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Technology and human purpose: the problem of solids transport on the earth's surface

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Abstract

Displacement of mass of limited deformability ("solids") on the Earth's surface is opposed by friction and (the analog of) form resistance – impediments relaxed by rotational motion, self-powering of mass units, and transport infrastructure. These features of solids transport first evolved in the biosphere prior to the emergence of technology, allowing slope-independent, diffusion-like motion of discrete objects as massive as several tons, as illustrated by animal foraging and movement along game trails. However, high-energy-consumption technology powered by fossil fuels required a mechanism that could support advective transport of solids, i.e., long-distance, high-volume, high-speed, unidirectional, slope independent transport across the land surface of materials like coal, containerized fluids, and minerals. Pre-technology nature was able to sustain large-scale, long-distance solids advection only in the limited form of piggybacking on geophysical flows of water (river sediment) and air (dust). The appearance of a generalized mechanism for advection of solids independent of fluid flows and gravity appeared only upon the emergence of human purpose. Purpose enables solids advection by, in effect, enabling a simulated continuous potential gradient, otherwise lacking, between discrete and widely separated fossil-fuel energy sources and sinks. Invoking purpose as a mechanism in solids advection is an example of the need to import anthropic principles and concepts into the language and methodology of modern Earth system dynamics. As part of the emergence of a generalized solids advection mechanism, several additional transport requirements necessary to the function of modern large-scale technological systems were also satisfied. These include spatially accurate delivery of advected payload, targetability to essentially arbitrarily located destinations (such as cities), and independence of structure of advected payload from transport mechanism. The latter property enables the transport of an onboard power supply and delivery of persistent-memory, high-information-content payload, such as technological artifacts ("parts").

1 Fossil energy

Large-scale technology is the term used here collectively for the power, communication, industrial, governmental, military, and other widely distributed and interconnected technological systems on whose function modern civilization and society is based. Large-scale technology is largely powered by fossil energy sources, which in 2009 supplied more than 80 % or 411EJ (International Energy Agency, 2011) of world total primary energy supply. In addition to solid-form energy resources like coal, global technological function also depends on rapid transport of a range of solid-like materials, or “solids”, of limited deformability, such as containerized hydrocarbons, ores, sand and gravel, food, freight, people, as well as assembled or partially assembled subsystems or parts destined for integration into larger technological systems. Fossil fuel deposits and other mineral deposits tend for geological reasons to be spatially confined to zones of concentration widely dispersed across the globe. Sources for parts (factories) are also scattered geographically. Thus the metabolism of large-scale technology, i.e., the sum of all energetic technological processes, demands that the requisite solids be transported over long distances, up to thousands of kilometers, between discrete locations with pinpoint accuracy.

2 Advective transport of solids

The fast metabolism of modern technology (~13 TW) requires movement of mass over long-distance (up to thousands of kilometers), at high-speed (meters per second) and high-volume (e.g., ~5 GT or 5 km^3 of coal was consumed worldwide per year in 2008, World Energy Council, 2010), i.e., an advective transport mechanism in which bulk mass is moved essentially unidirectionally. The alternative is a diffusion-like (referred to below for simplicity as “diffusive”) transport mechanism in which small parcels of mass are moved about with frequent changes in direction of motion. In the lexicon of this paper the dispersal of goods by car, delivery trucks, and similar conveyances through city streets is a diffusive process, whereas transport over major long distance highways or rail lines is an advective process. If a unit of mass is transported over a straight-line distance L at a given speed v (advection), and the same unit of mass is transported over the same net distance at the same (instantaneous) speed v, but by means of a large number of small displacements $l \ll L$ that are quasi-randomly oriented with respect to one another (diffusion), then the ratio of diffusive to advective time scales for transporting the mass the distance L is L/l. If a fleet of trucks traveling at fixed speed on a highway that connects two cities that are 100 km part requires 1 h to make the trip, the same trucks moving at the same speed on a random network of roads each with length 0.1 km (the length of a typical city block) would require on the order of (100/0.1) = 1000 h, or almost six weeks, before a significant fraction of the trucks had moved 100 *km* from their starting point.

