic examples: Many

Caveats: None

Technical notes: People using anchoring and adjustment in the real world often fail to adjust enough.

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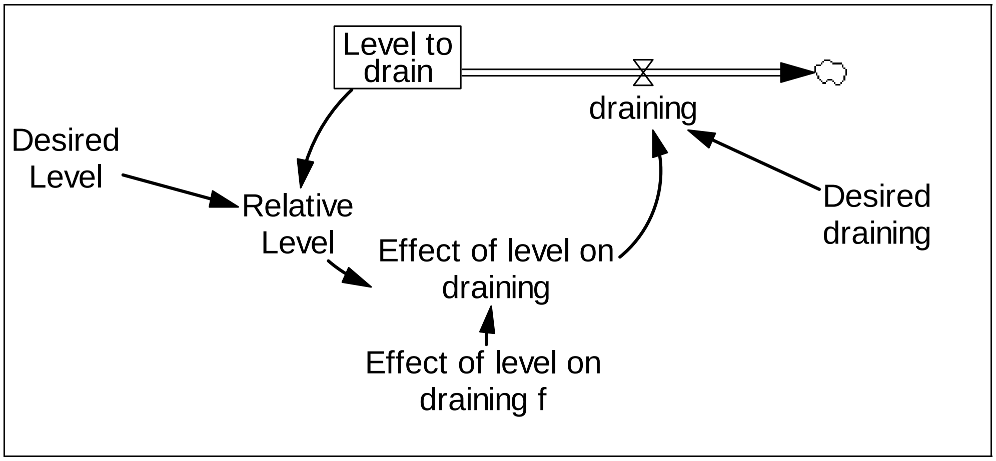
Level Protected by Level



Immediate parents: Univariate anchoring and adjustment
Ultimate parents: Dmnl input to function

Used by: Backlog shipping protected by level

Problem solved: How to ensure that a stock does not go negative

Equations:

Level to drain = INTEG(-draining,Desired Level, ___) Units: Widgets draining = Desired draining * Effect of level on draining Units: Widgets/Month Desired draining = Units: Widgets/Month Effect of level on draining = Effect of level on draining f(Relative Level) Units: dmnl Effect of level on draining f = user defined funciton Units: dmnl Relative Level = Level to drain / Desired Level Units: dmnl Desired Level = Units: Widgets

Description: The actual outflow is the product of the desired draining and a function that shuts off the outflow as the level approaches zero. This formulation is considered much more desirable than an IF-THEN-ELSE statement both because it is less subject to integration error and, even more importantly, because it is appropriate for a stock that aggregates many items which are not identical (e.g. a finished goods inventory containing many different products and models)..

Behavior: The level will not go below zero.

Classic examples: Shipping out of an inventory. The inventory must not go negative.

Caveats: Watch out for functions that drop suddenly to zero, which may introduce an integration error that lets the level go slightly negative before it shuts off.

Technical notes: The table function should go through (0,0). A table function going through (1,1) will be easier to put into equilibrium. To represent probabilistic stocking out, the function should lie above the 45 degree line in the region below the point (1,1).

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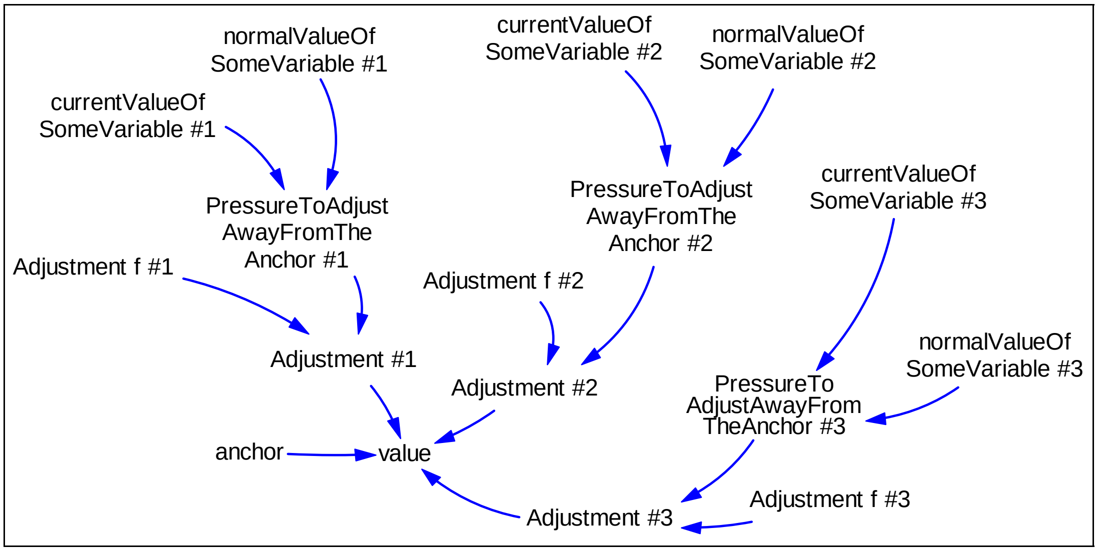
Multivariate Anchoring and Adjustment



Immediate parents: Univariate anchoring and adjustment
Ultimate parents: Dimensionless input To Function

Used by: Productivity, Quality, Sea anchor and adjustment, Multi-dimensional split

Problem solved: How to model the human process of judging the "appropriate" value (e.g. actual value or ideal value) of some constant or variable. How to represent something that is a function of many things. How to create a function whose equilibrium value is easy to change.

Equations:

```
value = Anchor * "Adjustment #1" * "Adjustment #2" * "Adjustment #3"
        Units: cases
Anchor = ___
        Units: cases
"Adjustment #1" = "Adjustment f #1" ( "PressureToAdjustAwayFromTheAnchor #1")
        Units: dmnl
"Adjustment #2" = "Adjustment f #2" ( "PressureToAdjustAwayFromTheAnchor #2")
Units: dmnl
"Adjustment #3" = "Adjustment f #3" ( "PressureToAdjustAwayFromTheAnchor #3")
Units: dmnl
"Adjustment f #1" = user defined function
        Units: dmnl
"Adjustment f #2" = user defined function
        Units: dmnl
"Adjustment f #3" = user defined function
        Units: dmnl
"PressureToAdjustAwayFromTheAnchor #1" =
```

```
                "currentValueOfSomeVariable #1" / "normalValueOfSomeVariable #1"
Units: fraction
"PressureToAdjustAwayFromTheAnchor #2" =
                "currentValueOfSomeVariable #2" / "normalValueOfSomeVariable #2"
Units: fraction
"PressureToAdjustAwayFromTheAnchor #3" =
                "currentValueOfSomeVariable #3" / "normalValueOfSomeVariable #3"
Units: fraction
"currentValueOfSomeVariable #1" = ___
        Units: unitsOfSomeVariable
"currentValueOfSomeVariable #2" = ___
        Units: unitsOfSomeVariable
"currentValueOfSomeVariable #3" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #1" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #2" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #3" = ___
        Units: unitsOfSomeVariable
```

Description: Anchoring and Adjustment is a common judgmental strategy (Hogarth). Rather than finding a new quantity by solving a problem from scratch, people often will simply take a known quantity (the anchor) and adjust it to account for new factors. For example to judge how long it will take me to write a paper, I might start with a usual or normal value, say one week. Then, I'll adjust that number for various factors that are3 currently different from normal – for example maybe I'm more fatigued than usual, so I'll lengthen the estimate by ten percent; perhaps the subject is one that I've written about many times in the past and so I'll lower my estimate by 15%; and so on to account for other factors like distractions, the number of figures in the paper, etc. The structure above represents this process: A normal (or maximum or minimum) value – the "anchor" -- is multiplied ("adjusted") by a series of factors representing the effects of various other quantities. The effects have neutral values of 1.

Behavior: None.

Classic examples: The birth rate and the death rate in Forrester's *World Dynamics.*

Caveats: When modeling multivariate anchoring and adjustment, people often over-estimate the strengths of the effects during initial parameterization.

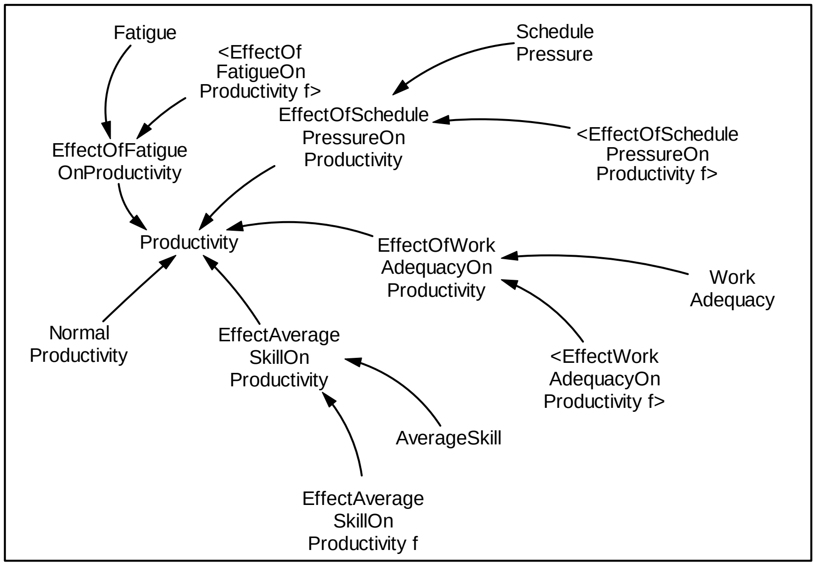
Technical notes: Although the original system dynamics simulation modeling language (DYNAMO) allowed users to design their own single-input functions (Table Functions), it did not permit users to design multi-input functions. Since then, this formulation has filled the need for multi-input functions. Although limited in some ways, this formulation is easy for the modeler to visualize (a general fourth-dimensional function would be difficult) and easy to explain.

Productivity (PDY)

Immediate parents:
[Multivariate anchoring and adjustment]
Ultimate parents:
[Dmnl input to f()]

Used by: None

Problem solved: How to determine productivity



Equations:

Productivity = NormalProductivity * EffectOfFatigueOnProductivity * EffectOfSchedulePressureOnProductivity * EffectOfWorkAdequacyOnProductivity * EffectAverageSkillOnProductivity
Units: widgets/(person*Month)
AverageSkill = ___
Units: fraction
EffectAverageSkillOnProductivity = EffectAverageSkillOnProductivity f (AverageSkill)
Units: dmnl
EffectAverageSkillOnProductivity f = user defined function
Units: dmnl
NormalProductivity = ___
Units: widgets/(person*Month)
EffectOfFatigueOnProductivity = EffectOfFatigueOnProductivity f (Fatigue)
Units: dmnl
EffectOfFatigueOnProductivity f = user defined function
Units: dmnl
Fatigue = ___
Units: fraction
EffectOfSchedulePressureOnProductivity =
EffectOfSchedulePressureOnProductivity f(SchedulePressure)
Units: dmnl
EffectOfSchedulePressureOnProductivity f = user defined function
Units: dmnl
SchedulePressure = ___
Units: fraction
EffectOfWorkAdequacyOnProductivity =

```
    EffectWorkAdequacyOnProductivity f ( WorkAdequacy )
        Units: dmnl
EffectWorkAdequacyOnProductivity f = user defined function)
        Units: dmnl
WorkAdequacy = ___
        Units: fraction
```

Description: The particular effects shown above are illustrative, though common in project models. Productivity is usually defined to mean *speed* that a single worder (or single machine or other resource) *produces.* Quality (the fraction of production that is actually done correctly) is modeled separately.

Behavior: No levels, so no endogenous dynamics

Classic examples: Project models

Caveats: None

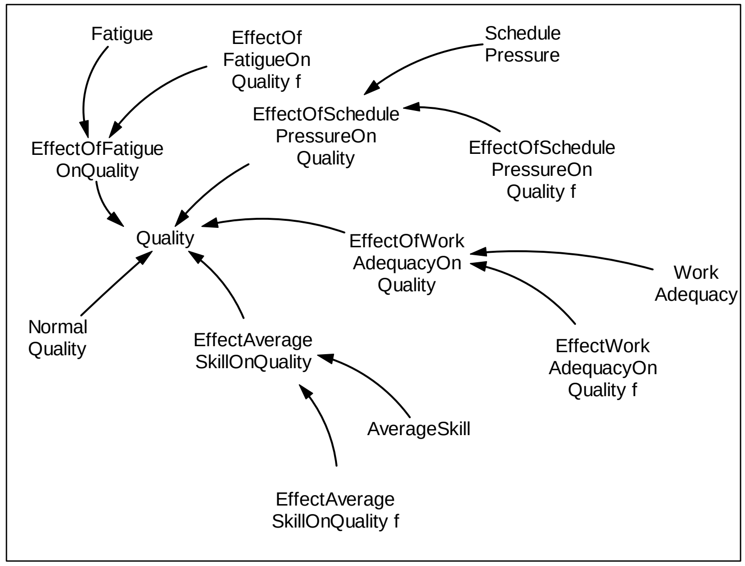
Technical notes: The first project models were developed by the consulting company Pugh Roberts. These early models used the abbreviation “PDY” for “productivity”. The same structure can be used to represent quality. Often in project models things that affect productivity also effect quality (though through different functions). An interesting effect in these formulations is the effect of schedule pressure which is usually represented as a positively sloped function for productivity (meaning more schedule pressure makes people work faster) and a negatively sloped function for quality (meaning as people work faster they make more mistakes).

Quality

Immediate parents: Multivariate anchoring and adjustment
Ultimate parents: Dmnl input to f()

Used by: None

Problem solved: How to determine quality



Equations:

Quality = min(1,NormalQuality * EffectOfFatigueOnQuality * EffectOfSchedulePressureOnQuality * EffectOfWorkAdequacyOnQuality * EffectAverageSkillOnQuality)
Units: widgets/(person*Month)
AverageSkill = ___
Units: fraction
EffectAverageSkillOnQuality = EffectAverageSkillOnQuality f (AverageSkill)
Units: dmnl
EffectAverageSkillOnQuality f = user defined function
Units: dmnl
NormalQuality = ___
Units: widgets/(person*Month)
EffectOfFatigueOnQuality = EffectOfFatigueOnQuality f (Fatigue)
Units: dmnl
EffectOfFatigueOnQuality f = user defined function
Units: dmnl
Fatigue = ___
Units: fraction
EffectOfSchedulePressureOnQuality =
EffectOfSchedulePressureOnQuality f(SchedulePressure)
Units: dmnl
EffectOfSchedulePressureOnQuality f = user defined function
Units: dmnl
SchedulePressure = ___
Units: fraction
EffectOfWorkAdequacyOnQuality =
EffectWorkAdequacyOnQuality f (WorkAdequacy)
Units: dmnl

EffectWorkAdequacyOnQuality f = user defined function)
Units: dmnl
WorkAdequacy = ___
Units: fraction

Description: The particular effects shown above are illustrative, though common in project models. Quality is defined as the fraction of work that is being done correctly. In project models, productivity – meaning the speed with which work gets done (whether or not its correctly done -- is defined separately from quality.

