Chapter 8: Processes

Up until now we have treated time (for the most part) as just another attribute. For example BACON used time to discover Kepler’s 3rd Law of Planetary Motion:

\[ \frac{D^3}{P^2} = c \]

where \( D \) is the mean distance between a planet and the Sun and \( P \) is the period (length of year) of its orbit. BACON uses time (in this case, \( P \)), but time does not stand out. It is just another attribute like \( D \). MECHEM was “time-aware” in the sense that it of necessity started with the reagents and went towards products. The concept of chemical mechanism, however, should not be construed as all of the reagents of the first reaction step going to make the products, then all of the reagents of the second reaction step going to make its products, etc. Chemists believe that all reaction steps are happening all the time in parallel, even the reverse reactions, at least as soon as their reagents become available. Thus while MECHEM may have a notion of “progress towards products”, this is different from time.

People, however, do distinguish time as a special dimension. Many (if not most) languages have a notion of tense to describe when or even if the specified action did, is or will occur. Scientists are no different. A lot of effort goes into figuring out how things change with time. Indeed calculus was invented early in the scientific revolution and has been used ever since. It lets us describe changes in time.

Of course calculus is more general than just describing changes in time, and there are changes in other dimensions that scientists want to describe too. Perhaps the strongest contender is space, chiefly when construed as height. How the pressure of a column of “incompressible” fluid varies with height is an interesting problem for those who design submarines and dams. How the pressure of a column of “compressible” fluid varies with height is an interesting problem to aerospace engineers.

Change with space may be important, but change with time is more important. Languages (at least Indo-European ones) generally have more built-in structures for talking about different times and changes in time than they do about space. If our programs fail to consider this then they will fail to generate knowledge corresponding to the richness of our intuitions of the world.

In this chapter we discuss processes: the notion of changes in time. Subsequent systems will be process-aware, and will yield fuller notions of scientific knowledge.

We should cover some notation before we start. I use the term process class to denote a set of related phenomena. (Other researchers like Langley et al use the term abstract process.) One particular happening of a process class is a process instance. When I do not choose to make the distinction between a class or an instance I just say process. A state may either be an instantaneous moment of length \( \epsilon \) or may have some finite (or maybe even infinite) duration. Process instances start at an initial state, occur during a duration state, and end at a final state respectively.
8.1 Attributes of Processes

Processes describe changes in attributes over time. Representing this requires a data structure rich enough to describe which attributes may be changed and over what time.

Let us first discuss time, the most important attribute of a process. A simple way to describe the time of a process is by giving a beginning time ($t_{\text{init}}$) and an ending time ($t_{\text{final}}$), or a beginning time ($t_{\text{init}}$) and a duration ($\Delta t$), or some equivalent pair of numbers. The attributes $t_{\text{init}}$ and $t_{\text{final}}$ may either be “natural” times when some action starts and stops (like the release time of a ball and its impact time with the ground) or may be arbitrary. Arbitrary delimitation times often occur with periodic measurements (e.g., quarterly earning statements) and with cyclic processes (e.g., a planet's orbit around the Sun). Delimitation times may be arbitrary, but for the purpose of process instance comparison and manipulation it is useful if they are consistent.

We can also consider how other attributes change with time. If you have instantaneous information concerning another attribute $\text{attr}$ then the first and second derivatives ($\frac{d\text{attr}}{dt}$ and $\frac{d^2\text{attr}}{dt^2}$) of that attribute may be useful. However, even with just duration information the net change of an attribute over the process' lifetime ($\Delta\text{attr}$) may be informative.

Also, besides relating the time of one process instance with other attributes of the same process instance, we can try to interrelate the attributes of several process instances, including time. An example of this comes from seismology. Aftershocks are earthquakes that come after large “main shock” earthquake events.

Besides the time of the process there are also the things that undergo the change. The changes are manifested as changes in the attributes of these things, or even as changes in the existence of the things themselves (i.e. their creation, destruction or mutation to or from some radical different form). Things are thought of as having attributes just in their nature of thing-ness: mass, charge, color, etc. Allowances must be made for composite objects: in some cases the attribute of a collection of things may simply be the sum of the parts (like mass). Other cases, like color, might require a weighted summing or multi-valued scheme. Additionally scientists allow for the deviation of the relevant attributes from the ordinary as the scale of the process becomes more removed from the everyday intuitive. For example, to a physicist the “color” of an electron is not a meaningful attribute. Color and other attributes are replaced with a new set that is relevant, like quantum spin.

