Model 3: Hunter-Gatherers with Evolving Technology

Narrative

Human technology had been evolving even before our genus *Homo* emerged about 2 million years ago. Our Australopithecine ancestors made stone tools at least by 3.3 million years ago. They also, presumably, made tools out of perishable materials like wood and fiber. Stone tools, by contrast, are extremely durable, so they are virtually all we have for most of the paleoanthropological record. Stone tools are also rather more abundant than the fossil bones of their tool makers, mostly because human bones are fragile compared to stone tools that they make, and because toolmakers make many tools in a lifetime but leave only one set of bones when they die.

Tools of the Oldowan industry were made by various Australopiths, among whom were species that later evolved into "official" humans, classified by anthropologists as members of *Homo*. More than two-million-year-old Oldowan tools were discovered in China, so humans, like the famous species *Homo erectus,* had already become very widespread. Bones of *H. erectus* are known from the Caucasus by 1.6 million years ago. Oldowan tools consisted of cobbles of fine-grained or glassy texture that, when struck in just the right way with another cobble, produced sharp flakes and a sharp scar on the cobble core. By knocking off 2 or 3 flakes, the cobble's sharp edge could be used like a hatchet while the sharp flakes could serve as knives.

It takes a powerful but precise hand grip to successfully knap stone and use the resulting tools. Attempts to teach chimpanzees to knap stone have been unsuccessful, although they do make other simple tools. Anthropologists have thought for some time that only the upright posture and free hands of the Australopiths, now little used in locomotion, could evolve the necessary, specialized power precision grip. Commentators since Darwin have long supposed that the tools our hands can make and use are at least one reason why we became such a large brained creature committed to exploiting highly specialized cultural adaptations.

About 1.7 million years ago Acheulean tools began to be made in Africa and not much later in Eurasia. These were the first tools with regular shapes. The signature Acheulean tool is a "handaxe" with a symmetrical teardrop shape, a rounded butt, and sharp point. They were thinned by flaking on both faces to produce a sharp edge along the circumference of the tool. Edge wear analysis suggests that handaxes and similar tools were used for a variety of cutting and chopping tasks including butchery, hide working, cutting of plants, and woodworking. Flakes produced in making them could be used as knives. Rare finds of plant remains suggest that *H. erectus* and similar species made wooden spears, built shelters, prepared food, and made use of fibrous plant material to make mats and cordage. The Acheulean lasted for around a million years and some of its tool forms lasted until 130 thousand years ago. Cultural evolution was very slow in the Olden Days!

Beginning something like 300 thousand years ago, sufficiently novel elements were added to the Acheulean tradition so that paleoanthropologists begin to speak of the Middle Stone Age or Mousterian industry. The use of advanced knapping techniques allowed Middle Stone Age craftspeople to produce longer, thinner, and larger flakes that could, in turn, be shaped into more formal knives, awls, hide scrapers, and chisels. Cordage and adhesives allowed stone points to be mounted on spears and blades on handles to make axes and adzes. By around 100 thousand years ago, still more innovations were being incorporated into Middle Stone Age toolkits. For example, in Southern Africa people sometimes put coarse grained stone into quite hot fires so that that they partially melted. Such heat-treated stone fractured like the fine-grained stone necessary for sharp edged tools. People also began to leave evidence of artistic behavior in the form of painting kits and shell beads.

Around 50 thousand years ago, the pace of change quickened. Brains had expanded to modern sizes or more! (Some evidence suggests that human brains got smaller when we became farmers.) *Homo sapiens* migrated out of Africa, mixed a bit genetically with the Eurasian species, like Neanderthals, and quickly reached the isolated islands of Southeast Asia and Australia. These Upper Paleolithic/Late Stone Age people made quite fancy tools in stone, bone, ivory, and, no doubt, wood. Bone and ivory needles suggest they wore well-tailored clothing. Reaching Australia and many of the islands in that region would have required decent watercraft, although no examples survive.

Utilitarian objects were routinely made with artistic flourishes. Spectacular cave art is well known from Western Europe, but equally early and impressive images have been discovered on the Southeast Asian island of Sulawesi. Paleoanthropologists think of these people as anatomically and behaviorally modern. In other words, if your sister or brother went on a time travel expedition and came back married to one of them, it would not be much different than if they had gone to another continent and married a native there. What caused this transition 50 thousand years ago is controversial. Richard Klein, a paleoanthropologist at Stanford argues that a mutation caused our brain and mind to become capable of modern behavior. One of us (PR) has proposed that a major uptick in the rate of climate variation about that time favored humans at the expense of our competitors because we could adapt culturally to the increased variation while our competitors depended more on slower genetic variation.

Around 50 thousand years ago, human populations on every continent then occupied, started to steadily increase from a low base number. There is no evidence that earlier humans were ever very common. There is also no evidence that humans had any dramatic impact on their prey populations. A palaeoecological modeler interested in times before 50 thousand years ago could ignore humans on the KISS rule in favor of important predators like lions and hyena. The slow evolution of technology did not have a dramatic impact, and if a modeler did want to study pre-modern humans, out Basic Hunter-Gatherers model would be good enough.