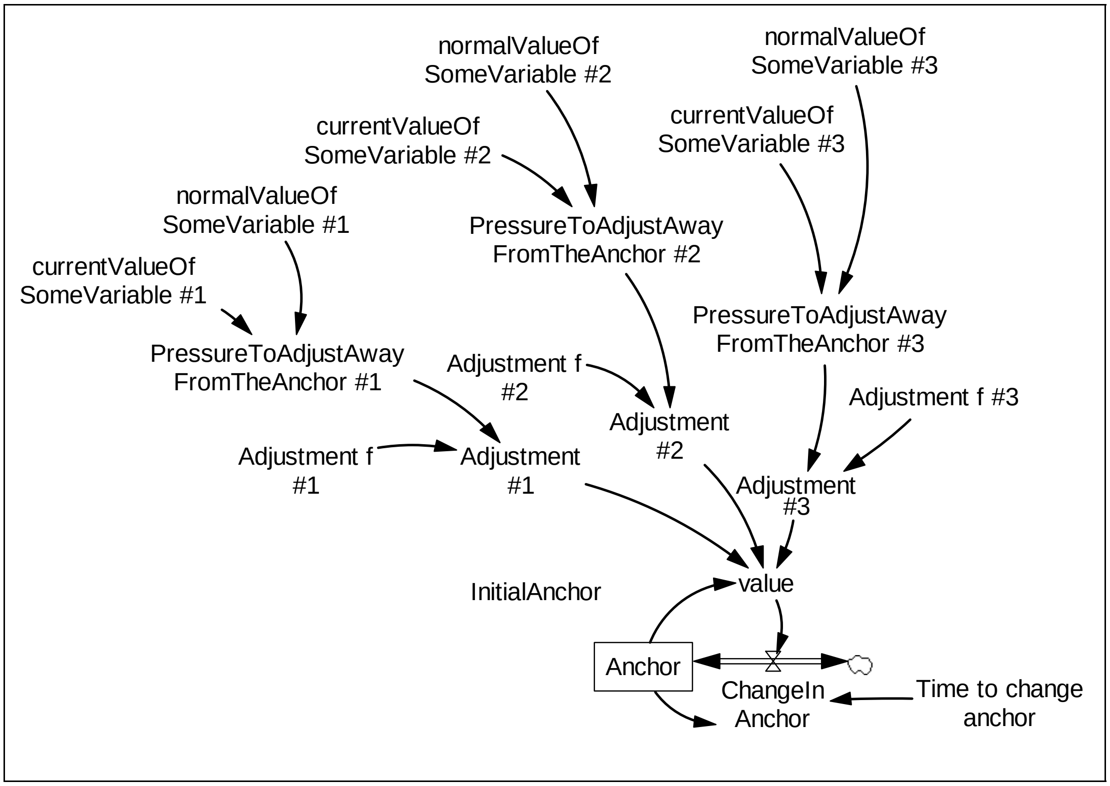
Behavior: No levels, so no endogenous dynamics

Classic examples: Project models

Caveats: Quality should not go above 1 or below 0. Usually the table functions won't go below zero, but they may go above one. Consequently, the result of multiplying normal quality by all the table functions *could* be a number greater than one. The use of the *MIN* function as shown in the equation for *quality* is a common solution to this risk.

Technical notes: The same structure can be used to represent productivity. Often in project models things that affect quality also affect productivity (though through different functions). An interesting item in these formulations is the effect of schedule pressure which is usually represented as a positively sloped function for productivity (meaning more schedule pressure makes people work faster) and as a negatively sloped function for quality (meaning as people work faster they make more mistakes).

Sea Anchor and Adjustment



Immediate parents: Multivariate anchoring and adjustment, Smooth (first order)
Ultimate parents: Dimensionless input to function, Close gap

Used by: Protected sea anchoring and adjustment, Sea anchor pricing

Problem solved: How to represent a process by which people will “grope” toward a proper quantity. How to form the anchor in an Anchoring and Adjustment process.

Equations:

```
value = Anchor * "Adjustment #1" * "Adjustment #2" * "Adjustment #3"
        Units: cases
Anchor = INTEG( ChangeInAnchor , InitialAnchor )
        Units: cases
InitialAnchor = ___
        Units: cases
ChangeInAnchor = ( value - Anchor ) / Time to change anchor
        Units: cases/Month
Time to change anchor = ___
        Units: Month
"Adjustment #1" = "Adjustment f #1" ( "PressureToAdjustAwayFromTheAnchor #1")
        Units: dmnl
"Adjustment #2" = "Adjustment f #2" ( "PressureToAdjustAwayFromTheAnchor #2")
        Units: dmnl
```

```
"Adjustment #3" = "Adjustment f #3" ( "PressureToAdjustAwayFromTheAnchor #3")
        Units: dmnl
"Adjustment f #1" = user defined function
        Units: dmnl
"Adjustment f #2" = user defined function
        Units: dmnl
"Adjustment f #3" = user defined function
        Units: dmnl
"PressureToAdjustAwayFromTheAnchor #1" =
           "currentValueOfSomeVariable #1" / "normalValueOfSomeVariable #1"
Units: fraction
"PressureToAdjustAwayFromTheAnchor #2" =
           "currentValueOfSomeVariable #2" / "normalValueOfSomeVariable #2"
Units: fraction
"PressureToAdjustAwayFromTheAnchor #3" =
           "currentValueOfSomeVariable #3" / "normalValueOfSomeVariable #3"
Units: fraction
"currentValueOfSomeVariable #1" = ___
        Units: unitsOfSomeVariable
"currentValueOfSomeVariable #2" = ___
        Units: unitsOfSomeVariable
"currentValueOfSomeVariable #3" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #1" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #2" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #3" = ___
        Units: unitsOfSomeVariable
```

Description: This is an elaboration on the judgmental strategy known as anchoring and adjustment. In anchoring and adjustment a judgment is made (or a quantity) by taking an underlying quantity (an anchor) and adjusting it on the basis of current information or pressures. This formulation contains the added idea that the anchor is formed on the bases of the past judgments.

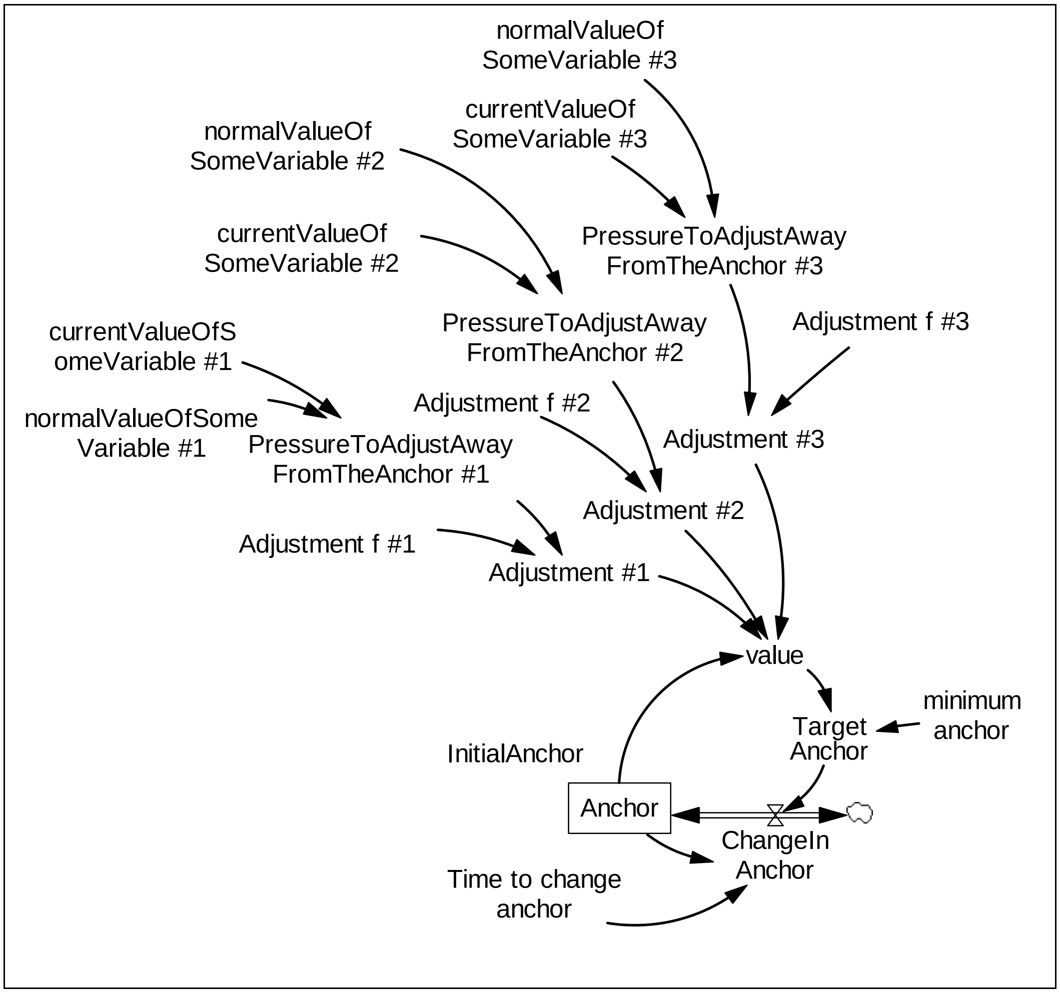
Behavior: A positive pressure will cause the quantity to immediately jump above the anchor. In the pressure persists, the quantity will begin to rise as the anchor does. If the pressure drops, the quantity will again respond immediately.

Classic examples: Anchor Pricing.

Caveats: This structure will get stuck at zero if the anchor becomes zero. To solve this use the protected sea anchoring and adjustment molecule.

Technical notes: Note there are two kinds of “parameters” to set: the adjustment time and the user function (s).

Protected Sea Anchoring and Adjustment



Immediate parents: Sea anchor and adjustment
Ultimate parents: Dimensionless input to function

Used by: Protected Anchor Pricing

Problem solved: Represent a judgmental strategy that will grope toward a solution, and which will not get "stuck" at zero.

Equations:

value = Anchor * "Adjustment #1" * "Adjustment #2" * "Adjustment #3"
Units: cases
Anchor = INTEG(ChangeInAnchor , InitialAnchor)
Units: cases
InitialAnchor = ___
Units: cases
ChangeInAnchor = (Target Anchor - Anchor) / Time to change anchor
Units: cases/MonthTime to change anchor = ___
Units: Month

```
Target Anchor = MAX ( value , minimum anchor )
        Units: cases
minimum anchor = ___
        Units: cases
"Adjustment #1" = "Adjustment f #1" ( "PressureToAdjustAwayFromTheAnchor #1")
        Units: dmnl
"Adjustment #2" = "Adjustment f #2" ( "PressureToAdjustAwayFromTheAnchor #2")
        Units: dmnl
"Adjustment #3" = "Adjustment f #3" ( "PressureToAdjustAwayFromTheAnchor #3")
        Units: dmnl
"Adjustment f #1" = user defined function
        Units: dmnl
"Adjustment f #2" = user defined function
        Units: dmnl
"Adjustment f #3" = user defined function
        Units: dmnl
"PressureToAdjustAwayFromTheAnchor #1" =
           "currentValueOfSomeVariable #1" / "normalValueOfSomeVariable #1"
        Units: fraction
"PressureToAdjustAwayFromTheAnchor #2" =
           "currentValueOfSomeVariable #2" / "normalValueOfSomeVariable #2"
        Units: fraction
"PressureToAdjustAwayFromTheAnchor #3" =
           "currentValueOfSomeVariable #3" / "normalValueOfSomeVariable #3"
        Units: fraction
"currentValueOfSomeVariable #1" = ___
        Units: unitsOfSomeVariable
"currentValueOfSomeVariable #2" = ___
        Units: unitsOfSomeVariable
"currentValueOfSomeVariable #3" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #1" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #2" = ___
        Units: unitsOfSomeVariable
"normalValueOfSomeVariable #3" = ___
        Units: unitsOfSomeVariable
```

Description: This molecule adds to its parent, Anchoring and Adjustment, a Target Anchor. The Target Anchor is the maximum of either the quantity itself or the smallest value that the anchor should take on.

Behavior: Similar to Anchoring and Adjustment, except it will not get stuck at zero (as long as the minimum anchor is greater than zero.

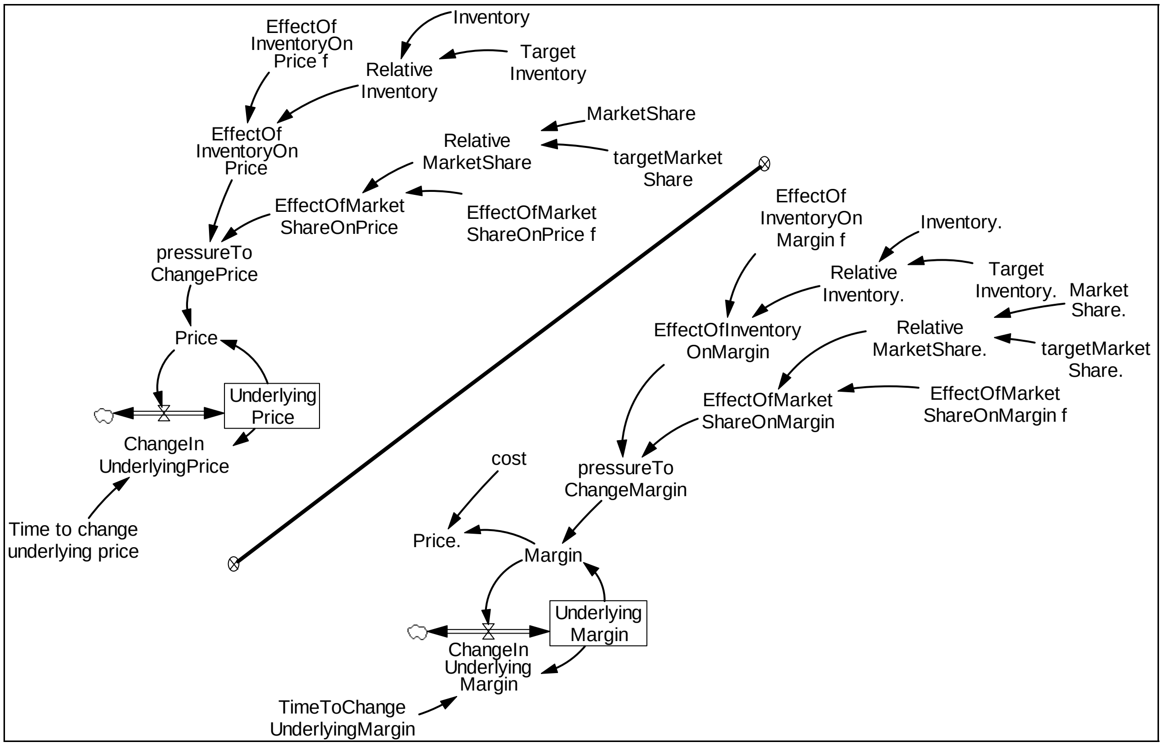
Classic examples: Protected sea anchor pricing

Caveats: None

Technical notes: The minimum anchor should be set above zero to ensure that this formulation will not get stuck at zero. There are two kinds of parameters that determine the dynamics the time constant and the user-defined functions.

(Continued on next page...)

Sea Anchor Pricing



Immediate parents: Sea Anchoring and Adjustment
Ultimate parents: Dmnl input to function, Close gap

Used by: Protected sea anchor pricing, Smooth pricing

Problem solved: How to formulate price setting

Equations:

Equations for price form

Price = UnderlyingPrice * pressureToChangePrice
Units: $/widget
UnderlyingPrice = INTEG(ChangeInUnderlyingPrice, ___)
Units: $/widget
ChangeInUnderlyingPrice =(Price - UnderlyingPrice) /Time to change underlying price
Units: $/widget/year
Time to change underlying price = ___
Units: year
pressureToChangePrice = EffectOfInventoryOnPrice * EffectOfMarketShareOnPrice
Units: dmnl
EffectOfInventoryOnPrice = EffectOfInventoryOnPrice f(RelativeInventory)
Units: dmnl
EffectOfInventoryOnPrice f = *user defined function*

Units: dmnl
EffectOfMarketShareOnPrice = EffectOfMarketShareOnPrice f(RelativeMarketShare)
Units: dmnl
EffectOfMarketShareOnPrice f = *user defined function*
Units: dmnl

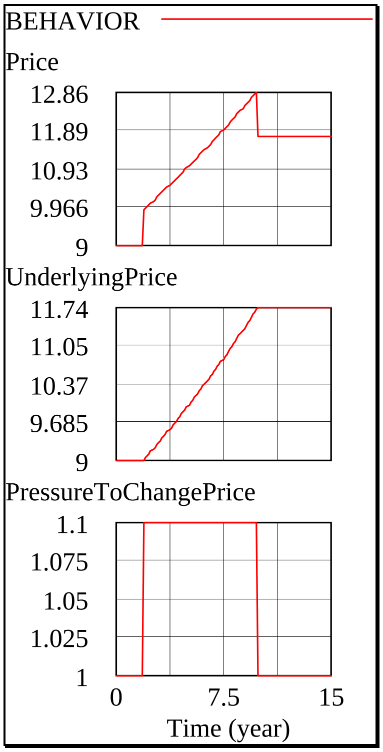
<u>Equations for margin form</u>

"Price." = cost * Margin
Units: $/widget
cost = ___
Units: $/widget
Margin = UnderlyingMargin * pressureToChangeMargin
Units: fraction
UnderlyingMargin = INTEG(ChangeInUnderlyingMargin , ___)
Units: fraction
ChangeInUnderlyingMargin = (Margin - UnderlyingMargin) / TimeToChangeUnderlyingMargin
Units: fraction/year
TimeToChangeUnderlyingMargin = ___
Units: year
pressureToChangeMargin = EffectOfInventoryOnMargin * EffectOfMarketShareOnMargin
Units: dmnl
EffectOfInventoryOnMargin = EffectOfInventoryOnMargin f ("RelativeInventory.")
Units: dmnl
EffectOfInventoryOnMargin f = *user defined function*
Units: dmnl
EffectOfMarketShareOnMargin = EffectOfMarketShareOnMargin f ("RelativeMarketShare.")
Units: dmnl
EffectOfMarketShareOnMargin f = *user defined function*
Units: dmnl

<u>Equations common to both the “price” and the “margin” forms</u>

RelativeInventory = Inventory / TargetInventory
Units: fraction
TargetInventory = ___
Units: widgets
Inventory = ___
Units: widgets
RelativeMarketShare = MarketShare / targetMarketShare
Units: fraction
targetMarketShare = ___
Units: $/widget
MarketShare = ___
Units: $/widget

Description: Usually the pressure to change price will be a function (often of relative inventory) or the product of several functions. Price setters have a sense for a fair or underlying price. Pressures that they face cause them to bump the price above or below the underlying price. After bumping price, the price setter waits. If the response is inadequate, she bumps again. Alternatively, one can view this as a process in which the price setter bumps the price, and then -- if pressures cause her to keep the price high -- begins to incorporate the new price into her conception of a fair or underlying price.