When one physical object has a clear majority of some quantity, such as mass as it relates to gravitational attraction, it might be useful to consider that thing and its property(ies) as part of the environment. An example of this is the acceleration due to Earth's gravitational pull on things much smaller than itself close to its surface.

Besides being pieces of matter some things can be thought of as having and following goals (or at least as having a complex stimulus-response repertoire) and thus as possessing attributes and participating in processes beyond that of “inert” matter. Such things include all living things to one degree or another (especially humans), some machines (especially...
programmed computers and robots), and things with significant metaphysical content to the
degree that scientists choose to believe in them (e.g. angels, devils and other spirits).
Computer science reserves the term agent for such things when they are the initiator and/or
controlling factor of a process or action. English grammar sometimes uses the term subject
for the same idea, and uses the terms direct object and indirect object as the thing being
acting on and the thing used to facilitate the action respectively.

The environment that a process takes place in is often an important factor in the identity of
the process. Further, as was mentioned above, this environment may be defined by presence
of particular dominating objects (and the implicit absence of even more dominant objects).
Acceleration due to Earth's gravity is a good example. It is taken as about 9.8 meters/second$^2$
close to the Earth's surface, and in the absence of anything more massive in the immediate
vicinity. Such things are often implicit in the process' identity, thus processes may lack
generality but be applicable to particular circumstances.

Finally, “magnitude” is measure of how big a process is or how much it influenced. It is
actually some attribute of some thing that underwent a change during the process, but
sometimes it is important enough to uniquely identify. Other times there may be competing
definitions of “magnitude”, so clarity requires we specify which we mean. Again seismology
provides an example. There are several definitions of an earthquake's magnitude: the original
“Richter-Gutenberg” scale is a measurement of observed shaking in the California area on a
particular make and model of seismometer. The $m_b$ and $m_s$ scales are measurements of the
energy released by an earthquake in two different types waves. Only the $m_w$ scale is a true
measure of the energy released by the event.

8.2 Understanding Processes: Discrete Events vs. Continually-Active Principles

An event is a process with the internal details abstracted away. This is useful when
comparing one event to others, or when the internal details poorly known.

![Diagram](image)

This abstraction is often useful, as when representing a series of earthquakes or the changes
in the recognized political boundaries of a country:

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Given an event it is natural to ask about its time (*When?*), its objects (*Who/What?*), its environment (*Where?*), its magnitude (*How big?*), and its relationship with other events. Relationship questions are often just extensions of the questions one may ask about a single event. For example we may ask “Given one or a series of prior events, what can one say about the time, objects, environment, or magnitude of subsequent ones?” The greater goal might be to look for patterns in time, related objects, space or magnitude.

Sometimes, however, when we have knowledge of what occurs during a process, we can decompose that process into a set of principles that are always active. For example a weight remaining stationary on a floor is a good example of a “non-event”. We can, however, understand this as the interplay of *gravity* accelerating the weight towards the center of the Earth and the *normal force* counter-accelerating it off the floor. Both gravity and the normal force are “always on”. The net result is no motion. Motion (an “event”) does result, however, when the weight exceeds the normal force the floor can sustain to support it.
Going back to the earthquake example we can model motion along a non-creeping fault as mostly dominated by friction. Occasionally plate motive forces exceed what friction can support and an event (an earthquake) results.

Having information about what happens during events lets us ask all of the questions pertaining to events plus the questions about the values of the attributes as a function of time, regardless of whether or not we see motion in an event. An important quantity is the maximum load that homeostatic forces, such as friction and the normal force, can sustain. We expect an “event” to occur soon after their limits are exceeded.