Coincident with the rise in modern human populations, the world’s megafauna started to suffer extinctions. “Megafauna” are the animals, from the size of small antelope upward in size, that were the prime targets for human hunters. These extinctions were earliest and least extreme in Africa, later and more extreme in Eurasia. Extinction were even yet more extreme in Australia and late and very extreme in the New World. African and Eurasian megafauna had a long evolutionary history in common with humans whereas in Australia and the Americas humans arrived very abruptly in the form of quite sophisticated hunters and these hunters rapidly evolved devastating strategies to hunt the native megafauna. Only a few of the shyest, fastest, and most elusive megafauna species survived the onslaught. On remote oceanic islands like New Zealand, extinctions also correspond to the arrival of modern humans, much like when humans arrived on our deserted island model.

The processes that led to the evolution of *Homo* and ultimately *Homo sapiens* are still a major scientific puzzle. Some “progressivist” theorists suppose that big brains and the things they can do, like make fancy cultures, are inherently better, but that the complexity of brains make them slow to evolve. Hence, it takes billions of years to get from simple forms of life like bacteria, to extraordinarily complex ones like humans. Progressive evolutionary ideas are especially associated historically with Darwin’s contemporary, Herbert Spencer.

Other evolutionists are “adaptationists” and think that the hands-brains-culture complex must have evolved because environmental factors favored it. In this view, big brains are not inherently better but are metabolically costly organs that must pay their way. Selection will favor brains that are as small as possible, consistent with what individuals have to do. In theory, brains are organs of phenotypic flexibility that use superior learning and cultural capacities to cope with variable environments. In this view, the fact that humans (and many other species) evolved bigger brains in the extraordinarily and progressively more variable Pleistocene environment is not a coincidence!

It bears mentioning that humans are still essentially “hunters” of many resources. Forests fall to loggers, we fish wild stocks, and ecosystem services are overexploited. Non-renewable fossil fuels and metal ores are like prey that have a large initial “population” but a reproductive rate very close to zero.

Hence, the need for models with dynamic technology that we introduce here.

Further Reading

Atkinson, Q. D., R. D. Gray and A. J. Drummond (2008). "mtDNA variation predicts population size in humans and reveals a major southern Asian chapter in human prehistory." *Molecular Biology and Evolution* 25(2): 468-474.

Bettinger, R. L. and M. A. Baumhoff (1982). "The numic spread: Great Basin cultures in competition." *American Antiquity* 47(3): 485-503.

Boyd, R. and J. B. Silk (2018). *How Humans Evolved.* WW Norton.

Kivell, T. L., P. Lemelin, B. G. Richmond and D. Schmitt (2016). *The Evolution of the Primate Hand.* Springer.

Klein, R. G. (2009). *The Human Career: Human Biological and Cultural Origins.* Chicago IL, University of Chicago.

Martin, P. S. and R. G. Klein (1984). *Quarternary Extinctions: A Prehistoric Revolution.* Tucson AZ, The University of Arizona Press.

Richerson, P. J. and R. Boyd (2013). “Rethinking paleoanthropology: A world queerer than we supposed.” In *Evolution of Mind, Brain, and Culture.* G. Hatfield and H. Pittman. Philadelphia, University of Pennsylvania Museum of Archaeology and Anthropology: 263-302.

Washburn, S.L (1960). “Tools and human evolution.” *Scientific American* 203(3):3-15.

Will, M., N. J. Conard and C. A. Tyron (2019). “Timing and trajectory of cultural evolution on the African continent 200,000-30,000 years ago.” In *Modern Human Origins and Dispersal.* Y. Sahle, H. Reyes-Centeno and C. Bentz. Teubingen, Kerns Verlag: 25-72.

https://en.wikipedia.org/wiki/Quaternary_extinction_event

https://en.wikipedia.org/wiki/Paleolithic

https://en.wikipedia.org/wiki/Hand

White Box Graphical Model

The White Box, under-the-hood model description below can be skipped and you can proceed directly to the Black Box Simulations if you just want to operate the simulator and skip the model diagram and equations. You can always come back to this section if you would like to explore the model further.

Overall Model

The graphic Stella model shown in Figure 3-1 is broken into three major sections, the prey, the humans who hunt them, and the hunter's evolving technology. Each major section of the model is discussed below. Please note that the first two major sections, the prey and the humans, are almost word-for-word repeats of what was already presented in Model 2, Basic Hunter-Gatherers, and are just repeated here for completeness and ease of reference.