Behavior: If pressure is constant above 1, price and underlying price will rise exponentially. If Pressure then returns to neutral value of one, price will drop to the underlying price.

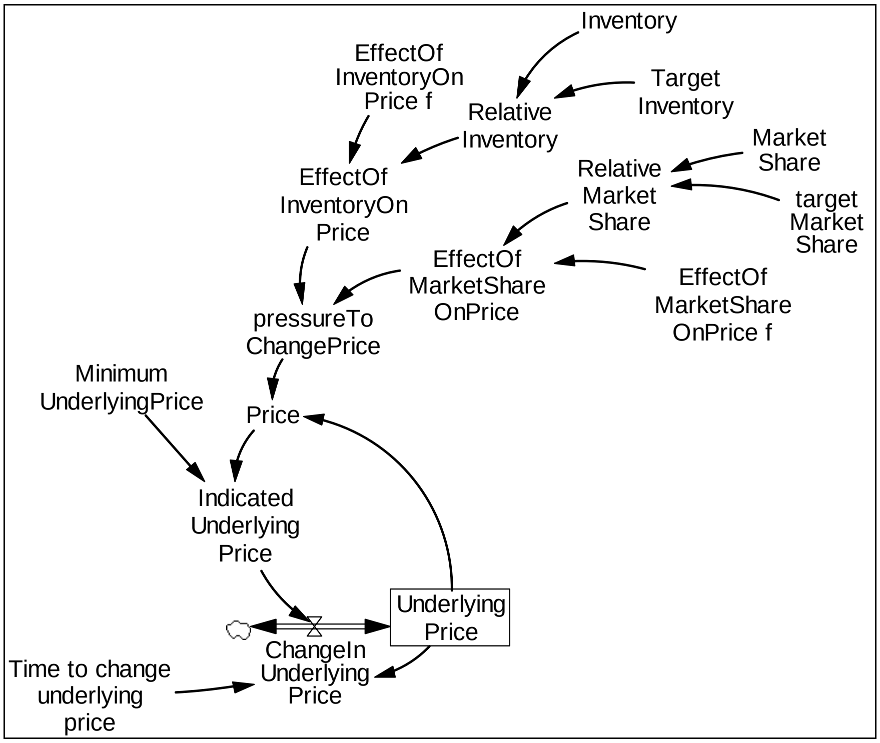
Classic examples: The System Dynamics National Model uses such a formulation to represent interest rates (the price of money).

Caveats: The modeler will need to tune both the time constant and the effects representing pressure. Very aggressive policies can lead price explosions.

Note: If underlying price gets to zero; there will be no further change -- underlying price and price will be stuck at zero. This danger does not arise suddenly, rather in the underlying price is almost zero; the structure will be "almost" stuck. To avoid this, one needs to use a strategy such as that in the Protected Anchor Pricing Molecule.

Technical notes: To represent an aggressive policy use a short time constant and a steep effect.

Protected Sea Anchor Pricing



Immediate parents: Protected sea anchoring and adjustment, Sea anchor pricing
Ultimate parents: Dmnl input to function, Close gap

Used by: None

Problem solved: How to represent pricing when the price can take on a value of (or close to) zero.

Equations:

Price = UnderlyingPrice * pressureToChangePrice
Units: $/widget
UnderlyingPrice = INTEG(ChangeInUnderlyingPrice, ___)
Units: $/widget
ChangeInUnderlyingPrice =
(IndicatedUnderlyingPrice - UnderlyingPrice) /Time to change underlying price
Units: $/widget/year
Time to change underlying price = ___
Units: year
IndicatedUnderlyingPrice = MAX(Price, MinimumUnderlyingPrice)
Units: $/widget
MinimuUnderlyingPrice = ___
Units: $/widget
pressureToChangePrice = EffectOfInventoryOnPrice * EffectOfMarketShareOnPrice
Units: dmnl

```
EffectOfInventoryOnPrice = EffectOfInventoryOnPrice f(RelativeInventory)
        Units: dmnl
EffectOfInventoryOnPrice f = user defined function
        Units: dmnl
EffectOfMarketShareOnPrice = EffectOfMarketShareOnPrice f(RelativeMarketShare)
        Units: dmnl
EffectOfMarketShareOnPrice f = user defined function
        Units: dmnl
RelativeInventory = Inventory / TargetInventory
        Units: fraction
TargetInventory = ___
        Units: widgets
Inventory = ___
        Units: widgets
RelativeMarketShare = MarketShare / targetMarketShare
        Units: fraction
targetMarketShare = ___
        Units: $/widget
MarketShare = ___
        Units: $/widget
```

Description: This molecule adds to the Anchor Pricing Molecule the idea of a minimum underlying price. The minimum underlying price represents what pricers regard as the lowest fair or sustainable price. This might be the cost of the product.

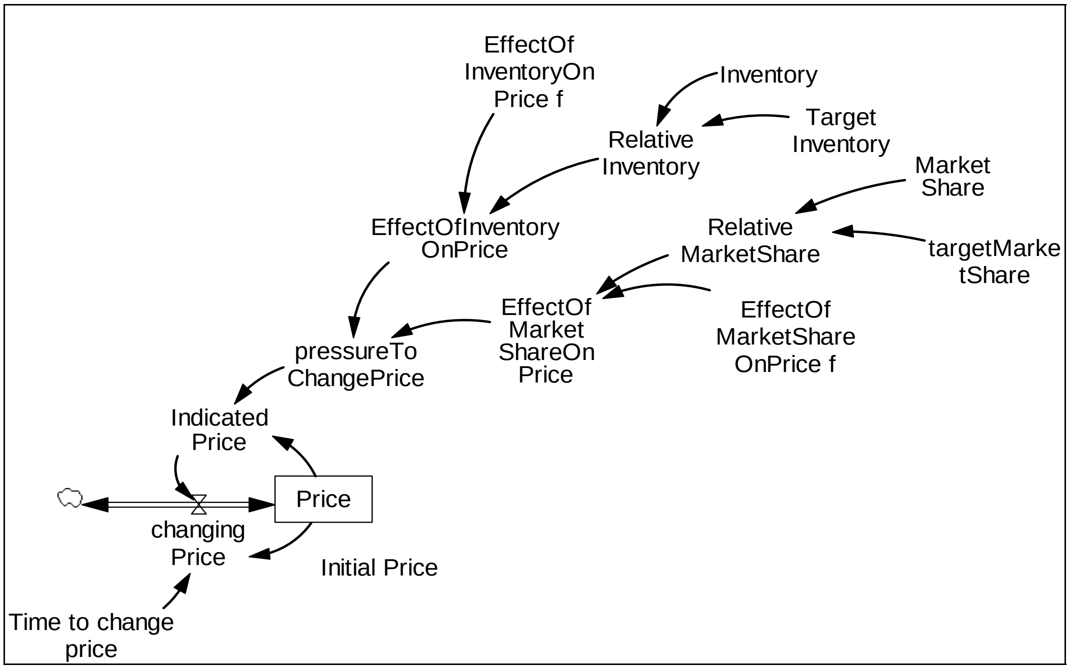
Behavior: Same as Anchor Pricing, but the underlying price will not go below the minimum.

Classic examples: National Model uses this formulation for the interest rate, the price of money

Caveats: See Protected sea anchor and adjustment and Sea anchor pricing

Technical notes: See Protected sea ancho and adjustment and Sea anchor pricing

Smooth Pricing



Immediate parents: Sea anchor pricing
Ultimate parents: Dmnl input to function, Close gap

Used by: None

Problem solved: How to represent price setting behavior where price does not change suddenly.

Equations:

Price = INTEG(changingPrice, InitialPrice)
Units: $/widget
InitialPrice = ___
Units: $/widget
changingPrice =(IndicatedPrice - UnderlyingPrice) /Time to change underlying price
Units: $/widget/year
Time to change underlying price = ___
Units: year
IndicatedPrice = UnderlyingPrice * pressureToChangePrice
Units: $/widget
pressureToChangePrice = EffectOfInventoryOnPrice * EffectOfMarketShareOnPrice
Units: dmnl
EffectOfInventoryOnPrice = EffectOfInventoryOnPrice f(RelativeInventory)
Units: dmnl
EffectOfInventoryOnPrice f = user defined function
Units: dmnl
EffectOfMarketShareOnPrice = EffectOfMarketShareOnPrice f(RelativeMarketShare)

Units: dmnl
EffectOfMarketShareOnPrice f = user defined function
    Units: dmnl
RelativeInventory = Inventory / TargetInventory
    Units: fraction
TargetInventory = ___
    Units: widgets
Inventory = ___
    Units: widgets
RelativeMarketShare = MarketShare / targetMarketShare
    Units: fraction
targetMarketShare = ___
    Units: $/widget
MarketShare = ___
    Units: $/widget

Description: In this version of price setting, the anchor is price itself which smooths to the indicated price.

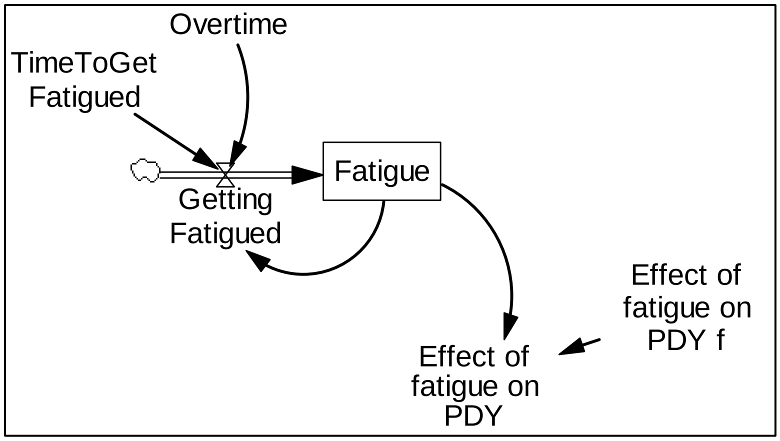
Behavior: Price rises exponentially as long as the pressure to adjust is greater than one. It stops adjusting when pressure returns to 1. Note that price is “sluggish” in that it cannot react immediately to changes in pressure, unlike the case for the otherwise similar Anchor Pricing Molecule.

Classic examples: None

Caveats: At a price of zero, the structure gets “stuck”. Further at a price of almost zero, the structure will almost be stuck.

Technical notes: The speed with which price changes depends on both the functions and on the adjustment time.

Effect of Fatigue



Immediate parents: Smooth (first order), Univariate anchoring and adjustment

Ultimate parents: Close gap, Dmnl input to function

Used by: None

Problem solved: How to represent the effect of fatigue (for example the effect of fatigue on productivity or on quality)

Equations:

```
Effect of fatigue on PDY = Effect of fatigue on PDY f(Fatigue)
        Units: dmnl
Effect of fatigue on PDY f  = user defined function
        Units: dmnl
Fatigue = INTEG(GettingFatigued, 1)
        Units: Fraction
GettingFatigued = (Overtime - Fatigue) / TimeToGetFatigued
        Units: Fraction / Month
TimeToGetFatigued = ___
        Units: Month
Overtime = ____
        Units: Fraction
```

Description: Fatigue is a smooth of overtime. The time to get fatigued is the lag between beginning to work at some overtime level and feeling its full effect on productivity (or quality). A nice feature of this formulation is that fatigue is measured in the same units a overtime. Consequently, in parameterizing the function one asks what the impact on productivity would be of working at each level of overtime for a very long time.

Behavior: Obvious

Classic examples: Used in project models

Caveats: None

Technical notes: This formulation needly solves the problem of (1) coming up with a representation of the abstract idea of fatigue, and (2) represesnting the fact that working hard accumulates slowly over time.

Proportional split

Immediate parents: None
Ultimate parents: None

Used by: Weighted split, Mulidimensional split, Nonlinear split

Problem solved: How to allocate a resource between two or more claims on the resource.

Equations:

```
ResourcesForA = Resources * RelativeStrengthOfA'sClaim
        Units: people
ResourcesForB = Resources * RelativeStrengthOfB'sClaim
        Units: people
ResourcesForC = Resources * RelativeStrengthOfC'sClaim
        Units: people
Resources = ___
        Units: people
RelativeStrengthOfA'sClaim = StrengthOfA'sClaim / TotalClaimStrength
        Units: fraction
RelativeStrengthOfB'sClaim = StrengthOfB'sClaim / TotalClaimStrength
        Units: fraction
RelativeStrengthOfC'sClaim = StrengthOfC'sClaim / TotalClaimStrength
        Units: fraction
TotalClaimStrength = StrengthOfA'sClaim + StrengthOfB'sClaim + StrengthOfC'sClaim
        Units: Widgets
StrengthOfC'sClaim = ___
        Units: Widgets
StrengthOfA'sClaim = ___
        Units: Widgets
StrengthOfB'sClaim = ___
        Units: Widgets
```

Description: Each "claim" on the resource is represented by its strength. The resource is then split up according to the strength of each claim, relative to the total "strength" of all claims.

Behavior:

Classic examples: The decision could involve how to split up a flexible resource among competing kinds of task. If each kind of task is represented as a stock of those tasks (e.g. working on new R&D ideas (or basic research), working on developing those ideas, and working on commercializing the ideas) and if the different kinds of tasks are measured in the same units, then the quantity in each task could represent the claim on the workforce. In this case the total strength of claim would equal the total amount of work waiting to be done. Alternatively, each claim could be the amount of workers that each area in the

R&D chain requests. In this case the total strength of claim would also be the total number of people requested.

Caveats: This formulation will allocate all of the resource even if that means that more resources are allocated to a particular area than are needed. Additional structure and careful thought is required to re-allocate any excesses from one claim to another.

Technical notes: None

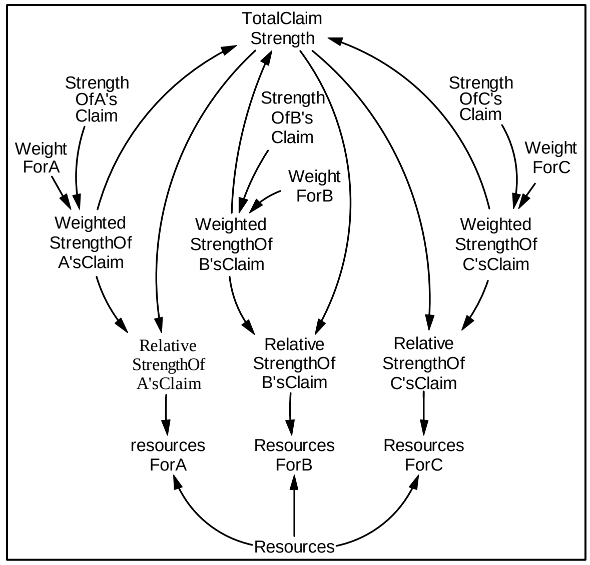
(Continued on next page...)