Even having information on just one state during a process lets us ask more questions. In chemistry, transition state theory deals with what happens during reactions. An important concept in it is the transition state, the highest energy configuration of molecules and fragments in between the reagent configuration and the product configuration. Without the concept of a transition state we can relate how energetic the reaction (\(\Delta H\)) is to the difference
in energy between the reactants and products. However, with the concept of the transition state we can talk about the rates of reaction. The difference in energy between the reagents and transition state determines the rate of the forward reaction. The difference in energy between the products and transition state determines the rate of the reverse reaction.

8.3 Compositional Processes

Process instances are often thought of as being composed of more primitive, more atomic, subprocess instances. Subprocesses may relate to their encompassing superprocess in a variety of ways but it often useful to break down the relationship into serial and parallel occurrences.

Serial occurrence is obviously that a sequence of subprocesses happens one after another, and that this series constitutes a larger process. Cycles in time (to be discussed in subchapter 8.5) provide many examples. For example, biologists have divided the act of cell division into interphase, prophase, metaphase, anaphase and telophase.

Parallel occurrences obviously share a significant amount of temporal overlap, and the sum of all of the subprocesses acting in concert comprises the superprocess. One example of this is the observed motion of the North American plate relative to the Pacific plate as observed off the coast of California. This motion can be decomposed into three simultaneous subprocesses: (1) the mostly northward movement of the Pacific plate along the San Andreas fault, (2) the north-west to south-east stretching Basin and Range region to the east of the San Andreas, and (3) the movement of the coastal region itself. Little was known about the coastal movement but its velocity vector was computed by vector arithmetic.

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Of course it may be natural to describe a composite process instance using both serial and parallel decomposition. Again, the North American and Pacific plate motion process serves as an example. The motion of the San Andreas fault happens in parallel with the stretching of the Basin and Range and the motion of the coast. Motion along the San Andreas, however, may itself be decomposed into individual creep and earthquake events. The creep events may happen in parallel but the earthquakes are largely serial.

8.4 The Fuzziness of Change

Real-world processes can be quite complex things. For example, the labeling of a time when a process is said to truly start (or stop) may arbitrary, even for non-cyclic processes. A good example of this is the difficulty in pinning down an exact time for a change.

Plutarch attributed the following to the ancient Greeks. The Athenians came in possession of a ship from Theseus for an extended period of time. As the planks of the ship rotted the Athenians dutifully replaced them with new planks. The philosophers among the Greeks argued whether the ship was still the same ship. Plutarch took the question to its limit by asking what if the whole ship had be replaced, plank by plank. And we can consider what if the old planks went to form another ship. Which ship, if either, was the ship of Theseus?

One solution can come from the our ability to decompose processes into subprocesses. We can (if we so choose) model each plank replacement “event” in the overall process of improving and increasing the Athenian-supplied content of just one ship. Each event increases the Athenian content on the ship from \( \frac{n}{m} \) to \( \frac{n+1}{m} \), up to a maximum limit of \( \frac{m}{m} \). The ownership of the ship as a whole can be defined by several things, including how much content of the ship was supplied by the various parties.

8.5 State and Process Sequences and Cycles

A series of processes often cycles back on itself. In the simplest case each completion of an instance of a process begins the next instance of the same, as when a planet orbits a star.
Other cases involve processes with a linear series of instances that spawn a new series of instances before they terminate. Each linear series can be called a generation. If we redefine “childhood” as the verb “the process of being a child”, and do the same for “adulthood” then the life of an organism may be thought of as the sequence of process instances.

Following the cross-generational process instance path yields a life cycle.

Life cycles are for more than just living things. Stars, for example, can be said to have a life cycle. Their end-of-life explosions adds high atomic mass atoms to interstellar dust clouds and may help jostle them into collapsing into new stars.

Several complications exist in formulating cycles. First is that if entropy affects the system then the cycles may gradually reduce in magnitude until they are indistinguishable from a...
static state. Such is the case for “real-world” pendulums, watch springs, etc. due to friction.

Energy can leave cyclic systems for other reasons. L-C circuits connect an inductor with a capacitor. Electricity in such a circuit alternates between manifesting itself as magnetic field energy in the inductor and electrical field energy in the capacitor. Electrical energy sloshes rhythmically between the two but will eventually dissipate. One reason is electrical resistance in the circuit itself. However, even if all components of the circuit were superconducting then this would still happen. Both the magnetic and electrical fields are spatially distributed. They would bleed away by interacting with matter around the circuit.