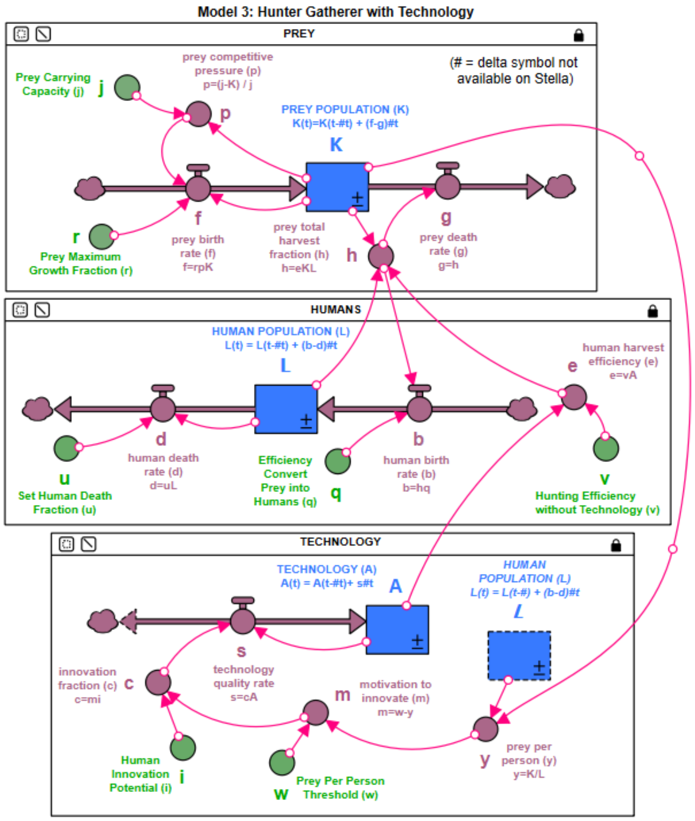


Figure 3-1: Stella Hunter-Gatherers with Technology model.

Prey Submodel

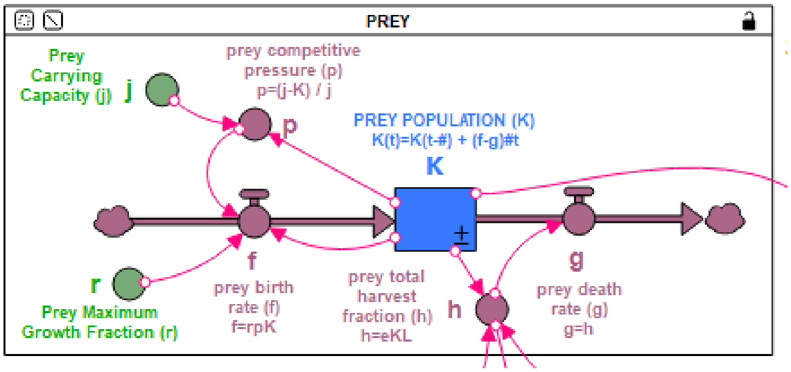


Figure 3-2: Prey submodel.

For the PREY section of the model, the PREY POPULATION (K) is a state variable (i.e., a “tank”) whose value can change during the simulation for each tiny iteration of the Stella model, each small step in time. The amount of change is the rate of input, the prey birth rate (f) minus the prey death rate (g) times the small increment of time, Δt (shown as #t in the model because Stella does not have the Δ symbol). Thus, for each step in time, the simulation makes the calculation

$K(t) = K(t-\Delta) + (f-g)\Delta t$

The prey birth rate (f) is the product of the Prey Maximum Growth Fraction (r), the prey competitive pressure (p), and the PREY POPULATION (K), i.e.

$f = rpK$

The Prey Maximum Growth Fraction (r) is the per individual growth rate of the prey population in the absence of any competition from other members of the population. It represents the per-capita birth rates in the absence of competition and hunting. Mathematically, r is the population growth rate when K is very near but not quite 0.

The prey competitive pressure (p), is, in essence, the prey competing against itself for a limited supply of what the prey eats to stay alive and reproduce. When K is small relative to j, p is approximately 1 and the prey population is free to grow exponentially. As K approaches j, p approaches 0 and competition alone stops the prey population from growing. For antelopes, for instance, it would be the grass in the meadows, knee deep when $K << j$, grazed tight to the ground as $K \rightarrow j$. This competition for a fixed resource is calculated, for each simulation step as

$p = (j - K) / j$

From this equation it can be seen that when K is zero or very small, then p is essentially equal to 1.0. This is the green light (excuse the pun) to the antelope that all the meadows are green with grass. However, as K gets larger, i.e. the number of antelope increase, then there is less uneaten grass in the meadows. As K gets larger and larger, p approaches 0.0 and the number of antelope is limited by the Prey Carrying Capacity (j). If there weren’t any humans hunting antelope, the PREY POPULATION (K) would, over time, asymptotically approach the Prey Carrying Capacity (j) and then stay at the number for ever.

$g = h$

The prey total harvest fraction (h) is the fraction of the antelope that humans kill.

$h = eLK$

This equation simply suggests that the more antelope there are, the more humans there are to hunt them, and the greater the efficiency of the humans, the more antelope that will be killed. Note that the Hunting Efficiency with Static Technology (v) in the equation for h has been replaced by human harvest efficiency (e) which is the product $e = vA$, thus making technology endogenous instead of exogenous. In the Basic Hunter-Gatherers model, v can be set low enough to represent the predatory efficiency of an imaginary australopith-like ancestor who, like living chimpanzees, hunted small game by using their hands and teeth to catch and kill the game. Or v could be set higher to represent the very slowly evolving technology of successive toolmaking populations. In this model, Hunter-Gatherers *with* Dynamic Technology, we introduce endogenously evolving technology (at first, simple spears and clubs, later stone tipped spears, then bows and arrows, and eventually guns).