A metric that captures (i) the amount of mass moved, (ii) the distance that it is moved between significant changes in direction (such as the highway or city-block distance measures of the preceding paragraph), and (iii) the instantaneous speed of displacement, is mass action (Haff, 2010), $A = mlv$, where m is the quantity of mass, l is the displacement distance or mean free path, and v is the average displacement velocity along l. When summed over the different masses moving in a given transport process, such as process A, highway traffic, or process B, city traffic, then the ratio of the summed mass actions for the two processes is the relative mass action number $\mathrm{Ma}_{A,B} = \sum_A mlv \Big/ \sum_B mlv$. (To make contact with a more familiar problem, if processes A and B refer to transport of molecules in a fluid by (A) eddies and of the *same* molecules by (B) their thermal motion, then $\mathrm{Ma}_{A,B}$ reduces to the Reynolds number of the fluid $\mathrm{Ma}_{a,b} \rightarrow Re$.) In the example of the previous paragraph, the mass action number for highway versus city street transport of the same mass at the same instantaneous speed would be in order of magnitude $\mathrm{Ma}_{\mathrm{highway,city}} \sim L/l = 1000$. The total mass action of technological land transport processes is of the same order of magnitude as the mass action associated with sediment transport by all the world's rivers (Haff, 2010).

Advection of solids over large distances occurs in nature where solids piggyback on fluid motion, as in the transport of river sediment. However, to support the high metabolic rate of technology using resources fluxed from randomly located sources, a mechanism is required that can transport solids across the Earth's surface in directions and at rates that do not necessarily have any connection to natural fluid flows. Sustained movement of large quantities of solids across the Earth's surface is difficult for several reasons. The first is that the friction coefficient between the land surface and most solid bodies is large. An irregularly shaped block of solid material will typically stay in place when positioned on a slope less than the angle of repose, which is usually on the order of 30° (Anderson and Anderson, 2010), implying a coefficient of friction $\mu \geq 0.6$. A solids transport mechanism in which the block was simply pushed across a horizontal surface would require a force $F_p = \mu m g$, where m is the mass of the block and g is the acceleration of gravity. If for illustration we take $\mu = 1$, then a 1 kg mass would require a minimum force of at least 10 newtons in order to keep it moving on level terrain. A block of coal with nominal mass density $\rho_{\text{coal}} \sim 1000\,\text{kg}\,\text{m}^{-3}$ and linear dimension $D = 0.1$ m has a mass of 1 kg and a cross-sectional area $A = 0.01\,\text{m}^2$. For a strong near-surface wind with speed on the order of $V_{\text{wind}} = 10\,\text{m}\,\text{s}^{-1}$, with air density $\rho_{\text{air}} = 1\,\text{kg}\,\text{m}^{-3}$ and aerodynamic drag coefficient $c \sim 1$, the force exerted on the block by the wind would be in order of magnitude $F_w \sim A c \rho_{\text{air}} V_{\text{wind}}^2 = 1$ N. Thus the ambient power $F_w V_{\text{wind}} \sim 10$ W supplied by even a strong wind at the surface is too small to displace even a relatively low density solid object of modest size. Small particles, for which the ratio of surface to body force is large, can be moved long distances by fluid forces, as happens in dust storms, or when sand and gravel are transported in a river, but until geologically recent times there existed no mechanism by which more massive solid objects could be moved unidirectionally across the land surface for a sustained period of time.

3 Onboard power source

Aside from displacement by occasional events like landslides, transport across the land surface of solid or limited-deformability objects as large as several tons became possible (and common) only with the evolution of land animals. The appearance of tetrapods in the middle to late Devonian (Niedzwiedzki et al., 2010) (and earlier for arthropods) overcame the low ambient power density, high-friction limitations to solids transport on land by the introduction of two innovations, both of which later also played a critical role in enabling technological transport. The first innovation was inclusion of the motive power source as part of the transported mass. A self-powered human weighing 50 kg walking on a level, firm surface at moderate speed ($1.3\,\mathrm{m\,s^{-1}}$) requires an energy expenditure rate of about 60*W* above base metabolic rate (Ainsworth et al., 1993), a level easily maintained for extended periods of time (hours). Self-transport by legged animals occurs mostly over relatively small distances with frequent changes in direction, i.e., it is diffusive. Nonetheless, the biological evolution of onboard power systems was an essential step in enabling land transport over a high-friction surface where reliable sources of ambient mechanical power were lacking. Technological transport on land faced the same power problem as biological transport, and adopted the same solution – onboard motors, such as those that propel cars, trucks, and trains.

4 Rotary motion

An onboard power source alone, however, is not sufficient to overcome frictional resistance to sustained motion either for biological or for technological systems. Using humans again as an example, the 60 W internal energy source would not be very effective by itself in powering translation across the land surface if the transport mode were sliding. For a 50 kg person to drag herself (with $\mu = 1$) across the ground at a typical walking speed would require the application of ∼500 N of force and an energy expenditure rate greater than ∼600 W. A second transport innovation was required to support large-animal locomotion on land. This was rotary motion, which appeared in the form of pendulum-like motion of limbs in animals. Rotary motion significantly reduced the retarding effect of friction on dry land, enabling slope independent diffusion of animals with mass measured in tons (e.g., mammals and dinosaurs). For the same reason rotary motion also emerged in technology in the modified form of the wheel, enabling transport of multi-ton objects across high-friction terrain.