An L-C circuit. Electrical energy alternates between manifesting itself as a magnetic field in the inductor on the left and an electrical field in the capacitor on the right.

A second complication of cyclic processes is that the system may be powered or modified in other ways. One example of this is the orbit of the Moon around the Earth. The Moon currently orbits the Earth once every 27 days, 7 hours and 43 minutes approximately. We believe this has not always been the case. We believe that the Moon used to be a lot closer the Earth but that it, over time, receded. The reason, we believe, is because of tidal torque.

We believe that tidal torque works like this. The Moon and Earth pull on each other. On the Earth this causes tides: two bulges of oceanic water both toward the Moon on the moon-facing side and away from the Moon on the opposite side. Another interesting question is “Why are there two tidal bulges?” The one on the Moon-facing side of the Earth is due to the gravitational pull of the water by the Moon. The one on the opposite side is due to Moon's pull on the Earth as a whole. If you think of the Earth as a dense rock wrapped in an envelope of less dense fluids (the ocean and atmosphere) then the Moon's pull is strong enough to preferentially attract the denser rock portion of the Earth toward it. The ocean, having less mass per unit volume (less density than rock) is not as attracted to the Moon as Earth's rocks are. And because the ocean is fluid, it can move. In this case it circles the globe as a bulge on the opposite side of the orbiting Moon.
This system would be in equilibrium if the Earth rotated in lock-step with the Moon so that the same face of the Earth always faced the Moon. The Earth, however, rotates faster than the Moon (once a day obviously instead of about once every 27 1/3 days). This causes the tides to be a lead the Moon.

Because the tides lead the Moon, the Moon's gravity pulls on them to hold them back. As the Moon pulls Earth's oceans back, and the oceans pull the rotating Earth back thus decreasing the Earth's rate of rotation. Currently this decrease is about 1.5 to 2.0 milliseconds per century.

Just as tidal torque serves to slow Earth's rotation, so it also powers the receding of the Moon. The torque continually pulls on the Moon, accelerating it into a higher orbit. The Moon currently recedes from the Earth at the rate of 3.8 centimeters a year.

Tidal torque exists because the Earth spins faster than the Moon orbits, but it also causes the Earth's rotation to slow. Eventually, either the Moon will orbit fast and far enough to leave the Earth completely, or the Earth will slow down enough to rotate in lock-step with orbit of the

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Moon. (The Moon probably also rotated along its own axis, but this tidal torque mechanism already forced it to rotate in lock-step with its orbit around the Earth. Thus, only one side of the Moon is visible from the Earth.)

A third complication of cyclic processes is that cycles may occur within cycles. The “Carbon Cycle” is one such example. One sub-cycle is the annual exchange of CO₂ between the atmosphere and living things through photosynthesis, predation on plants and decomposition. Another sub-cycle is the exchange of CO₂ between the atmosphere and the Earth’s waters. Another longer sub-cycle is the burying of plant and animal matter in the Earth, and its uncovering by the natural and man-made processes.

The Carbon Cycle. Pools, shown in black, are in gigatons. Flows, shown in purple, are in gigatons/year. Courtesy of United States National Aeronautics and Space Administration Earth Science Enterprise.

8.6 Timescale

Processes may be hard to recognize because of their timescales. For example, some things look static because they are so slow. A human scale example is the growth of many organisms. Geological scale examples include the motion of the Earth's tectonic plates, and the afore mentioned recession of the Moon and slowing of Earth’s rotation.

There are several options for tracking slow processes. For slow but still human-scaled processes like the growth of organisms we may use time-lapse photography and other time-lapse imagery. For geological scale processes like the motion of plates, the slowing of the Earth's rotation and the recession of the Moon we may use the very precise measurement, when possible².

² Plate motion has been confirmed by precise measurements using (among other techniques) the United States' Global Positioning System (http://sideshow.jpl.nasa.gov/mbh/series.html). The Earth's rotational slowing has been confirmed by Very Long Baseline Interferometry where several radio telescopes observe quasars: very old and very distant radio sources. The rotation of the radio telescopes at the surface of the Earth can be measured by letting the wave fronts of several telescopes interfere and then examining the Doppler shifts. (Police radar guns work in a similar fashion; they compare the sent and received waves to deduce the speed difference between observer and the target car.) Lunar recession has been confirmed by bouncing laser beams off reflectors left by Apollo astronauts and timing their flight.