Humans Submodel

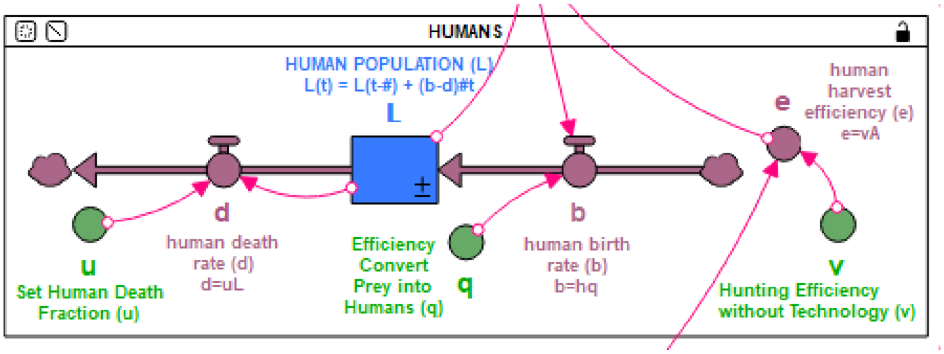


Figure 3-3: Humans submodel.

For the HUMANS section of the model, HUMAN POPULATION (L) is a state variable (i.e., a "tank") whose value can change, during the simulation, for each tiny iteration of the Stella model, each small step in time. The amount of change is the rate of input, the human birth rate (b) minus the human death rate (d) times the amount of time, Δt (shown as #t in the model because Stella does not have the Δ symbol). Thus, for each step in time, the simulation makes the calculation. Note that in this submodel the flow is from right to left, the opposite direction of the other sub-models.

$$L(t) = L(t-\Delta) + (b-d)\Delta t$$

The human birth rate (b) is the product of the prey total harvest fraction (h) and the Efficiency Convert Prey into Humans (q). The more antelope the hunters can kill and the more efficiently they use this food (cooking all the parts and breaking the bones open for the marrow) to produce more humans, the more baby humans will be born.

$$b = hq$$

The human death rate (d) is the product of the Human Death Fraction (d) and the HUMAN POPULATION (L).

$$d = uL$$

human death rate (d) is the *number* of humans that die of old age, diseases, accidents, etc., each year.

Human Death Fraction (u) is the *fraction* of humans that die each year.

Technology Submodel

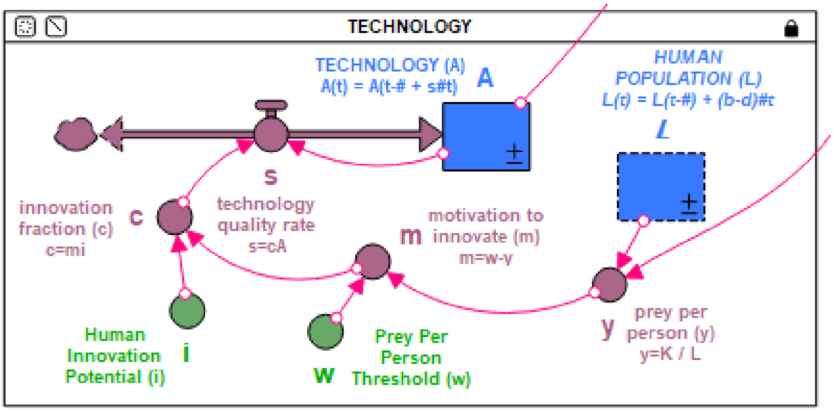


Figure 3-4: Technology sub-model.

For the TECHNOLOGY section of the model, TECHNOLOGY (T) is a state variable (i.e., a "tank") whose value can change during the simulation for each tiny iteration of the Stella model, Δt, i.e., each small step in time (Δt is shown as #t in the model because Stella does not have the Δ symbol). The amount of change can be positive or negative (but is usually positive) times the amount of time. This ability to add to or subtract from the state variable, T, i.e., to fill or drain the tank, is denoted in the model by having arrows on *both* ends of the flow into and out of the "tank."

For each step in time, the simulation makes the calculation.

$A(t) = A(t-\Delta) + s\Delta t$

The overall per generation improvement in technology (s) is

$s = cA$

where **c** measures the innovation fraction (how enthusiastically people innovate), and **A** is the previous level of technology.

The innovation fraction (c) is a function of i, the intrinsic innovativeness of people, and **m**, their motivation to imitate.

$c = mi$

The motivation to innovate (m) is a function of w a hunger threshold and y a hunger index.