Weighted Split

Immediate parents: Proportional split
Ultimate parents: Proportional split

Used by: None

Problem solved: How to represent managerial preferences (or bias) in an allocation decision



Equations:

resourcesForA = Resources * RelativeStrengthOfA'sClaim
Units: people
ResourcesForB = Resources * RelativeStrengthOfB'sClaim
Units: people
ResourcesForC = Resources * RelativeStrengthOfC'sClaim
Units: people
Resources = ___
Units: people
RelativeStrengthOfA'sClaim = WeightedStrengthOfA'sClaim / TotalClaimStrength
Units: fraction
RelativeStrengthOfB'sClaim = WeightedStrengthOfB'sClaim / TotalClaimStrength
Units: fraction
RelativeStrengthOfC'sClaim = WeightedStrengthOfC'sClaim / TotalClaimStrength
Units: fraction
TotalClaimStrength = WeightedStrengthOfA'sClaim + WeightedStrengthOfB'sClaim + WeightedStrengthOfC'sClaim
Units: Widgets
WeightedStrengthOfA'sClaim = StrengthOfA'sClaim * WeightForA
Units: Widgets
WeightedStrengthOfB'sClaim = StrengthOfB'sClaim * WeightForB
Units: Widgtets
WeightedStrengthOfC'sClaim = StrengthOfC'sClaim * WeightForC
Units: Widgets
StrengthOfA'sClaim = ___
Units: Widgets
StrengthOfB'sClaim = ___
Units: Widgets

```
StrengthOfC'sClaim = ___
        Units: Widgets
WeightForA = ___2
        Units: dmnl
WeightForB = ___
        Units: dmnl
WeightForC = ___
        Units: dmnl
```

Description: This molecule adds to the proportional split a "managerial weight". The weight can represent managerial preferences (conscious or unconscious, logical or illogical) for the allocation of resources. The weights can be constants or can respond to other conditions in the model.

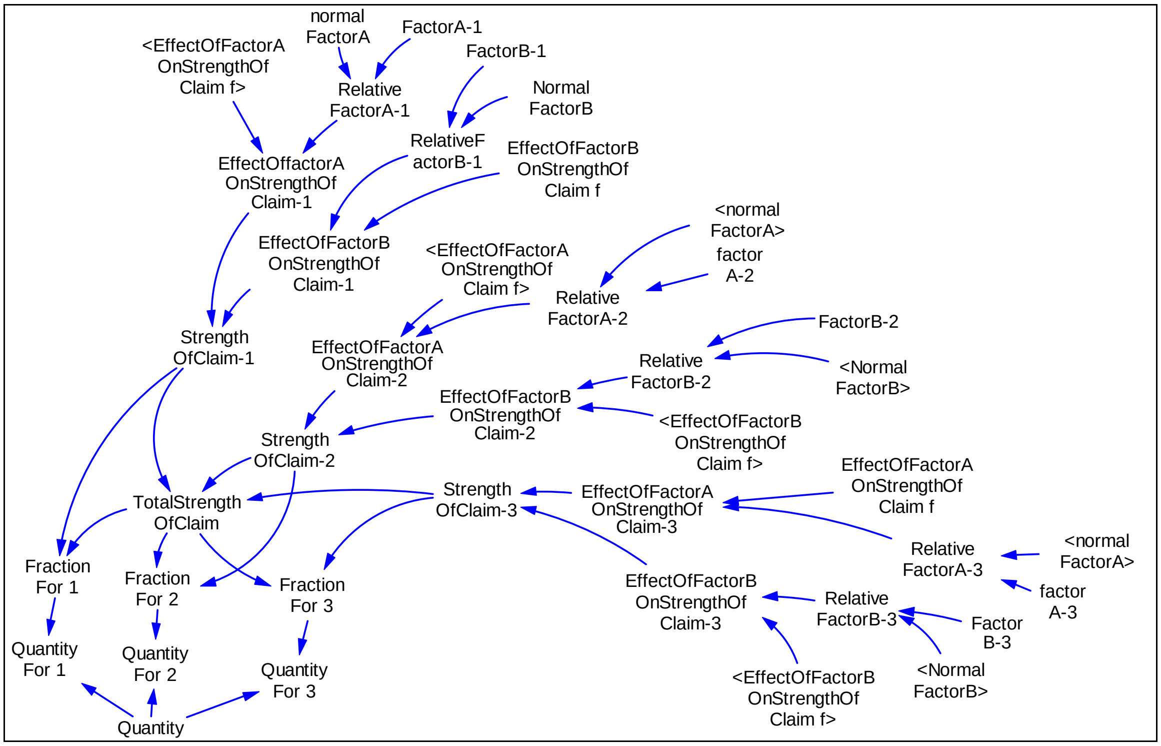
Behavior: No stocks, so no behavior

Classic examples: For example, if the allocation decision involves dividing a flexible workforce amongh different tasks in an R&D effort, it may be that managers will weight commercialization more heavily as unit-sales decline.

Caveats: As in the case of proportional allocation, this structure allocates all of the resource even if that means over-allocating to one or more of the claims.

Technical notes: None

Multidimensional Split



Immediate parents: Multivariate anchoring and adjustment, Proportional split
Ultimate parents: Dmnl input to function, Proportional split

Used by: Market share

Problem solved: How to allocate a resource when the strength of each claim is determined by a number of factors.

Equations:

QuantityFor 1 = Quantity * FractionFor 1
Units: stuff
QuantityFor 2 = Quantity * FractionFor 2
Units: stuff
QuantityFor 3 = Quantity * FractionFor 3
Units: stuff
Quantity = ____
Units: stuff
FractionFor 1 = "StrengthOfClaim-1" / TotalStrengthOfClaim
Units: fraction
FractionFor 2 = "StrengthOfClaim-2" / TotalStrengthOfClaim
Units: fraction
FractionFor 3 = "StrengthOfClaim-3" / TotalStrengthOfClaim
Units: fraction
TotalStrengthOfClaim =

```
        "StrengthOfClaim-1" + "StrengthOfClaim-2" + "StrengthOfClaim-3"
    Units: dmnl
"StrengthOfClaim-1" =
        "EffectOffactorAOnStrengthOfClaim-1" * “EffectOfFactorBOnStrengthOfClaim-1"
    Units: dmnl
"StrengthOfClaim-2" =
        "EffectOfFactorAOnStrengthOfClaim-2" * "EffectOfFactorBOnStrengthOfClaim-2"
    Units: dmnl
"StrengthOfClaim-3" =
        "EffectOfFactorAOnStrengthOfClaim-3" * "EffectOfFactorBOnStrengthOfClaim-3"
    Units: dmnl
"EffectOffactorAOnStrengthOfClaim-1" =
        EffectOfFactorAOnStrengthOfClaim f ( "RelativeFactorA-1" )
    Units: dmnl
EffectOfFactorAOnStrengthOfClaim f = user defined function
    Units: dmnl
"RelativeFactorA-1" = "FactorA-1" / normalFactorA
    Units: fraction
normalFactorA = ___
    Units: FactorAUnits
"FactorA-1" = ___
    Units: FactorAUnits
"EffectOfFactorBOnStrengthOfClaim-1" =
        EffectOfFactorBOnStrengthOfClaim f ( "RelativeFactorB-1")
    Units: dmnl
"RelativeFactorB-1" = "FactorB-1" / NormalFactorB
    Units: fraction
NormalFactorB = ___
    Units: FactorBUnits
"FactorB-1" = ___
    Units: FactorBUnits
EffectOfFactorBOnStrengthOfClaim f = user defnined function
    Units: dmnl
"EffectOfFactorAOnStrengthOfClaim-2" =
        EffectOfFactorAOnStrengthOfClaim f ( "RelativeFactorA-2")
    Units: dmnl
"RelativeFactorA-2" = "factorA-2" / normalFactorA
    Units: fraction
"factorA-2" = ___
    Units: FactorAUnits
"EffectOfFactorBOnStrengthOfClaim-2" =
        EffectOfFactorBOnStrengthOfClaim f ( "RelativeFactorB-2")
    Units: dmnl
"RelativeFactorB-2" = "FactorB-2" / NormalFactorB
    Units: fraction
"FactorB-2" = ___
    Units: FactorBUnits
```

```
"EffectOfFactorAOnStrengthOfClaim-3" =
            EffectOfFactorAOnStrengthOfClaim f ( "RelativeFactorA-3")
        Units: dmnl
"RelativeFactorA-3" = "factorA-3" / normalFactorA
        Units: fraction
"factorA-3" = ___
        Units: FactorAUnits
"EffectOfFactorBOnStrengthOfClaim-3" =
            EffectOfFactorBOnStrengthOfClaim f ( "RelativeFactorB-3")
        Units: dmnl
"RelativeFactorB-3" = "FactorB-3" / NormalFactorB
        Units: fraction
"FactorB-3" = ___
        Units: FactorBUnits
```

Description: This molecule adds to the proportional split molecule a definition for claims based on the multivariate anchoring and adjustment molecule. The resource is split proproationally between the claims, but each claim is a nonlinear function of a one (and usually two) or more factors.

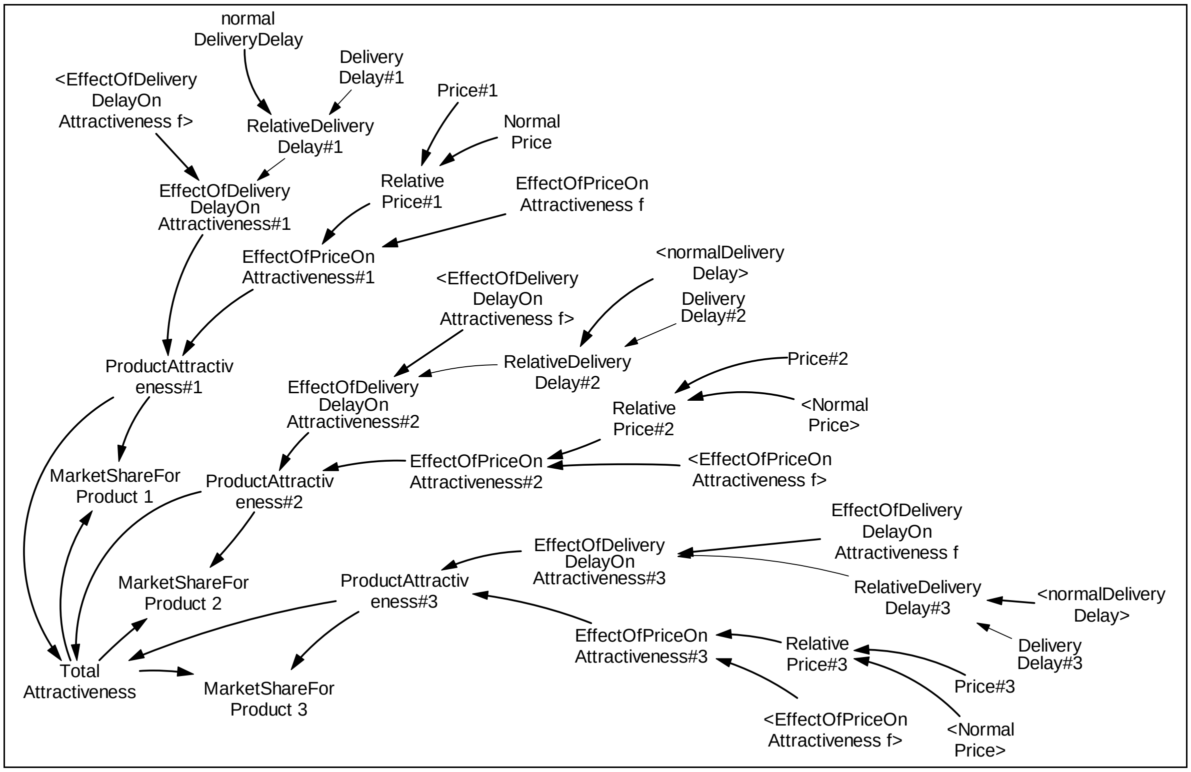
Behavior: No stocks, so no dynamics.

Classic examples: Market share

Caveats: The resource is allocated completely, so one needs to be careful of over-allocating.

Technical notes: None

Market Share



Immediate parents: Multidimensional split
Ultimate parents: Dmnl input to function, Proportional split

Used by: None

Problem solved: How to calculate market shares based on product attractiveness

Equations:

```
MarketShareForProduct 1 = "ProductAttractiveness#1" / TotalAttractiveness
        Units: fraction
MarketShareForProduct 2 = "ProductAttractiveness#2" / TotalAttractiveness
        Units: fraction
MarketShareForProduct 3 = "ProductAttractiveness#3" / TotalAttractiveness
        Units: fraction
TotalAttractiveness =
  "ProductAttractiveness#1" + "ProductAttractiveness#2" + "ProductAttractiveness#3"
        Units: dmnl
"ProductAttractiveness#1" =
  "EffectOfDeliveryDelayOnAttractiveness#1" * "EffectOfPriceOnAttractiveness#1"
        Units: dmnl
"ProductAttractiveness#2" =
  "EffectOfDeliveryDelayOnAttractiveness#2" * "EffectOfPriceOnAttractiveness#2"
```

Units: dmnl
"ProductAttractiveness#3" =
"EffectOfDeliveryDelayOnAttractiveness#3" * "EffectOfPriceOnAttractiveness#3"
Units: dmnl
"EffectOfDeliveryDelayOnAttractiveness#1" =
EffectOfDeliveryDelayOnAttractiveness f ("RelativeDeliveryDelay#1")
Units: dmnl
"EffectOfDeliveryDelayOnAttractiveness#2" =
EffectOfDeliveryDelayOnAttractiveness f ("RelativeDeliveryDelay#2")
Units: dmnl
"EffectOfDeliveryDelayOnAttractiveness#3" =
EffectOfDeliveryDelayOnAttractiveness f ("RelativeDeliveryDelay#3")
Units: dmnl
EffectOfDeliveryDelayOnAttractiveness f = *user defined function*
Units: dmnl
""RelativeDeliveryDelay#1" = "DeliveryDelay#1" / normalDeliveryDelay
Units: fraction
"RelativeDeliveryDelay#2" = "DeliveryDelay#2" / normalDeliveryDelay
Units: fraction
"RelativeDeliveryDelay#3" = normalDeliveryDelay / "DeliveryDelay#3"
Units: fraction
normalDeliveryDelay = ___
Units: weeks
DeliveryDelay#1" = ___
Units: weeks
"DeliveryDelay#2" = ___
Units: weeks
"DeliveryDelay#3" = ___
Units: weeks
"EffectOfPriceOnAttractiveness#1" = EffectOfPriceOnAttractiveness f ("RelativePrice#1")
Units: dmnl
"EffectOfPriceOnAttractiveness#2" = EffectOfPriceOnAttractiveness f ("RelativePrice#2")
Units: dmnl
EffectOfPriceOnAttractiveness#3" = EffectOfPriceOnAttractiveness f ("RelativePrice#3")
Units: dmnl
EffectOfPriceOnAttractiveness f = user defined function
Units: dmnl
"RelativePrice#1" = "Price#1" / NormalPrice
Units: fraction
"RelativePrice#2" = "Price#2" / NormalPrice
Units: fraction
"RelativePrice#3" = "Price#3" / NormalPrice
Units: fraction
NormalPrice = ___
Units: $/widget
"Price#1" = ___
Units: $/widget

```
"Price#2" = ___
          Units: $/widget
"Price#3" = ___
          Units: $/widget
```

Description: Market share for each product is attractiveness relative to the "total" amount of attractiveness in the market. Attractiveness is formulated as a normal attractiveness (or perhaps a maximum attractiveness) multiplied by a series of effects. The Effects shown in the diagram and the equations are illustrative only. A key aspect of this formulation is that attractiveness is in absolute terms, not relative to a competitor: For any given factor, each relative factors the *same* constant (or variable) in the denominator in the denominator. The attractiveness of competitors enters only in the calculating the Market Share.

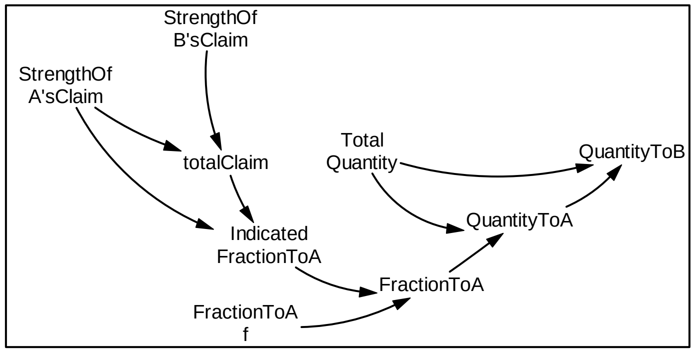
Behavior: No levels, so no endogenous dynamics.

Classic examples: This formulation is very common in models of competitive dynamics

Caveats: The quantity TotalAttractiveness has no obvious real-world counterpart.

Technical notes: The reason to define the relative quantities (e.g. relative price) in terms of an absolute (in fact usually a constant) quantity (e.g. accepatable price) i9s to permit saturation effects. For example if the price of a Ford automobile were two cents and the price from General Motors competitor were one cent, consumers probably wouldn't distinguish between the two – the price of either one is "completely" inexpensive. That is, when prices are this low it doesn't matter that Ford's price is twice GM's. On the other hand if the price of a Ford was $20,000 and the price of a GM was $10,000, this would make a big difference. Hence, we want to normalize prices by an absolute number, run the result through a table function and only then compare attractiveness.