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When objects are not accessible for direct measurement it is common to look at a population of objects, and to use some model to infer where subpopulations are in their lifespan. One example of this is the lives of stars. Stars were observed and categorized by their luminosity and their exterior temperature. When stars were understood as being heated by fusion they could be modeled over their lifetimes based on their initial mass and knowledge of fusion reactions. Thus, the star classes, which dated in one form or another to the 19th century could be related to temperature and brightness, and then to age and mass.

Another example of observation and the usage of a model to infer ages of subpopulations comes from the inferred relative ages of Saturn's rings. The age of Saturn's rings has been debated. Some have said that they are about the same age as the Solar System (about 4,500 MY). Others have said that they are only about 100 MY old. Rather than rely on the planetary observations of Cretaceous Age dinosaurs the United States' National Aeronautics and Space Administration sent the Cassini probe to Saturn with an Ultraviolet Imaging Spectograph (UVIS). This instrument measured the ring light as a function of radius from Saturn and frequency. From this information, in addition to measurements of the attenuation of Sun light passing through the rings at different ring radii and different frequencies, the albedo\textsuperscript{3} and phase function\textsuperscript{4} of the rings' particles can be computed. Finally, the albedo and phase function information was used to guess the composition of the rings as a function of radius.

We believe the rings to be mostly water-ice. The longer the rings have existed, the more time they have been around to be collided into by mainly ferrous meteors, the higher the proportion of rock in them should be. A picture taken by Cassini's UVIS on 2004 June 30 shows more rocky material in the inner rings and less in the outer rings. This suggests that the inner rings have existed for longer. (It has also been suggested that Saturn's rings are continually being destroyed and created.)

\textbf{False color ultraviolet picture of Saturn’s rings from NASA Cassini spacecraft. The pink color of inner rings indicates “dirtier”, perhaps smaller-sized particles. The turquoise color of outer rings indicates more icy composition. Image courtesy of NASA/JPL/University of Colorado}

\textsuperscript{3} The fraction of photons reflected from the surface; the brightness.  
\textsuperscript{4} Refractive scattering profile of a particle for light. The refractive angle depends on the particle’s composition, size, and shape; and upon the incoming light’s frequency and incident angle.

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In addition to states that look static because the underlying processes are so slow, states may look blurred because they are so fast. Fast processes may even appear static if the forward process occurs at the same rate and the reverse process. An example is the mostly random motion of air molecules, where about as many impact the left side body as strike the right side in a windless room to impart about equal amounts of momentum.

The most direct way to handle this is with high-speed photography or other high-speed imaging. For example, this is sufficient for resolving how hummingbirds flap their wings to hover and fly.

![Hummingbird](image.jpg)

Higher speed photography at least slows down the motion of hummingbird. Image courtesy of Joe Phillips.

Several technologies exist for the extremely high speed photography needed to examine explosions and small but fast biological processes. Systems of rotating prisms and mirrors have given way to CMOS technology capable of recording 1 million frames per second.

If the underlying process is periodic then strobing techniques that highlight brief but repeating states may be employed. One example is the use of strobe lighting to check the timing of engines. Another example is the use of oscilloscopes in periodic behavior that is electrical in nature, or which can be converted to electrical signals.

Laser pulses have been employed to examine even quicker processes. The science of femtosecond chemistry studies chemical events that occur at speeds on the order of picoseconds (10^{-12} seconds) or femtoseconds (10^{-15} seconds). A common technique is to shine two very short laser pulses at a sample in quick succession. The first pulse serves to initiate some reaction among most molecules in some sample at exactly the same time (for example the breaking of a bond). The second pulse serves to query the molecular species by seeing what they will absorb. Varying the frequency of the second pulse of light sweeps out a spectra that tells us about structure of the on-going reaction at one instant in time. Varying the time between the first and second pulse tells us how the reaction develops over time. Together they tell us how the whole structure evolves over time, and give us more evidence for transition state theory.