$m = w – y$

The prey per person (y) is the size of the prey population relative to the human population. In the spirit of "necessity is the mother of invention," when prey get scarce enough hungry hunters turn their attention to ways to hunt more effectively.

y = K / L

Model Variables and Equations

The visual flow diagram "white box" model, described above, can be reduced to a set of initial conditions and independent (and intermediate) variables which, through mathematical relationships (equations) provide the results (the independent variables). These, without the graphical flow diagram, are given in the table below:

Key: STOCKS, Parameters, and intermediate variables

PREY	Units	Stella Equations
PREY POPULATION (K)	Prey unit	K(t) = K(t-Δt) + (f-g)Δt
Prey Carrying Capacity (j)	Prey unit	
Prey Maximum Growth Fraction (r)	1/year	
prey birth rate (f)	Prey unit/year	f = rpK
prey competitive pressure (p)	Unitless	p = (j – K) / j
prey death rate (g)	Prey units/year	g = h
prey total harvest fraction (h)	Prey unit/year	h = eKL
HUMANS		
HUMAN POPULATION (L)	People	L(t) = L(t-Δt) + (b-d)Δt
Human Death Fraction (u)	1/year	
Efficiency Convert Prey into Humans (q)	People/prey unit	
Hunting Efficiency without Technology (v)	1/(people*year)	
human death rate (d)	People/year	d = uL
human birth rate (b)	People/year	b = hq
human harvest efficiency (e)	1/(people*year)	e = vA
TECHNOLOGY		
TECHNOLOGY (A)	Unitless	A(t) = A(t-Δt) + sΔt
Human Innovation Potential (i)	People/(pre unit* year)	
Prey Per Person Threshold (w)	Prey unit/person	
technology quality rate (s)	1/year	s = cA
innovation fraction (c)	1/year	c = mi
motivation to innovate (m)	Prey unit/person	m =w - y
prey per person (y)	Prey unit/person	y = K / L

Table 3-1: Variables, units, and equations.

Equations without Intermediate Variables

The intermediate variables can be eliminated by substitution, leaving just the dependent variables as a function of the intermediate variables. Shown below are the equations in a simulation, one-step-at-a-time form. Given the values of the state variables in the previous step, how do you calculate their value in the next increment of time?

K(t) = K(t-Δ) + [rK(j-K/j) – vAKL]Δt

L(t) = L(t-Δ) + [vqAKL – uL]Δt

A(t) = A(t-Δ) + iA(w-K/L)Δt

If Δt is made smaller, we reach, in the limit, the differential equations where the prime, as in K', indicates the first derivative with respect to time, i.e., dK/dt.

K' = rK(j-K/j) – vAKL

L' = vqAKL – uL

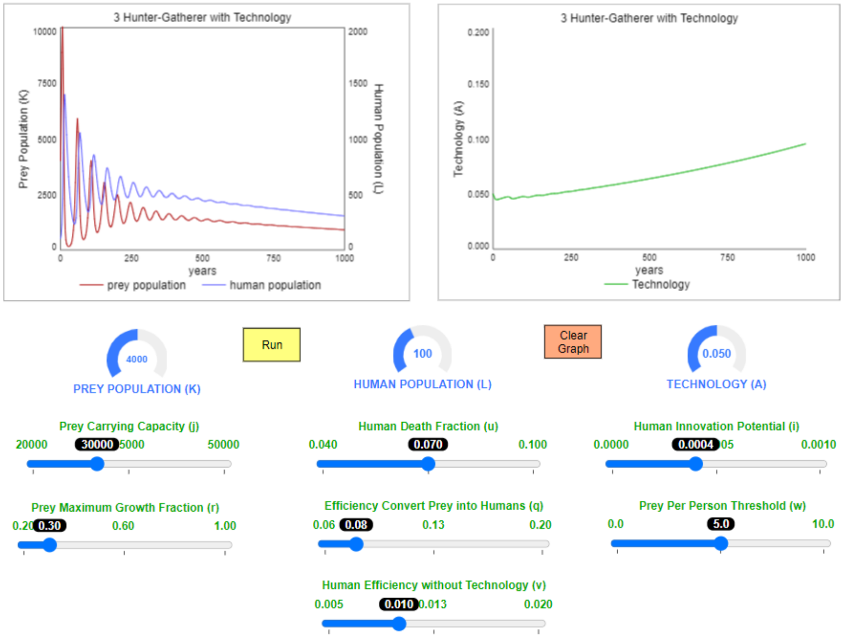
A' = iA(w-K/L)

Black Box Model

As suggested in the course Introduction, when using a black box model, one is just concerned with the model's inputs, not its internal workings which can be extraordinarily complex. To run the Hunter-Gatherers with Technology model from this black box perspective, bring it up at:

https://exchange.iseesystems.com/public/cherylgenet/hunter-gatherer-with-technology

This is what you should get after you press click *run*:



Prey Carrying Capacity (j) 30000

Human Death Fraction (u) 0.070

Human Innovation Potential (i) 0.0004

Prey Maximum Growth Fraction (r) 0.30

Efficiency Convert Prey into Humans (q) 0.08

Prey Per Person Threshold (w) 5.0

Human Efficiency without Technology (v) 0.010

Figure 3-5: Hunter-Gatherers with Technology model interface.