5 Form resistance and infrastructure

Even with an onboard power supply and a rotational mechanism that avoids the braking effect of friction, there remains a mechanical impediment to advective transport, namely, what in fluid mechanics would be called form resistance. The flow of water in a river is driven by gravity and is resisted by two kinds of forces. The first is (skin) friction between the moving water and the bed. This frictional force is mediated by small scale roughness of the bed and is analogous to the frictional resistance that is felt by a solid body dragged across a surface. Form resistance, or form drag (Furbish, 1997), on the other hand, arises from larger-scale surface roughness where the size of roughness elements may approach an appreciable fraction of the depth of flow. An analog to fluid form resistance is the impediment to motion offered a solid object on land by an obstacle with vertical dimension comparable to that of the object or to parts of the object that are critical to the transport process, as a rock or shrub might offer resistance to the passage of an automobile or, with the same result, to its wheel. Form resistance to water flow across the Earth's surface is reduced by the spontaneous formation of a river channel, an emergent structure whose effect is to remove larger obstacles that might impede flow, as when a river cuts through rugged terrain and clears debris along the immediate flow path, and to decrease the relative size of remaining surface irregularities by locally increasing the water depth. The river channel in its modification of the transport environment to reduce form resistance represents a kind of transport infrastructure. Advective transport of solids on land requires transport infrastructure like highways and railways for the same reason – to smooth the natural landscape.

6 Absence of continuous potential gradient

In the case of steady-state transport, a driving force or affinity must do work in order to maintain the flow of mass, and to form and maintain infrastructure. For natural systems the origin of the driving force is a gradient in an environmental variable, such as elevation in the case of a river. The gradient also defines the direction of transport. For the river we understand the physical processes that act to overcome friction and generate the infrastructural channel. These processes are direct consequences of extraction of energy from the gravitational potential and the consequent application of a force that causes flow and generates infrastructure via erosion and sediment transport (e.g., Anderson and Anderson, 2010). Sustained advection of solids across the Earth's surface must likewise be driven by a gradient in a suitable environmental variable. The oil pools and coal beds sequestered below the Earth's surface define an average gradient in stored chemical energy relative to any point where such deposits are scarce. However, unlike the space-filling gradient of elevation that at most points on the land surface provides a force that can power river flow, the chemical energy in fossil energy deposits is confined to the geologic source area and can exert no intervening influence by which to power motion of mass to distant points. This is one reason that fossil-fuel deposits have not already undergone wholesale depletion. Some depletion does occur naturally of course, as in coal-bed fires (Heffern and Coates, 2004) or biodegradation of crude oil (Jones et al., 2008), but this tends to occur in situ and to be slow compared to the rates of technological energy extraction.

7 Purpose and transport

To help focus on the missing factor necessary to understand the origin of advective solids transport we first consider the example of atmospheric convection. In the temperature inversion that occurs when solar radiation heats the ground and adjacent layers of the atmosphere, the temperature difference between lower and upper atmospheric layers generates density differences and hence a buoyancy force that propels parcels of hot air upward as convective plumes. At each point in the motion of a typical ascending parcel of air, local pressure differences overcome the frictional retarding force and sustain the parcel motion. Transport of an element of mass across the Earth's surface also requires continuous application of a suitable force to overcome friction. In the case of rail transport of coal from a mine to a populated area the physical force that drives mass transport and overcomes air resistance and internal friction is the force exerted by the rails on the wheels of the locomotive. The force is applied at every point along the transport path. Identifying this force is as full an answer to the question of what causes advection of fossil fuels as the identification of the buoyancy force answers the question of what "causes" hot air to rise. A fuller explanation of each phenomenon requires answering a different question, namely, what is the origin of the applied force? Because we can easily imagine how thermal conduction heats a layer of near surface air and because we have a physical understanding of why heated air expands in volume, and because we understand the basic physics of buoyancy, the explanation of thermal convection of the atmosphere can be made entirely in the language of physics.