And, as with slow processes, confirmatory theory may also be applied. The kinetic theory of gases tells us to expect that invisibly small air molecules are always on the move at speeds around the speed of sound. Brownian motion, particle diffusion and speed of sound and shockwave measurements offers confirmatory macroscopic evidence.

8.7 Magnitude
Processes that appear to be unique may sometimes be related to others at different magnitudes. For example, the largest terrestrial impact for which we have evidence was quite large. It is hypothesized that after the core-forming “Iron Catastrophe”\(^5\) the Earth was hit by a Mars-sized object. That impact was violent enough to cause the cores of both bodies to meld into a larger core for Earth, and to tilt the Earth to its current 22 degree angle. Some of the ejecta and residue clumped together in Earth’s orbit as our core-less Moon.

Images from a computer simulation of the early Earth being impacted by a Mars-sized body.

Certainly this was quite an unprecedented meteoric event; fortunately nothing like it has ever happened since. Was it that truly that unique? If we make a log-log plot of the frequency of impact events against their sizes we get the following.

**Frequency of meteor impacts by diameter, with Moon-forming event at far bottom right.** The Moon-forming event is slightly off the main line, but this might be attributable to expected higher number of impacts on the early Earth. Data from ‘The Impact Hazard’, \(^5\)

\(^5\) The Iron Catastrophe happened early in the Earth’s history. Once the combination of imparted meteoric heat and radioactive energy heat warmed the early Earth to the melting point of Iron, much of the previously randomly distributed Iron on Earth fell into the center to form the Earth’s core. This process released even more gravitational energy, and heated the Earth even hotter.

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The Moon-forming event is slightly off the main line, but this might be attributable to the expected higher frequency of impacts to which we believe the early Earth was subjected. Thus we can think of even this unprecedented occurrence as an event on a continuum of similar events (in gross description, if not result).

8.8 Representation

Computer scientists, and artificial intelligence researchers in particular, have generally associated several pieces of information with processes process-like objects. These include boolean expressions telling the conditions that must be true before the process can be done, boolean expressions telling what is true after the process is finished, and equations and other knowledge structures telling what might be true during the process. However, how shall we related one class of processes to others?

Each could be conceptualized as independent from all others. This is “safe” in the software engineering sense because there is no or little dependence between process classes. However, it offers little opportunity for generalization across process classes.

An alternative is to use a hierarchy. A given process can be thought of as a more specific subclass of one or more “base” classes, as is done with classes in object-oriented languages. This allows for more natural sharing of properties through inheritance. A potential problem with this, however, is how well the language's multiple-inheritance scheme agrees with the user-scientist's conceptualization of their domain. For example, attributes like forces are often cumulative: one just sums all forces active at a time. However, for attributes like _____.

Another question is “How shall a sequence of process instances be represented?” Computer scientists, of course, rank languages by their expressiveness: regular expressions for those expressible by finite state machines, context free languages for those expressible as push down automatons, and recursively enumerable languages for those expressible as Turing Machines.

I believe most scientific occurrences to be expressible with regular expressions/finite state automatons. For example, consider the act of following one Carbon atom around the multicyclic “Carbon Cycle” diagram given in subchapter 8.5. If we limit ourselves to the resolution of sinks given in the diagram then when it appears in any one particular sink it may either stay there or follow any given flow, independent of its prior history. Because scientists try to identify and characterize the relevant state information so as to make the computation of the properties of the next state as deterministic (or at least as Markovian stochastic) as possible, we may indeed have the historical knowledge needed to compute the next state from just the current one.

Computer scientists are familiar with context free languages because many programming languages have this syntactic form. Context free grammars let us match beginning and ending quotes, parentheses, curly-braces, square-brackets, begin and end statements, etc.
to an arbitrary depth and with variable nesting. I believe that they may have limited application in science to keep track of hidden state. For example, in geology three layers can be deposited (A, B and C) in order and then eroded away in reverse order (C, B, and A).

![Diagram](image)

Geologists, however, would be among the first to tell you that this is a toy example. Even a cursory look at a river or canyon tells us that erosion is often uneven, so that all layers A, B and C are often simultaneously visible throughout much of the existence of the structure.