The simulation model has three initial condition control knobs:

- PREY POPULATION (K)
- HUMAN POPULATION (L)
- TECHNOLOGY (A)

And seven independent variable parameter adjustment sliders:

- Prey Carrying Capacity (j)
- Prey Maximum Growth Fraction (r)
- Human Death Fraction (u)
- Efficiency Convert Prey into Humans (q)
- Hunting Efficiency without Technology (v)
- Human Innovation Potential (i)
- Prey Per Person Threshold (w)

The initial condition knobs and independent parameter sliders require minimum, maximum, increment (resolution), and reset values. These are provided in the table below.

Key: STOCKS, **and** Parameters

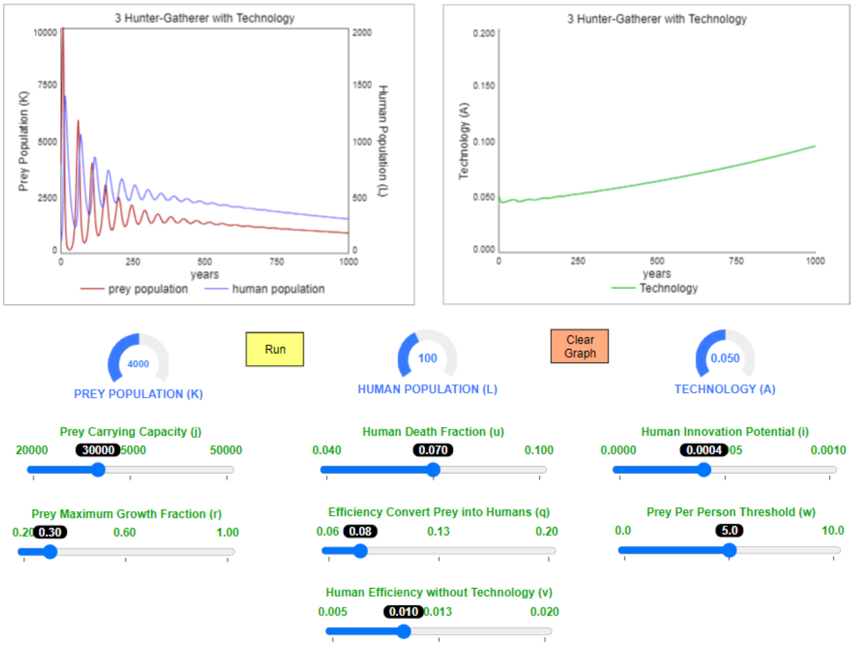
	Min	**Max**	**Increment**	**Reset**
PREY POPULATION				
PREY POPULATION (K)	0	8000	100	4000
Prey Carrying Capacity (j)	20000	50000	100	30000
Prey Maximum Growth Fraction (r)	0.20	1.00	0.01	0.30
HUMAN POPULATION				
HUMAN POPULATION (L)	0	250	1	100
Set Human Death Fraction (u)	0.04	0.10	0.01	0.07
Efficiency Convert Prey into Humans (q)	0.06	0.20	0.01	0.08
Hunting Efficiency Without Technology (v)	0.005	0.020	0.001	0.010
TECHNOLOGY				
TECHNOLOGY (A)	0	0.1	0.001	0.05
Human Innovation Potential (i)	0	0.001	0.0001	0.0004
Prey Per Person Threshold (w)	0	10.0	1	5.0
OUTPUT GRAPHS				
prey population	0	10000		
human population	0	2000		
technology	0	200		
years (t)	0	1000		

Table 3-2: Simulator interface values.

Each simulator control has a minimum and maximum value. Each control also has an increment (resolution) and default reset values that will be in place if you press *Clear Graph*. These values cannot be changed by the model user and have been set by the model designers to allow the model to be exercised over a useful range of values while avoiding extreme values that would be confusing. While they are "fixed" values in the simulation program, the table is provided not only as background information, but as a starting point for those who would like, on their own, to modify the Stella model.

Gradual Prey Extinction

In our baseline (default) scenario, we think in terms of Africa, where the prey population has coevolved with human predators. Human hunting innovations are small surprises to the game because they can incrementally adapt to them and minimize their impacts. In line with the megafaunal extinction data, there is a mild and prolonged decline in hunting as technology slowly increases. In Africa, the thread of wholesale megafaunal extinction was delayed until today.



PREY POPULATION (K) 4000
HUMAN POPULATION (L) 100
TECHNOLOGY (A) 0.050

Prey Carrying Capacity (j) 30000
Human Death Fraction (u) 0.070
Human Innovation Potential (i) 0.0004
Prey Maximum Growth Fraction (r) 0.30
Efficiency Convert Prey into Humans (q) 0.08
Prey Per Person Threshold (w) 5.0
Human Efficiency without Technology (v) 0.010

Figure 3-6: Gradual prey extinction (repeat of Figure 3-5).