Nonlinear split



Immediate parents: , Univariate anchoring and adjustment, Proportional split
Ultimate parents: Proportional split, Dmnl input to funciton

Used by: Weighted average, Ceiling, Floor

Problem solved: Allocate a quantity between two parties, each with a claim on it.

Equations:

QuantityToA = TotalQuantity * FractionToA
 Units: people
QuantityToB = TotalQuantity - QuantityToA
 Units: people
TotalQuantity = ___
 Units: people
FractionToA = FractionToA f (IndicatedFractionToA)
 Units: dmnl
FractionToA f = *user defined function*
 Units: **undefined**
IndicatedFractionToA = StrengthOfA'sClaim / totalClaim
 Units: fraction
StrengthOfA'sClaim = ___
 Units: widgets/week
totalClaim = StrengthOfA'sClaim + StrengthOfB'sClaim
 Units: widgets/week
StrengthOfB'sClaim = ___
 Units: widgets/week

Description: This formulation uses the an indicated split (to one of the claims) which is based on the proportional split molecule. However this indicated split is then run through a lookup function in order to capture nonlinear effects such as the idea that each claim must get a certain minimum fraction.

Behavior: No stocks so no behavior

Classic examples:

Caveats: All of the quantity is allocated, so in a situation where each “claim” is a request for the quantity, its possible to allocate more than is requested. Avoiding this problem takes careful thought and modeling.

Technical notes: None

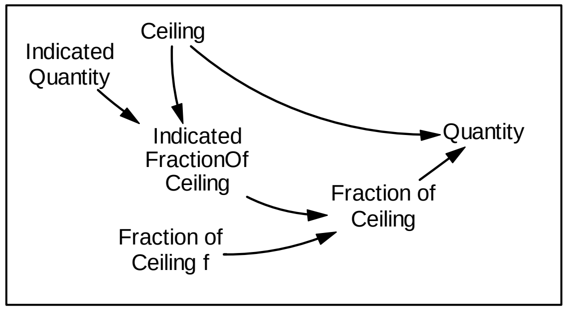
Ceiling

Also known as **Soft Min**

Immediate parents: Nonlinear split
Ultimate parents: Dmnl input to function, Proportional split

Used by: Capacity utilization, Level protected by flow

Problem solved: How to represent a situation where a quantity can approach, but can exceed, a ceiling value



Equations:

Quantity = Ceiling * Fraction of Ceiling
Units: Output units
Ceiling = ___
Units: Output units
Fraction of Ceiling = Fraction of Ceiling f (IndicatedFractionOfCeiling)
Units: dmnl
IndicatedFractionOfCeiling = Indicated Quantity / Ceiling
Units: fraction
Indicated Quantity = ___
Units: Output units
Fraction of Ceiling f = (See notes under technical)
Units: dmnl

Description: This formulation creates a ceiling which is approached gradually. The molecule is basically a nonlinear split where the "other half" is not shown. Implicitly, the "other half" is the part "unused portion" of the ceiling.

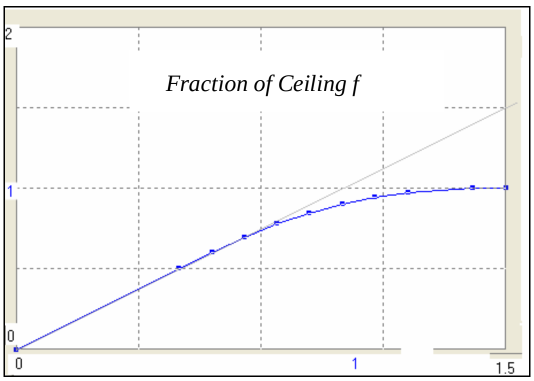
Behavior: No levels so no endogenous behavior.

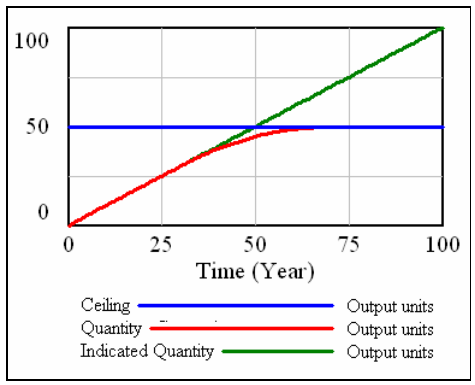
Classic examples: Say we have a labor force which can produce an indicated quantity. We also have a fixed amount of machinery. The output that the machinery can potentially produce is the ceiling. As we add more labor, indicated output increases; until it is constrained by machinery (the ceiling). The constraint is not suddenly felt the instant IndicatedOutputFromLabor = CeilingOutputFromMachinery, instead the machinery constraint begins to be felt before the ceiling is reached. Why? There are many kinds of machines. As indicated output approaches the ceiling, there is an increasing likelihood that the particular machine that some person needs to operate is already taken, even though there are still other machines (not the right ones, though) that are idle

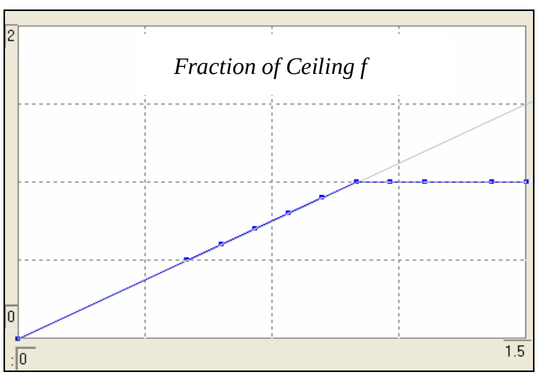
Caveats: This formulation can make it difficult to calculate an equilibrium for a model, unless the function goes through (1,1) or the ceiling the equilibrium is below the ceiling. See description.

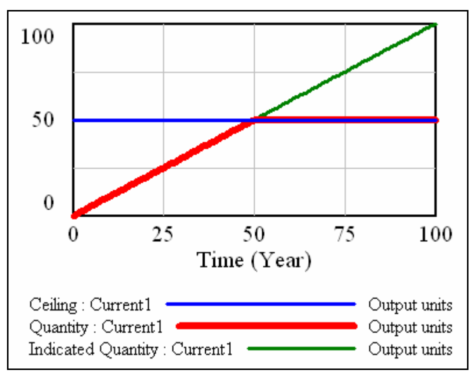
Technical notes: This formulation is a continuous version of the discrete MIN function. Unlike the MIN function -- where the output quantity is *either* the indicated quantity or the *ceiling*, whichever is less – in this formulation the output does not suddenly equal the ceiling, rather there is a gradual approach. Depending on how the *Fraction of Ceiling f* is parameterized, the ceiling can be reached either before or after the IndicatedQuantity equals the ceiling. (see technical notes). It is also possible to let the Quantity rise above the ceiling.

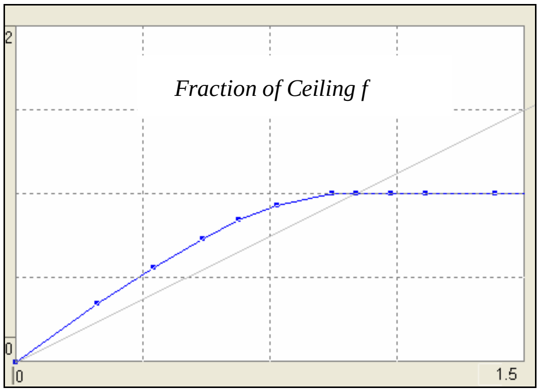
The following shows the behavior of the Quantity for various shapes of the function *Fraction of Ceiling f.* The shape of the first function gives the behavior described in classic examples, above. The shape of the middle function yields behavior that is identical to the discrete MIN function. The shape of the third function might be appropriate in a situation where the indicated quantity represents indicated output and the ceiling represents fixed capacity in a homogeneous-machine situation. When indicated output falls, managers may feel pressured to produce above indicated output in order to use as much of the capacity as possible.

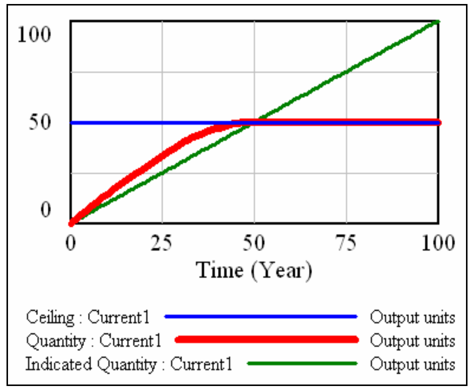









2
Fraction of Ceiling f
0
0
1.5

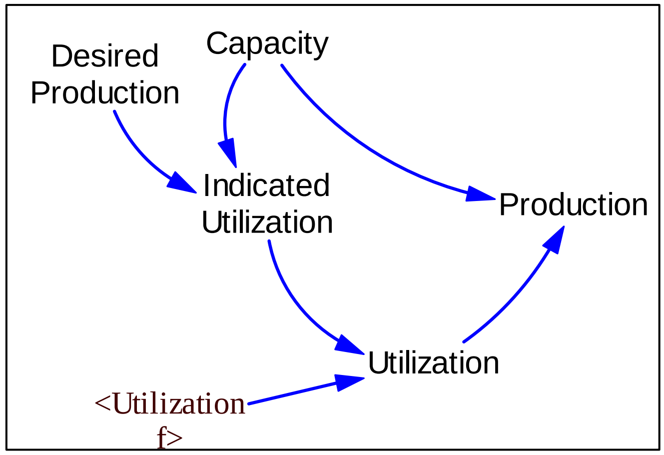

100
50
0
0
25
50
75
100
Time (Year)
Ceiling : Current1 Output units
Quantity : Current1 Output units
Indicated Quantity : Current1 Output units

Capacity Utilization

Immediate parents: Ceiling
Ultimate parents: Dmnl input to function, Proportional split

Used by: None

Problem solved: How to determine production when desired production can exceed capacity.



Equations:

```
Production = Capacity * Utilization
        Units: Widgets/Week
Capacity = ___
        Units: Widgets/Week
Utilization = Utilization f ( IndicatedUtilization )
        Units: fraction
ndicatedUtilization = DesiredProduction / Capacity
        Units: fraction
DesiredProduction = ___
        Units: Widgets/Week
Utilization f ( ) = [User defined function]
        Units: dmnl
```

Description: *Production* is determined by the fraction of capacity actually used (i.e. *utilization).* As *desired production* increases, *utilization* increases, but only until the capacity is maxed out. Often, modelers allow utilization to go above 1, representing a situation where output can exceed “rated” capacity through skipping routine maintenance shut downs, eliminating the use of the facilities for testing, or other measures.

Behavior: no stocks, so no dynamics.

Classic examples: Common

Caveats: If the function does not go through the point (1,1) calculating an analytical equilibrium for the model will be a bit more difficult.

Technical notes: none

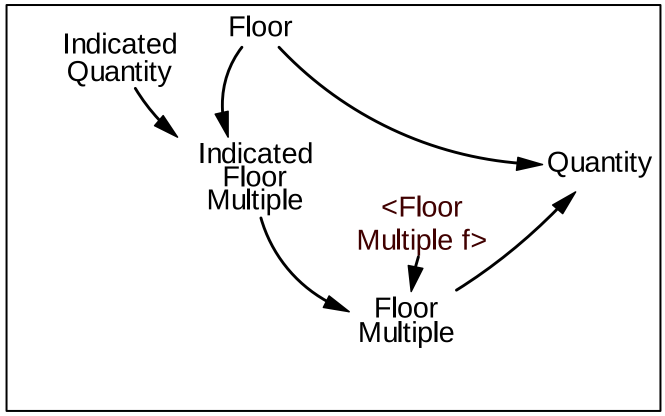
Floor

Also known as **SoftMax**

Immediate parents: Univariate anchoring and adjustment
Ultimate parents: Dmnl input to function

Used by: None

Problem solved: How to represent a variable that cannot decline lower than a certain point.



Equations:

Quantity = Floor * Floor Multiple
Units: Output units
Floor = ___
Units: Output units
Floor Multiple = Floor Multiple f (Indicated Floor Multiple)
Units: dmnl
Floor Multiple f = see technical notes
Units: dmnl
Indicated Floor Multiple = Indicated Quantity / Floor
Units: dimensionless
Indicated Quantity = ___
Units: Output units

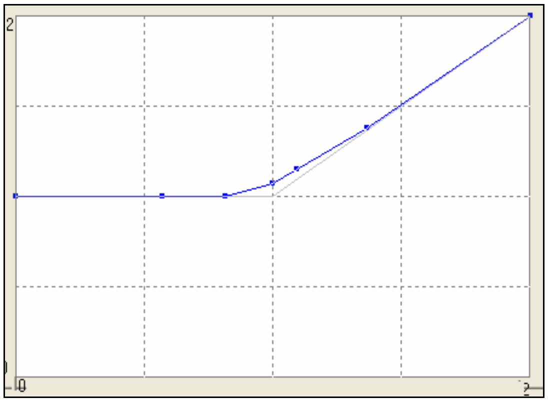
Description: This formulation is a continuous version of the discrete MAX function. Unlike the MAX function -- where the output quantity is *either* the indicated quantity or the *ceiling*, whichever is *greater* – in this formulation the output does not suddenly equal the floor, rather there is a gradual approach. Depending on how the *Floor Multiple f* is parameterized, the floor can be reached either before or after the IndicatedQuantity equals the floor. (see technical notes). It is also possible to let the Quantity rise above the ceiling.

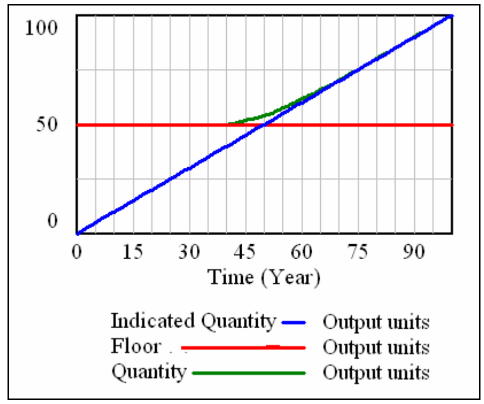
Behavior: No levels so no endogenous behavior.

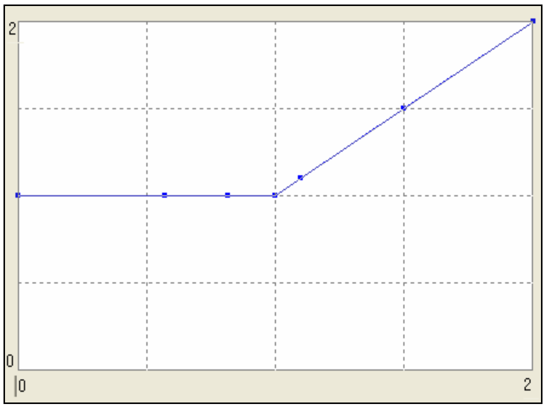
Classic examples: This formulation formed is much rarer than its counterpart, the Ceiling.

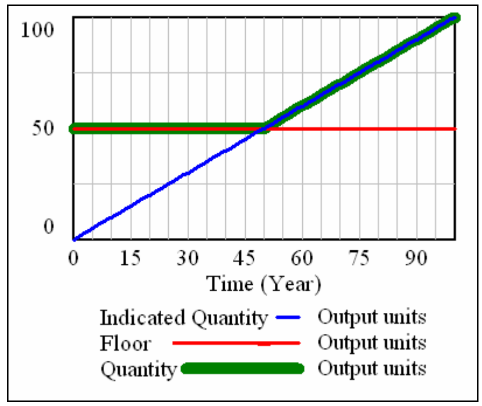
Caveats: Make sure that the table function rises high enough to cover the possible range of the *indicated floor multiple*.

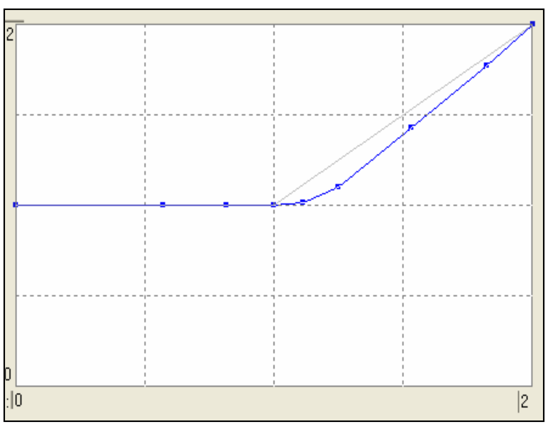
Technical notes: The following shows the behavior of the Quantity for various shapes of the function *Floor Multiple f*. The shape of the middle function yields behavior that is identical to the discrete discrete MAX function.