Last and most expressive are, of course, the recursively enumerable languages recognized by Turing Machines. Turing Machines are useful in dealing with context. Context appears in constructs like natural language. For example, in English we can use either the reverse-order matching expressible in context-free languages:

```
The first, second and third prime numbers are 5, 3 and 2 in reverse order.
```

or in order listing:

```
The first, second and third prime numbers are 2, 3 and 5 respectively.
```

The listener (or in your case, reader) is unsure which listing technique is being used until being told at the end of the sentence. This flexibility, this context, requires a Turing machine (or its equivalent) in the general case.

To the degree that natural language is in the set of natural phenomena being modeled one might need the full expressiveness of recursively enumerable languages, and the full computational power of Turing Machines. However, I believe this to be an anomaly. How most process instances actually occur can (I believe) be expressible with nothing more than finite state automatons.

Finally there is the matter of describing the change itself. There are several approaches to this. We have already seen the **qualitative physics** approach. This approach seeks to abstract away from particular values of attributes in favor of noting whether they are at or in
between landmark values. Thus, previously real-valued attributes have their domains restricted to a finite ordered set of alternating landmark, in-between-landmark values. Only the first derivative is noted, and then only at the resolution of increasing, steady or decreasing.

If this is all the information that you have then this is the best you can do. Handling numeric information, however, requires a more powerful representational approach.

Another representational form from artificial intelligence is situation calculus. Situation calculus was developed for planning domains in which one or more agents (e.g. robots) have near deterministic control over the interesting aspects of the environment. (If their control was highly random why bother planning?) It sees the environment as abstracted into a list of situations or states, each defined by what is true in it. Fluents (what we have been calling attributes) can have different values in different situations. The job of the agent is to manipulate the situations into one where a set of goals have been met. This is done by taking actions to change one situation into another. The actions have conditions that must be true in the starting situation and result in fluents assuming particular values in the resulting situation. Fluent values in the resulting situation are computable from the actions, and an explicit or implicit set of frame axioms that tell how the environment changes, and especially how it stays the same.

The situation calculus notions of situation and action are directly analogous to the scientific notions of state and process, but situation calculus was designed for the needs of planning rather than scientific representation. There is the implicit assumption that the results of actions are known with a reasonable degree of probability. There is sometimes also the assumption that only a small number of agents are responsible for changing the environment. In general we cannot make these assumptions in scientific modeling and discovery.

**Difference equations** allow one to also specify how attribute values change between one state to its next by abstracting away from the details that happen during the process. For example, we may state a difference equation where attribute attr depends on three other attributes: x, y and z:

\[
\text{attr}(t+1) = \text{attr}(t) + \text{changeFunction}(x,y,z)
\]

Difference equations are useful when we want to (or have to) abstract away from the details of the process as it happens. Sometimes, however, that is what we want to model.

**Ordinary differential equations** let us describe what happens during a process as functions of some independent attribute, often time. With this we now may, for example, express Newton’s 2\textsuperscript{nd} Law:

\[
F(x) = d^2x(t)/dt^2
\]

Lastly, for even more representational power there are **partial differential equations**, which allow more than one independent variable:
\[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0 \]

Such systems are general but can be hard to model and manipulate. How to work with them is an on-going issue in the numerical methods community.

### 8.9 Summary

The modeling of processes is important because much of science is about changes in time. There are many complications in representing processes, including:

- Do you have just *before* and *after* information, or do you have any *during* information?
- If you do have during information, how much do you have? 1st derivative? 2nd derivative?
- Can you decompose the process into parallel or serial subprocesses?
- Can you understand the process as the interplay of two or more forces that are always active?
- Can you give a principled definitions for saying when a process really starts or stops?
- Can you handle cyclic processes? Poly-cyclic processes?
- Can you recognize and work with processes that occur very slowly? Very quickly?
- Can you find the commonality among processes that happen on radically different scales and magnitudes?
- How do you intend to represent your set of processes so they share their common traits and express the changes that you need?

The systems that we will discuss in subsequent chapters will be explicitly aware of changes in time, and will be able to model how states progress over time.

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