Fast Prey (and Human) Extinction

When sophisticated Homo sapiens populations finally met the megafauna of the Americas at the end of the Pleistocene, extinctions were rapid and catastrophic. The same thing happened on remote oceanic islands, where humans arrived suddenly—only about 700 years ago in the case of New Zealand. There, the giant flightless Moa bird and other vulnerable species rapidly became extinct.

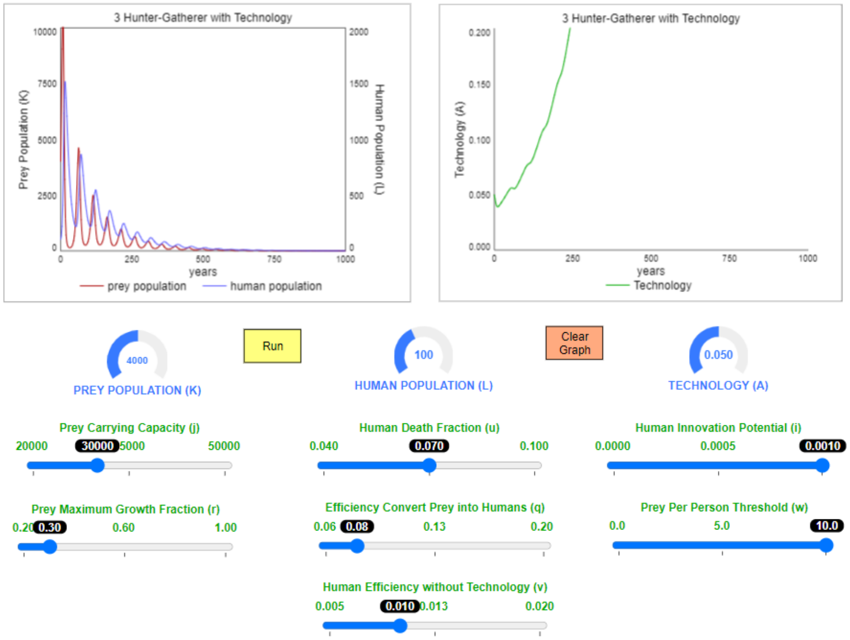
In the gradual prey extinction scenario, both prey and human populations were gradually falling as technology increased. One could project that by 10,000 years, both populations would become small and, eventually both die out (although if just a few prey were left when the last humans died, the prey would, presumably, bounce back and rapidly head toward the prey carrying capacity.

If, instead of having to wait for a long time to get to the end of the story, how could we speed up the prey extinction. How could we make it happen faster?

We can do this by increasing the rate of technology growth, either by increasing the Human Innovation Potential (i), or the Prey Per Person Threshold (w), or both. Shown below is what happens when we max out both of these independent variables. Technology, as expected, takes off.

As we have said elsewhere, all models are wrong. Sometimes this is for deep reasons that bear thinking about. Other times the failure is trivial but can still fool us. For example, in Stella, you have to make sure that when populations fall to zero, they really are dead. Stella will keep track of fractional people, a sort of mathematical zombie, that allows simulated populations to recover from extinction. Sexually reproducing populations require at least two people to reproduce and, in reality, once populations become very small their chances of extinction shoot up for various reasons.

To some extent we tolerate artifactual behavior in simulations because fixing them is not worth the trouble. It is easy enough to just ignore such artifacts while properly fixing them may be more trouble than it is worth. Many parameter values may be wholly unrealistic and give rise to wild behavior. We have tried to give you ranges of independent variables and initial values of state variables, but if you set several of our sliders to extreme values at the same time you can produce some pretty unrealistic behavior. It is good to get fully familiar with any model you want to use for any serious purpose. Making a substantive error in modeling is bad enough. Science is hard, especially when it comes to complex, non-linear systems, so being wrong comes with the territory. Being misled by a frank artifact or simple programming error is more embarrassing!



Prey Carrying Capacity (j) 30000
Prey Maximum Growth Fraction (r) 0.30
Human Death Fraction (u) 0.070
Efficiency Convert Prey into Humans (q) 0.08
Human Efficiency without Technology (v) 0.010
Human Innovation Potential (i) 0.0010
Prey Per Person Threshold (w) 10.0

Figure 3-7: Fast prey (and human) extinction.

Steady State

Human predator prey systems can have steady states. Some prey populations are elusive and cannot be driven to extinction. Deer in North America are an example (given Stone Age technology at least). An extreme example are donor-controlled cases where humans just cannot have a significant impact on prey populations. Open ocean fish and whales are an example. Given stone age technology, human populations can only nibble at the edges of whale, porpoise and tuna populations with small boats and limited technology. Of course, given industrial technology, even open ocean species are vulnerable, and it takes active management to prevent extinctions.