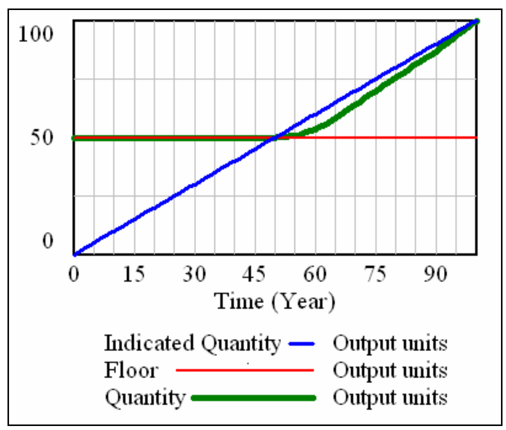

2
0
2


100
50
0
0 15 30 45 60 75 90
Time (Year)
Indicated Quantity Output units
Floor Output units
Quantity Output units


2
0
0
2


100
50
0
0 15 30 45 60 75 90
Time (Year)
Indicated Quantity Output units
Floor Output units
Quantity Output units


2
0
0
2

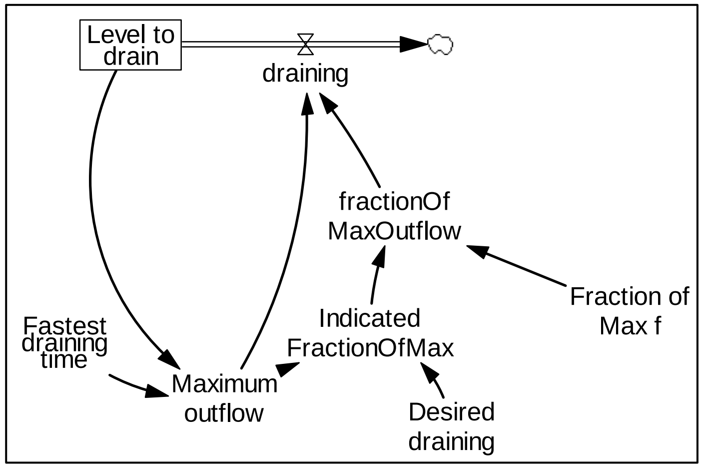

100
50
0
0 15 30 45 60 75 90
Time (Year)
Indicated Quantity Output units
Floor Output units
Quantity Output units

Level Protected by Flow

Immediate parents: Ceiling, Go to zero
Ultimate parents: Dmnl input to function, Go to zero, Proportional split

Used by: BacklogShipping Protected By Flow

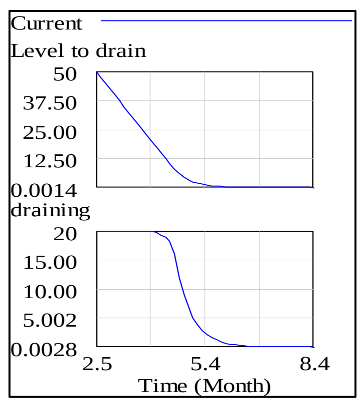
Problem solved: How to ensure that a stock does not go negative



Equations:

draining = Maximum outflow * fractionOfMaxOutflow
 Units: Widgets/Month
Maximum outflow = Level to drain / Fastest draining time
 Units: Widgets/Month
Fastest draining time = ___
 Units: Month
Level to drain = INTEG(- draining , ___)
 Units: Widgets
fractionOfMaxOutflow = Fraction of Max f (IndicatedFractionOfMax)
 Units: dmnl
Fraction of Max f = see technical notes
 Units: dmnl
IndicatedFractionOfMax = xidz (Desired draining , Maximum outflow , 10)
 Units: dmnl
Desired draining = ___
 Units: Widgets/Month

Description: The actual outflow is approximately the minimum of desired draining and the maximum possible outflow rate, however the actual draining is between the desired and maximum. This formulation is considered more desirable than an IF-THEN-ELSE statement both because it is less subject to integration error and, even more importantly, because it is appropriate for a stock that represents an aggregation of non-identical items - like a finished goods inventory containing many different models or products.

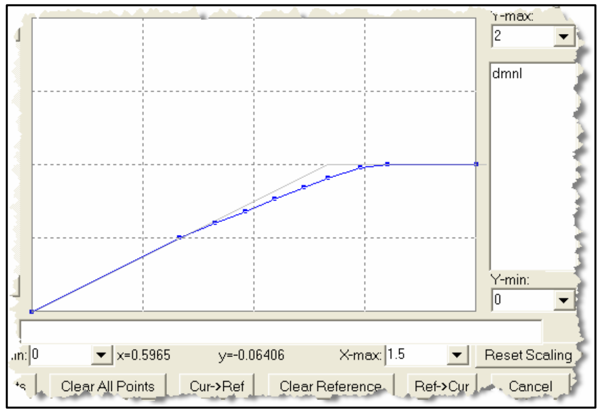


Behavior: The level will not go below zero.

Classic examples: Shipping out of an inventory. The inventory must not go negative.

Caveats: none

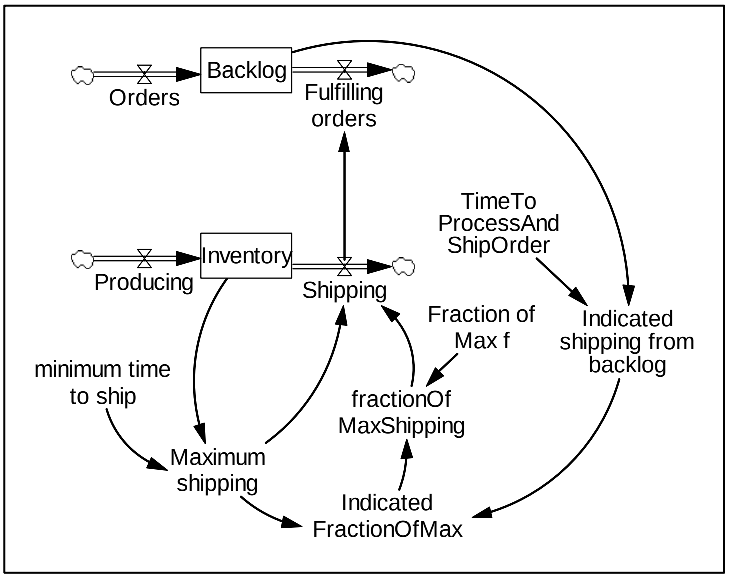
Technical notes: The proper function is usually one that causes the actual draining to drop below desired before the point at which *desired draining = maximum outflow*.



Backlog Shipping Protected by Flow

Immediate parents: Level protected by flow
Ultimate parents: Dmnl input to function, Go to zero, Proportional split

Problem solved: How to coordinate the shipping of product with the filling of backlogged orders, taking into account that product cannot be shipped without an order and an order cannot be filled if there is no inventory



Equations:

Shipping = Maximum shipping * fractionOfMaxShipping
Units: Widgets/Month
Maximum shipping = Inventory / minimum time to ship
Units: Widgets/Month
minimum time to ship = ___
Units: Month
Inventory = INTEG(Producing - Shipping , ___)
Units: Widgets
Producing = ___
Units: Widgets/Month
fractionOfMaxShipping = Fraction of Max f (IndicatedFractionOfMax)
Units: dmnl
Fraction of Max f = user defined function
Units: dmnl
IndicatedFractionOfMax = Indicated shipping from backlog , Maximum shipping
Units: dmnl
Indicated shipping from backlog = Backlog / TimeToProcessAndShipOrder
Units: Widgets/Month
TimeToProcessAndShipOrder = ___
Units: Month
Backlog = INTEG(Orders - Fulfilling orders , Orders * TimeToProcessAndShipOrder)
Units: Widgets
Fulfilling orders = Shipping
Units: Widgets/Month
Orders = ___
Units: Widgets/Month

Description: In this formulation, desired shipping is intended to drain inventory formulated as a protected level. Actual shipping is approximately the minimum of desired and the maximum shipping rate.

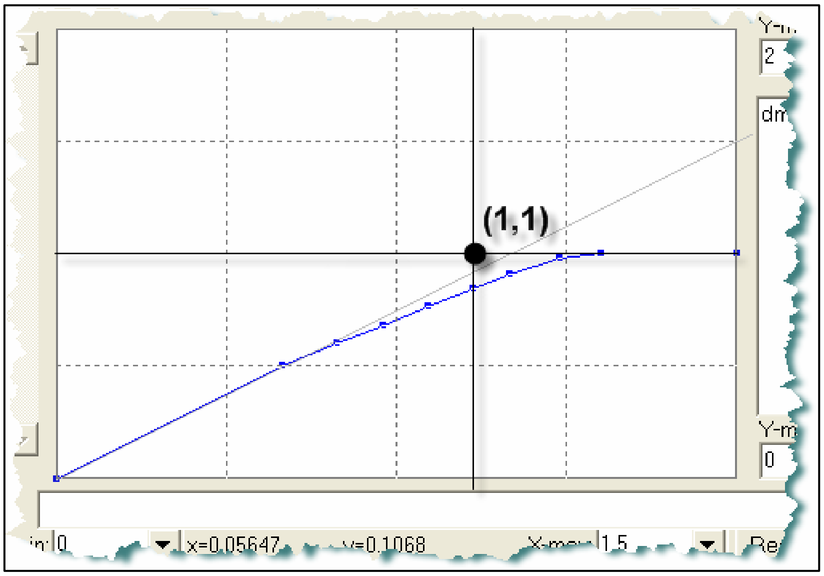
Behavior: The stock will not go below zero.

Classic examples: This formulation (or one like it) is common in manufacturing models

Caveats: The minimum time to ship is usually a small number. Make sure that dt is set appropriately.

Technical notes: The maximum shipping rate should probably represent the "ideal" maximum the fastest shipping that can be achieved if the orders correspond *exactly* to what is left in stock. Because there is some probability distribution around what will be ordered, on average orders will not exactly match what remains in stock, and hence actual shipments fall below desired shipments of orders exactly matching what remains in stock, , however actual shipping drops below desired shipments except when desired shipments are a relatively low fraction of maximum. This means that the function *Fraction of Max f*() lies below (1,1). A function that goes above the 44 degree line as is approaches 0,0) would represent a situation in which a company ships faster than normal when it can.A closely related alternative to this formulation is the Inventory Backlog Shipping Protected by Level molecule

Fraction of Maximum

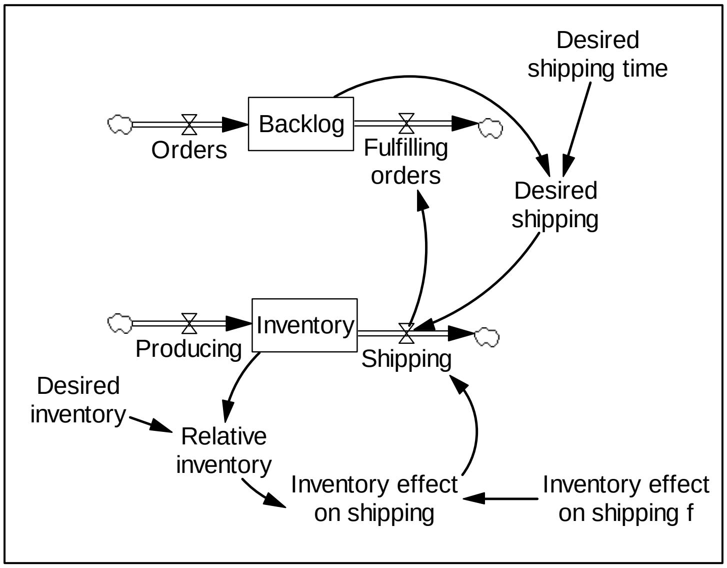


Backlog Shipping Protected By Level

Immediate parents: Go to zero, Level protected by level
Ultimate parents: Go to zero, Dmnl input to function

Used by: None

Problem solved: How to coordinate the shipping of product with the filling of backlogged orders, taking into account that product cannot be shipped without an order and an order cannot be filled if there is no inventory



Equations:

Backlog = INTEG(Orders - Fulfilling orders , Orders * Desired shipping time)
Units: Widgets
Desired inventory = ___
Units: Widgets
Desired shipping = Backlog / Desired shipping time
Units: Widgets/Month
Desired shipping time = ___
Units: Month
Fulfilling orders = Shipping
Units: Widgets/Month
Inventory = INTEG(Producing - Shipping , Desired inventory)
Units: Widgets
Inventory effect on shipping = Inventory effect on shipping f (Relative inventory)
Units: dmnl
Inventory effect on shipping f = user defined function
Units: dmnl
Orders = ___
Units: Widgets/Month
Producing = ___
Units: Widgets/Month
Relative inventory = Inventory / Desired inventory
Units: dmnl
Shipping = Desired shipping * Inventory effect on shipping
Units: Widgets/Month

Description: In this formulation, desired shipping is intended to drain inventory formulated as a protected level. Actual shipping however also obeys the physical law that we can't ship what we don't have. The backlog is depleted by actual shipping.

Behavior: Obvious

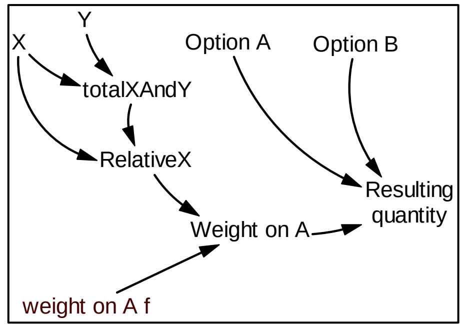
Classic examples: This formulation is common in manufacturing models

Caveats: None

Technical notes: The Inventory Effect on Shipping represents the impact of stockouts as the inventory gets lower and lower. A closely related alternative to this formulation is the Inventory Backlog and Shipping Protected by Flow molecule.

(Continued on next page...)

Weighted Average



Also known as **Soft If Then**
Parents: None

Used by: Activity split

Problem solved: How to represent a blend of two "pure" choices.

Equations:

Resulting quantity = WeightOnA * OptionA + (1-WeightOnA) * OptionB
    Units: people
OptionA = ___
    Units: people
Option B = ___
    Units: people
WeightOnA = weight on A f(RelativeX)
    Units: dmnl
weightOnA f = *user defined function*
    Units: dmnl
RelativeX = X / totalXandY
    Units: fraction
totalXAndY= X + Y
    Units: widgets/week
X = ___
    Units: widgets/week
Y = ___
    Units: widgets/week

Description: As X increases relative to Y, the blend favors A relative to B.

Behavior: No internal dynamics because no levels.

Classic examples:

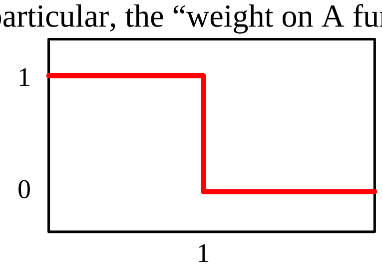
Caveats: None

Technical notes: The structure is a generalization of the common if-then logic in computer programming. For example the statement

IF X < Y THEN A ELSE B

is represented by a one weighting function. In particular, the "weight on A function" for this example would be

$$f(X/Y) = \boxed{\{} \begin{matrix} 1 \text{ when } X/Y<1 \\ 0 \text{ when } X/Y \geq 1 \end{matrix}$$

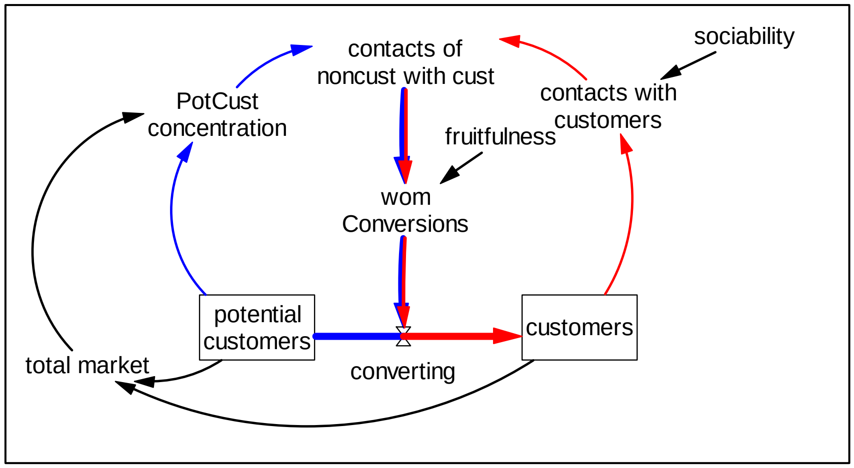


Diffusion

Immediate parents:
Proportional split,
Conversion
Ultimate parents:
Proportional split,
Bathtub

Used by: None

Problem solved:
How to represent growth by work of mouth



Equations:

customers = INTEG(converting, ___)
Units: people
converting = wom Conversions
Units: people/Year
wom Conversions = contacts of noncust with cust*fruitfulness
Units: people/Year
fruitfulness = ___
Units: people/contact
contacts of noncust with cust = contacts with customers*PotCust concentration
Units: contacts/Year
contacts with customers = customers*sociability
Units: contacts/Year
sociability = ___
Units: contacts/person/Year
PotCust concentration = potential customers/total market
Units: dmnl
total market = customers+potential customers
Units: people
potential customers = INTEG(-converting, ___)
Units: people

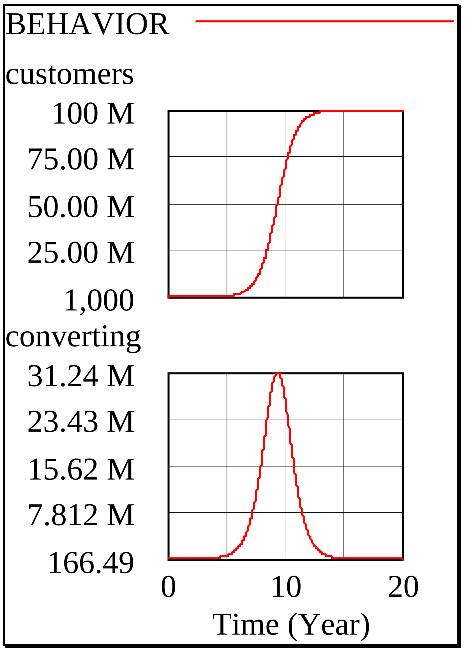
Description: Non Customers become customers through a process that involves customers having contacts with people, some fraction of which are non-customers. Some proportion of contacts that customers have with non-customers results in conversion of non-customers to customers.

Behavior: Produces S-shaped growth in customers.

Classic examples: This is the structure that underlies B&B Enterprises.

Caveats: If customers are initialized to zero this structure will not move because there will be no customers to have contacts.

Technical notes: This structure produces logistic growth. The Bass diffusion model includes an addition flow, formulated as a decay from *potential customers* into *customers*. This additional flow is often interpreted as being an effect of advertising. With this additional flow, the initial value of *customers* can be set to zero.



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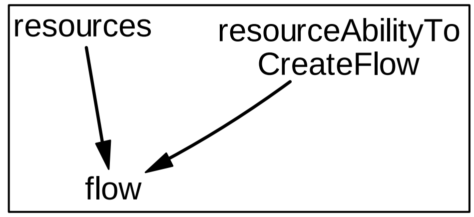
Action From Resource

Immediate parents: None
Ultimate parents: None

Used by: Producing, Resource from flow, Ability from flow, Financial flow from resource



Problem solved: How to create an action (a flow) from a resource or aggregate of resources.

Equations:

```
flow = resources * resourceAbilityToCreateFlow
        Units: gallons/Month
resourceAbilityToCreateFlow = ___
        Units: gallons/(Month*resource)
resources = ___
        Units: resources
```

Description: The action (flow) is created by multiplying a resource by its ability to create an action (i.e. its productivity). Often the activity will be conceptualized as a flow, as shown in the structure above.

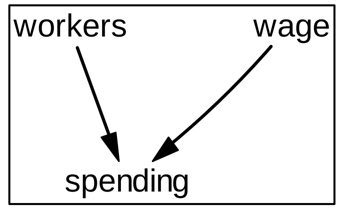
Behavior: No stocks, so no loops so no behavior.

Classic examples: Producing, Financial flow from resource

Caveats: None

Technical notes: This is one of three general ways to create an action. The other two are Close gap and Go to zero

Financial Flow From Resource



Immediate parents: Action from resource
Ultimate parents: Action from resource

Used by: Workforce from budget

Problem solved: How to figure out the continuing rent (income or expense) of a resource.

Equations:

spending = workers * wage Units: $/Month wage = ___ Units: $/(Month*person) workers = ___ Units: people

Description: The financial flow is the resources multiplied by the rent, which will have units of money-unit/resource-unit/time-unit (e.g. dollars/person/month). The flow is usually conceptualized as either an expense or a revenue stream, depending on whether the viewpoint is that of the owner of the resource (ncome) or the user of the resource (expense). The rent of a worker is her wage or salary and the financial flow is an expense to the employer and income to the employee. The rent of a building or machine is usually termed "lease payments" and the financial flow is expense to the person occupying the building and income to the building owner. The rent of money is usually called "interest rate" and the financial

Behavior: No stocks so no behavior.

Classic examples: Common

Caveats: None

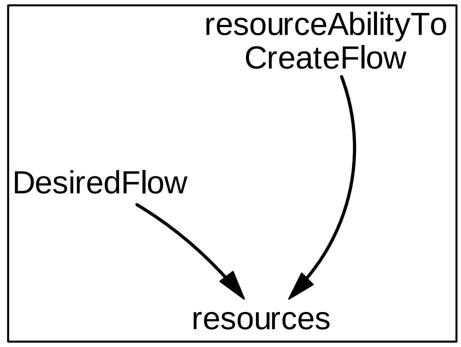
Technical notes: None

Resources From Action

Immediate parents: Action from resource
Ultimate parents: Action from resource

Used by: Workforce from budget

Problem solved: How to determine the resources we have (or need) based on the (desired) action (or flow) and the resources' ability to create the action (i.e. the resources' productivity)



Equations:

```
esources = DesiredFlow / resourceAbilityToCreateFlow
          Units: resources
 resourcesDesiredFlow = -___
          Units: gallons/Month
resourceAbilityToCreateFlow = ___
          Units: gallons/(Month*resource)
r
```

Description: Given the action (flow), dividing by the resource's creative ability (productivity) yields the necessary resources.

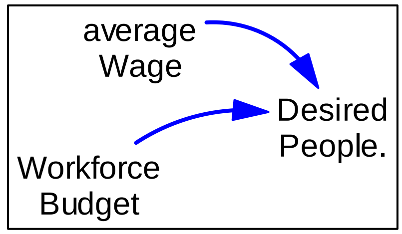
Behavior: No stocks so no behavior

Classic examples: Workorce from budget in Jay Forrester's Market Growth as Influenced by Capital Investment.

Caveats: None

Technical notes: None

Workforce From Budget



Immediate parents: Resources from action, Financial flow from resource
Ultimate parents: Action from resource

Used by: None

Problem solved: How to find the desired (or affordable) workforce, given a budget and an average wage.

Equations:

```
"DesiredPeople." = WorkforceBudget / averageWage
        Units: people
averageWage = ___
        Units: $/(person*year)
WorkforceBudget = ___
        Units: $/year
```

Description: Dividing the available budget by the average wage gives the number of people we can afford.

Behavior: No stocks, so no behavior

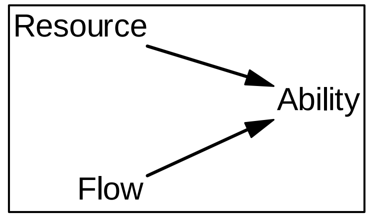
Classic examples: Market Growth as Influenced by Capital Investment

Caveats: If the average wage can go to zero, protect against divide by zero errors.

Technical notes: None

Ability From Action

Immediate parents: Action from resource
Ultimate parents: Action from resource



Used by: Estimated productivity

Problem solved: How to figure out what the creative ability (e.g. productivity) is a resource if we know the activity (or flow) that it causes.

Equations:

Ability = Flow / Resource
Units: gallons/(resource*Month)
Flow = ___
Units: gallons/Month
Resource = ___
Units: resources

Description: The creative ability of a resource is simply the action (or flow) devided by the resource that generates that activity. This molecule is simply a rearrangement of the elements of the action from resource molecule

Behavior: No stocks so no behavior

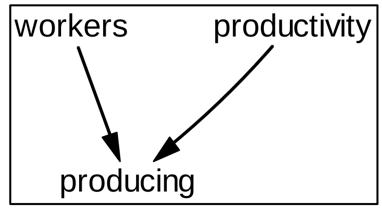
Classic examples: Sometimes used to figure out productivity in project models (see Estimated productivity).

Caveats: If the resource can go to zero, protect against a of divide-by-zero error.

Technical notes: None.

Producing

Immediate parents: Action from resource
Ultimate parents: Action from resource



Used by: Reducing backlog by doing work, Desired workers from workflow, Estimated productivity

Problem solved: How to produce or accomplish work

Equations:

```
producing = workers*productivity
        Units: drawings/Month
productivity = ___
        Units: drawings/person/Month
workers = ___
        Units: people
```

Description: Workers times their productivity yields what they accomplish or produce.

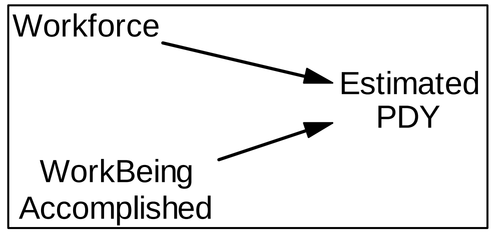
Behavior: No levels, so no endogenous behavior

Classic examples: Project models, workforce inventory oscillator, Forrester's Market Growth as Influenced by Capital Investment

Caveats: None

Technical notes: None

Estimated Productivity



Immediate parents: Ability from action, Producing
Ultimate parents: Action from resource

Used by: None

Problem solved: Estimating productivity

Equations:

```
EstimatedPDY = WorkBeingAccomplished / Workforce
        Units: widgets/(person*Month)
WorkBeingAccomplished = ___
        Units: widgets/Month
Workforce = ___
        Units: people
```

Description: Given a flow of work and the number of workers doing it, the implied productivity has to be the flow divided the number of workers.

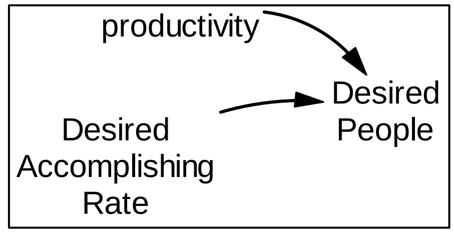
Behavior: No stocks, so no behavior.

Classic examples: None

Caveats: None

Technical notes: *Work being accomplished* wouldn't actually be known by real world managers if it is an actual flow. In this case the modeler may wish to either use a knowable estimate of *Work being accomplished* (e.g. a smooth of it) or use the *estimated PDY* from this formulation as an input into a formulation (e.g. a smooth) for perceived productivity.

Desired Workforce From Workflow



Immediate parents: Resource from action, Producing
Used by: Overtime

Problem solved: How to determine the number of workers we need

Equations:

```
DesiredPeople =  DesiredAccomplishingRate / productivity
          Units: people
productivity = ___
          Units: SquareFeet/person/Week
DesiredAccomplishingRate = ___
```

Description: The key here is the rate at which we need to accomplish work in order to finish on time. Once we know this, we can figure out how many people it takes to produce such a work flow.

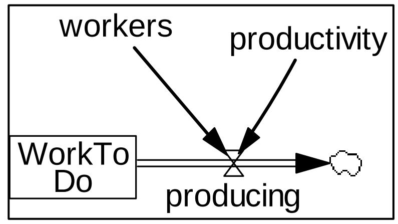
Behavior: No levels so no endogenous behavior.

Classic examples: Most project models make use of a formulation like this one.

Caveats: None

Technical notes: This formulation uses the same understanding as that used in the Producing molecule. Outputs and inputs, though are different. Here we know the (desired) production rate and we calculate the (desired) workforce. In the Producing molecule we know the workforce and calculate the production rate. In this formulation, we could use a perceived productivity. The max on remaining duration prevents remaining duration from getting so small that the desired workforce gets huge. This we could use a SoftMax in this formulation.

Reducing Backlog by Doing Work



Immediate parents: Producing
Ultimate parents: Action from resource

Used by: Estimated remaining duration, Level protected by PDY

Problem solved: Draining a stock of work to do via workers accomplishing the work.

Equations:

```
WorkToDo = INTEG( - producing , ___)
          Units: tasks
producing = workers * productivity
          Units: tasks/Month
productivity = ___
          Units: tasks/(Month*person)
workers = ___
          Units: people
```

Description: The stock is drained by a producing molecule.

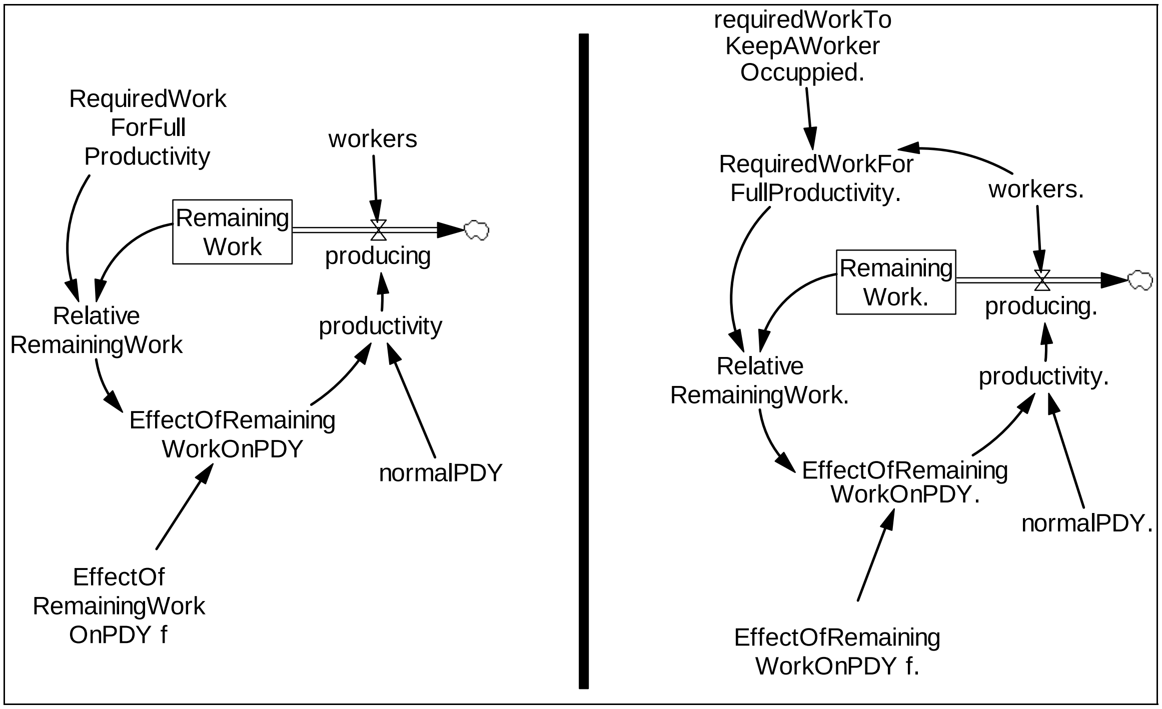
Behavior: *Work to do* will decline. If Workers and productivity are constant, *work to do* will decline linearly.

Classic examples: Project models.

Caveats: Nothing in this molecule prevents *work to do* from going negative. (See Level protected by PDY for a solution)

Technical notes: The "inverse" of this molecule – filling a stock with a producing molecule is also common, as is a cascade of levels where the outflow of one (defined by a producing molecule) is the input to the next.

Level Protected by PDY



Immediate parents: Reducing backlog by doing work, Univariate anchoring and adjustment
Ultimate parents: Action From Resource, Dmnl input to function
Used by: None

Problem solved: How to prevent the level of remaining work going below zero when workers are producing from a backlog.

Equations:

RemainingWork = INTEG(- producing , RequiredWorkForFullProductivity)
    Units: tasks
producing = workers * productivity
    Units: tasks/Month
workers = ___
    Units: people
productivity = normalPDY * EffectOfRemainingWorkOnPDY
    Units: tasks/(person*Month)
normalPDY = 5
    Units: tasks/(person*Month)
EffectOfRemainingWorkOnPDY = EffectOfRemainingWorkOnPDY f (RelativeRemainingWork)
    Units: dmnl
EffectOfRemainingWorkOnPDY f = *user defined function*
    Units: dmnl
RelativeRemainingWork = RemainingWork / RequiredWorkForFullProductivity

Units: fraction
RequiredWorkForFullProductivity = ___
Units: tasks

Additional equations for second version

"RequiredWorkForFullProductivity." = "workers." * "requiredWorkToKeepAWorkerOccuppied."
Units: tasks
"requiredWorkToKeepAWorkerOccuppied." = ___
Units: tasks/person

Description: This molecule solves the problem of the stock in the reducing backlog by doing work molecule going negative as workers continue to drain the stock after it hits zero. The solution is recognize that productivity must become zero when there is no longer any tasks to do. As the level of tasks falls below an amount of tasks required for full productivity, the resource's productivity falls. This could be because there is a time consuming step (e.g. having to bake clay pots in a kiln for two days) and to reach full productivity a worker needs enough other tasks to occupy him during the time that other tasks are in the time-consuming phase. In a formulation where the single workforce is an aggregate of a number of different skills, the reduction of productivity could be caused by workers having to take on tasks for which they are not in their "specialty" and hence on which they are less productive.