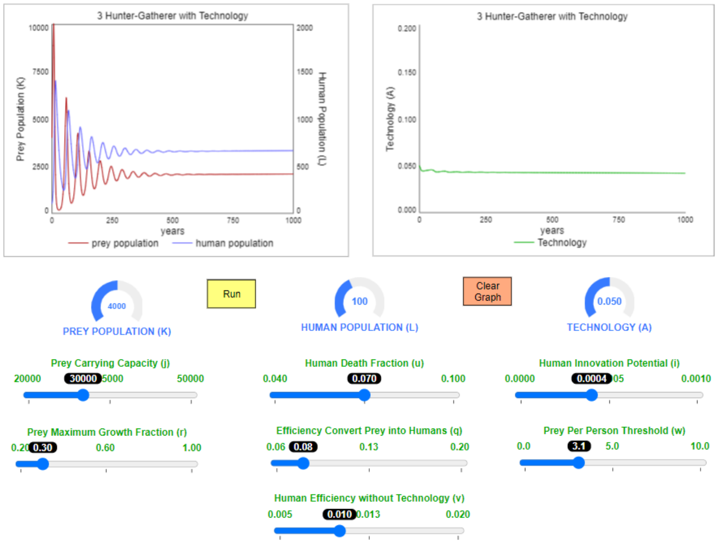
It appears that increasing technology always leads to extinction of the prey and, without anything to eat, the humans. Unless humans switch to another food source (such as farming, in the next two models), then they are doomed. But perhaps human could not only control their technology growth, but they could bring it to a comfortable level (not working too hard to kill prey) and freeze it at that level. What would it take to have a constant technology? What combination of parameters would allow technology to remain constant at a comfortable level?

For the mathematically inclined, we know that for technology to eventually remain constant, A', the first derivative of technology, must become zero. Thus:

$A' = iA(w-K/L) = 0$

Solving this yields $w = K/L$.

So, adjust the Prey Per Person Threshold (w) until things steady out in a flat-line steady state. This is what you may get (not unique as there are many combinations that will give a steady state result):



PREY POPULATION (K) 4000
HUMAN POPULATION (L) 100
TECHNOLOGY (A) 0.050

Prey Carrying Capacity (j) 30000
Human Death Fraction (u) 0.070
Human Innovation Potential (i) 0.0004
Prey Maximum Growth Fraction (r) 0.30
Efficiency Convert Prey into Humans (q) 0.08
Prey Per Person Threshold (w) 3.1
Human Efficiency without Technology (v) 0.010

Figure 3-8: Steady state.

Conclusions

The two hunter-gatherer models presented us with a somewhat depressing picture of humans. The potential of cultural evolution to adapt us to variable environments using technology is a recipe for success and we rapidly became a very widespread species, although not a very common one. When the evolution of technology eventually became swifter, we tended to evolve into superpredators capable of causing mass extinctions.

In the next two modules, we introduce models of farming and herding first with fixed and then with evolving technology. Agricultural systems are mutualisms in which humans invest time and technology in creating and protecting the domesticated species they eat. This reverses the logic of a normal predator prey system. However, it also introduces a new form of potential instability, a tendency for the positive feedback in the system to cause it to shoot towards infinity. Of course, nothing can really go to infinity in a finite world, so agricultural systems, particularly our current agro-industrial systems, tend to plow headlong into planetary limits that make the dynamics inherent in hunter-gatherer models relevant again! Humans are a species “built for speed not for comfort” some wag wrote once.

Appendix / Stella Top Level Model Code

Stella’s top-level code for the Hunter-Gatherers with Technology Model is given below. It is useful for determining what the model is actually doing (and hence for trouble shooting the model). It could also be useful for those who want to understand the model in more detail or to use this model as a starting point for their own Stella model.

```
Top-Level Model:
A(t) = A(t - dt) + (s) * dt
   INIT A = 0.050
   UNITS: unitless
   INFLOWS:
      s = c*A
         UNITS: 1/year
K(t) = K(t - dt) + (f - g) * dt
   INIT K = 4000
   UNITS: prey unit
   INFLOWS:
      f = r*K*p {UNIFLOW}
         UNITS: prey unit/years
   OUTFLOWS:
      g = h {UNIFLOW}
         UNITS: prey unit/years
L(t) = L(t - dt) + (b - d) * dt
   INIT L = 100
   UNITS: people
   INFLOWS:
      b = h*q {UNIFLOW}
         UNITS: people/years
   OUTFLOWS:
      d = u*L {UNIFLOW}
         UNITS: people/years
c = m*i
   UNITS: 1/year
e = v*A
   UNITS: 1/(people *year)
h = e*K*L
   UNITS: prey unit/year
i = .0004
```

```
   UNITS: people/(prey unit*year)
j = 30000
   UNITS: prey unit
m = w-y
   UNITS: prey unit/person
p = (j-K)/j
   UNITS: unitless
q = .08
   UNITS: people/prey unit
r = .30
   UNITS: 1/year
u = 0.07
   UNITS: 1/year
v = 0.010
   UNITS: 1/(people*year)
w = 5
   UNITS: prey unit/person
y = K/L
   UNITS: prey unit/person
{ The model has 21 (21) variables (array expansion in parens).
  In root model and 0 additional modules with 3 sectors.
  Stocks: 3 (3) Flows: 5 (5) Converters: 13 (13)
  Constants: 7 (7) Equations: 11 (11) Graphicals: 0 (0)
  }
```