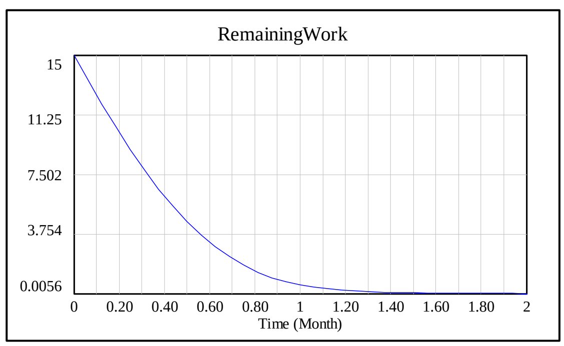
The second version of the molecule includes a formulation for the number of tasks required for full productivity. This formulation says that each worker needs (on average) a certain number of tasks in the backlog in order to work at full productivity.

Behavior: The stock will not fall below zero.

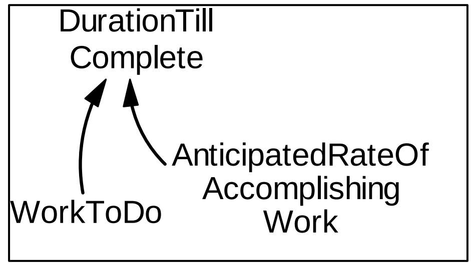
Classic examples: The balancing R&D chain model

Caveats: None

Technical notes: None



Estimated remaining duration



Immediate parents: Reducing backlog by doing work
Ultimate parents: Action from resource

Used by: Estimated completion date

Problem solved: How to estimate the remaining time to completion of an amount of work to do. How to estimate the average time to complete a task in a stock of work to do (see technical note).

Equations:

```
DurationTillComplete = WorkToDo / AnticipatedRateOfAccomplishingWork
        Units: week
WorkToDo = ___
        Units: square feet
AnticipatedRateOfAccomplishingWork = ___
        Units: square feet / week
```

Description: The estimated duration to completion is simply the amount of work left divided by the rate at which we can do the work..

Behavior: No levels, so no endogenous behavior.

Classic examples: Used in project models

Caveats: If people or productivity can be zero, you will need to protect against a divide by zero error in the equation for *durationTillComplete*.

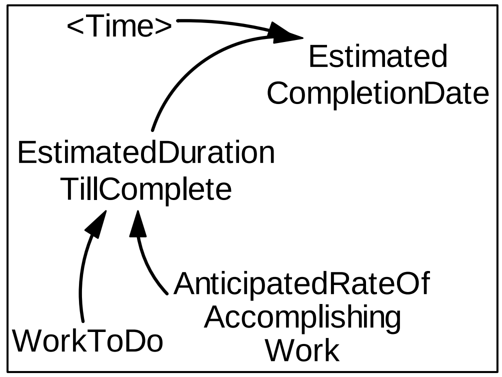
Technical notes: This formulation is related to the residence time molecule. Consequently, the variable *durationUntilComplete* can also be interpreted as the estimated average time to complete an individual task in the stock of work to do. Under this interpretation the variable's name should be changed to something more appropriate (e.g. *estimatedTaskResidenceTime*).

Estimated Completion Date

Immediate parents: Estimated remaining duration
Ultimate parents: Action from resource

Used by: None

Problem solved: How to represent the estimate of a completion date



Equations:

```
EstimatedCompletionDate =DurationTillComplete + Time
        Units: week
DurationTillComplete = WorkToDo / AnticipatedRateOfAccomplishingWork
        Units: week
WorkToDo = ___
        Units: square feet
AnticipatedRateOfAccomplishingWork = ___
        Units: square feet / week
```

Description: The estimated time until completion is simple the estimate duration until completion plus the simulation's current *Time*.

Behavior: No levels, so no endogenous behavior.

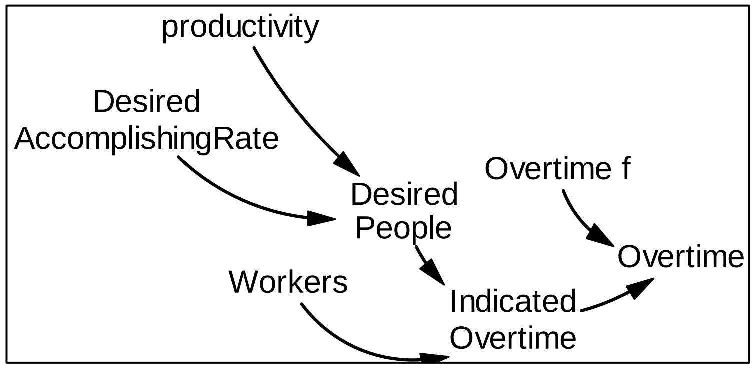
Classic examples: Used in project models

Caveats: If people or productivity can be zero, you will need to protect against a divide by zero error in the equation for *durationTillComplete*.

Technical notes: None

Overtime

Immediate parents: Workforce, Univariate anchoring and adjustment, Desired workers from workflow
Ultimate parents: Smooth (first order), Flow from resource, Dmnl input to function



Used by: none

Problem solved: How to calculate the required amount of overtime.

Equations:

Overtime = Overtime f (IndicatedOvertime)
Units: Fraction
Overtime f = *user defined function*
Units: Fraction
IndicatedOvertime = DesiredPeople / Workers
Units: Fraction
Workers = 10
Units: people
DesiredPeople = DesiredAccomplishingRate / productivity
Units: people
DesiredAccomplishingRate = ___
Units: tasks/week
productivity = ___
Units: tasks/(week*person)

Description: Overtime might be measured as a fraction of a normal day. If possible overtime would simply be the number of workers we wished we had divided by the number of workers we actually have. In practice, of course, the amount of overtime is limited by the number of hours in a day, by management policy, and by what workers are willing to do. The overtime function represents this practical limitation.

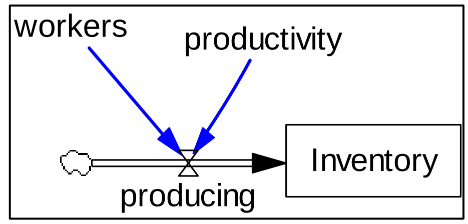
Behavior: No levels so no endogenous behavior.

Classic examples: Formulation like this are used in many project models.

Caveats: If the workforce can be zero, the modeler needs to protect against a divide by zero error in the calculation of IndicatedOvertime.

Technical notes: *DesiredPeople* here means "people needed to get the work done". Any formulation that yields such a definition of desired people is fine. Although we use the desired workers from workflow molecule, other formulation are possible.

Building Inventory by Doing Work



Immediate parents: Producing
Ultimate parents: Action from resource

Used by: Population growth, Doing work cascade

Problem solved: How to create an inventory inflow from people working.

Equations:

```
Inventory = INTEG( producing , ___
        Units: widgets
producing = workers * productivity
        Units: widgets/Month
productivity = ___
        Units: widgets/(Month*person)
workers = ___
        Units: people
```

Description: The inflow to the stock is a producing molecule.

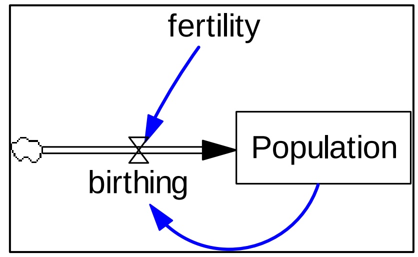
Behavior: If workers and productivity are constant, the stock will rise linearly.

Classic examples: Workforce Inventory Oscillator

Caveats: None

Technical notes: None

Population Growth



Immediate parents: Building inventory by doing work
Ultimate parents: Action from resource

Used by: None

Problem solved:

Equations:

```
Population = INTEG( birthing , ___
          Units: people
birthing = Population * fertility
          Units: people/Month
fetility = ___
          Units: people/(Month*person)
```

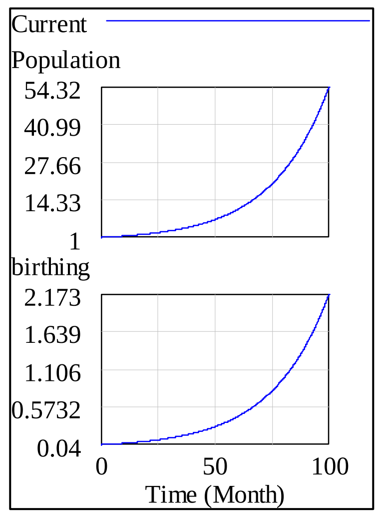
Description: The inflow to population is the population multiplied by the average fertility of the population.

Behavior: Exponential growth (if fertility is a constant).

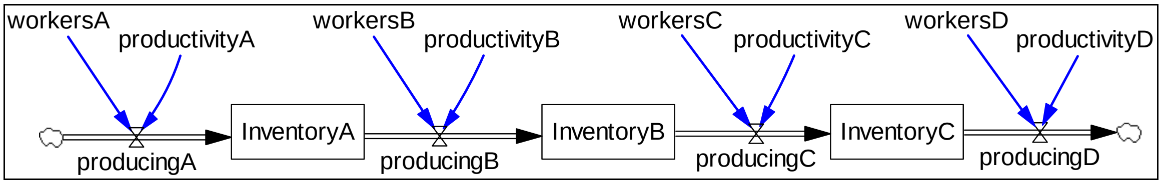
Classic examples: Common

Caveats: With a large enough growth rate or a long enough simulation length, this formulation can produce a population size that exceeds the largest number the computer can represent. In this case, the machine will throw a floating point overflow error and the simulation will stop.

Technical notes: Fertility is the productivity of the population in producing babies. This is simply a Building Inventory by Doing Work molecule where the "inventory" is the workforce itself.



Doing Work Cascade



Immediate parents: Cascaded levels, Building inventory by doing work, Reducing backlog by doing work
Ultimate parents: Bathtub, Action from resource

Used by: Cascade protected by PDY

Problem solved: How to represent something that accumulates at a number of points where the "something" is moved from accumulation to accumulation by people working.

Equations:

```
InventoryA = INTEG( producingA - producingB , ___)
          Units: widgets
InventoryB = INTEG( producingB - producingC , ___)
          Units: widgets
InventoryC = INTEG( producingC - producingD , ___)
          Units: widgets
producingA = workersA * productivityA
          Units: widgets/Month
producingB = workersB * productivityB
          Units: widgets/Month
producingC = workersC * productivityC
          Units: widgets/Month
producingD = workersD * productivityD
          Units: widgets/Month
productivityA = ___
          Units: widgets/(Month*person)
productivityB = ___
          Units: widgets/(Month*person)
productivityC = ___
          Units: widgets/(Month*person)
productivityD = ___
          Units: widgets/(Month*person)
workersA = ___
          Units: people
workersB = ___
          Units: people
workersC = ___
          Units: people
```

workersD = ___ Units: people

Description: A cascade of levels in which the flows are all caused by workers working at some productivity and where the outflow from one level is the inflow into the next.

Behavior: If the workers and their productivities are all constant, the stocks will rise or fall linearly.

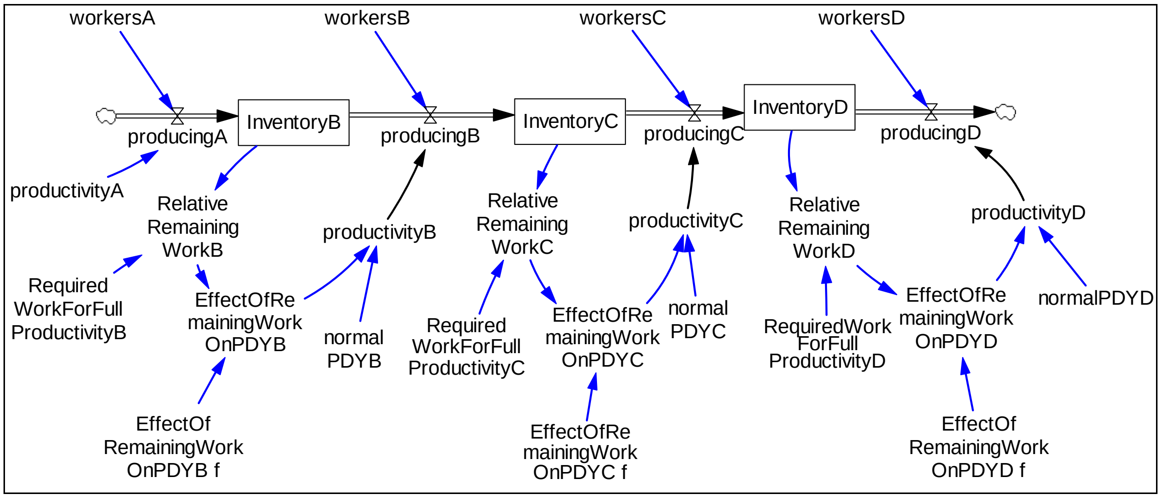
Classic examples: R&D Chain

Caveats: There's nothing to prevent any of these levels from going negative. (See Cascade protected by pdy).

Technical notes: None

(Continued on next page...)

Cascade Protected By PDY



Immediate parents: Level protected by PDY, Doing work cascade
Ultimate parents: Close gap, Action from resource, Dmnl input to function, Bathtub

Used by: None

Problem solved: How to prevent workers from drawing down cascaded levels below zero.

Equations:

InventoryB = INTEG(producingA - producingB , RequiredWorkForFullProductivityB)
Units: widgets
InventoryC = INTEG(producingB - producingC , RequiredWorkForFullProductivityC)
Units: widgets
InventoryD = INTEG(producingC - producingD , RequiredWorkForFullProductivityD)
Units: widgets
producingA = workersA * productivityA
Units: widgets/Month
producingB = workersB * productivityB
Units: widgets/Month
producingC = workersC * productivityC
Units: widgets/Month
producingD = workersD * productivityD
Units: widgets/Month
workersA = 5
Units: people
workersB = 5
Units: people
workersC = 5
Units: people

workersD = 12
    Units: people
productivityA = 5
    Units: widgets/(Month*person)
productivityB = normalPDYB * EffectOfRemainingWorkOnPDYB
    Units: widgets/(Month*person)
productivityC = normalPDYC * EffectOfRemainingWorkOnPDYC
    Units: widgets/(Month*person)
productivityD = normalPDYD * EffectOfRemainingWorkOnPDYD
    Units: widgets/(Month*person)
normalPDYB = 5
    Units: widgets/(Month*person)
normalPDYC = 5
    Units: widgets/(Month*person)
normalPDYD = 5
    Units: widgets/(Month*person)
EffectOfRemainingWorkOnPDYB= EffectOfRemainingWorkOnPDYB f(RelativeRemainingWorkB)
    Units: dmnl
EffectOfRemainingWorkOnPDYB f = *user defined function*
    Units: dmnl
EffectOfRemainingWorkOnPDYC= EffectOfRemainingWorkOnPDYC f(RelativeRemainingWorkC)
    Units: dmnl
EffectOfRemainingWorkOnPDYC f = *user defined function*
    Units: dmnl
EffectOfRemainingWorkOnPDYD= EffectOfRemainingWorkOnPDYD f (RelativeRemainingWorkD)
    Units: dmnl
EffectOfRemainingWorkOnPDYD f = *user defined function*
    Units: dmnl
RelativeRemainingWorkB = InventoryB / RequiredWorkForFullProductivityB
    Units: fraction
RelativeRemainingWorkC = InventoryC / RequiredWorkForFullProductivityC
    Units: fraction
RelativeRemainingWorkD = InventoryD / RequiredWorkForFullProductivityD
    Units: fraction
RequiredWorkForFullProductivityB = 15
    Units: widgets
RequiredWorkForFullProductivityC = 15
    Units: widgets
RequiredWorkForFullProductivityD = 15
    Units: widgets

Description: Material moves f]through a chain of accumulations by people working at some productivity. The productivity of the people working on any one flow is a function of the amount of material in stock that is being drained (i.e a function of the amount of material in the source).

Behavior: The levels will not go negative.

Classic examples: R&D Balance Chain

Caveats: None

Technical notes: None