In the example of transport of coal, while we can explain the physics of the force that causes the coal to advect in terms of the action of a diesel engine and all the internal linkages that end up exerting a force on the rail and then back on the train, there is no explanation in the language of physics for the origin of the force. Rather the origin is explained as a consequence of human purpose: people want the coal to appear in a place that is distant from its source location. The dynamical problem that purpose solves by, in effect, enabling action-at-a-distance dynamics is the problem of lack of a suitable continuous potential gradient between separated source and sink zones. Purpose provided a basis for emergence of a nonlocal Earth system dynamics in which mass and energy could propagate between widely separated points in the absence of an intervening force field. Human purpose is an ultimate cause of transport and the diesel engine is a proximate cause. The distinction between proximate and ultimate cause is well understood in biology (Mayr, 1961) where for example the proximate cause of the bird taking flight is the approach of a predator and the ultimate cause is a genetically determined survival instinct. The concepts embodied in Darwinian evolution provide an overarching theory of biological systems and the origin of certain ultimate causes. Construction of a comparable meta-theory of large-scale technology has begun (e.g., Arthur, 2009), but is not yet well developed. We are still stuck in the "organismal" phase of technology where the focus is on materialized artifacts and systems rather than on the collective dynamics of technology in the large. Consequently, attributions of ultimate causation to phenomena such as human purpose appear to skirt the issue of providing valid dynamical, explanations of modern earth function

Invoking human purpose as the cause of a physical force seems like an abandonment of the principles of science, which, since Darwin, has mostly abjured teleological explanations (e.g., Mayr, 1992). There are often good reasons for this stance-experience shows that physics, chemistry, and most of biology are explicable in terms that have nothing to do with human intention. However, it is also true that the explanation of the behavior of any sufficiently complex system requires appeal to emergent phenomena or properties suggested by observation of the system itself and not (only) by reference to the underlying physics (Werner, 2003). The behavior of an ant colony is explained (Holldobler and Wilson, 1990) in terms of the actions or behavior of the queen, of drones and workers, of chemical trails and external environmental factors, and so on, not in terms of the underlying molecular physics. Physics and chemistry can inform our understanding of specific mechanisms of complex system function, such as the role of pheromones in ant signaling, but fail to provide a complete explanatory basis for whole system behavior. New levels of explanation are required. Human purpose, a product of Earth evolution, is an emergent real-world phenomenon that has physical effects, such as its role discussed here in enabling solids transport. It should be expected that in general purpose or intention cannot be excluded from the dynamics of systems that include humans among their parts.

8 Independence of payload from transport mechanism

The appearance of rapid long-distance solids transport made possible long-distance conveyance of payloads with arbitrary physical structure and properties. That is, (part of) the transported mass could be decoupled from the transport process itself. This is not the case with the Earth's other mechanism for large scale movement of mass-fluid flow. The difference in transport mode of fluids and solids reflects differences in constraints on internal degrees of freedom of the transported mass. The easy deformability of fluids results in the accommodation of their internal configuration to the demands of transport. For example part of the mass of a river flowing over a rough bed is configured in a way that effectively smooths out surface irregularities, thus reducing friction for the rest of the flow, while the bulk of the flow configures itself into eddies that operate to transport momentum internally toward the bed as part of the transport process. In solids transport, by contrast, most internal degrees of freedom are uninvolved in the transport process – they are frozen in place and come along for the ride. Unlike in fluid flow, in solids transport there is a clear separation of "payload" from transport mechanism. There is then, in general, no necessary restriction on the constitution of the payload.

9 Solids and memory

A significant consequence of decoupling of payload from transport mechanism follows from the fact that solids have an enduring memory. Solids can maintain their information content throughout the transport process because they need not restructure on the fly to participate in transport dynamics. A knife retains its sharp blade and a computer retains its transistors, keyboard and other elements of its design, and both retain their functionality, however far they are moved. Preservation of memory during transport is a key property that allows construction of large technological systems from a collection of smaller technological parts or artifacts that are assembled at geographical locations removed from the point of manufacture. This is a physical reflection of the combinatorial process that underlies technological evolution (Arthur, 2009). In-place construction of parts and subsystems that together comprise a large technological system is generally not possible because the distribution of source materials and information (knowledge) to be encoded in structure and function are determined by exogenous factors (like the distribution of geologic resources or human expertise) that bear no necessary relation to the disposition of the technology into which they will be incorporated. A transformer in an electrical distribution system does not grow organically in place but is imported in one piece from the location where it was assembled. The information built into the transformer in the factory, and not otherwise available to the grid, is preserved in transit to become part of the total information content of the grid system. In a similar way all large technological systems are comprised of many composite solid parts, each with pre-installed memory, the overwhelming majority of which were advectively transported over large distances prior to incorporation as system parts.

10 High accuracy transport to arbitrary destinations

A portable power source together with transportation infrastructure provides the basis for another property necessary to the function of spatially extensive, high-metabolism technologies – namely, high spatial accuracy of delivered payload to essentially any location. Large technological systems contain many parts and require resources whose placement relative to other parts is critical for system function. For example, coal from a mine must end up at the power plant that burns the coal even though the power plant has no necessary geographical relation to the mine and may lie at a great distance.

The Scherer power plant in Atlanta (McPhee, 1997) is a tiny target, subtending an angle of only 0.04° as seen from its coal source at the Black Thunder Mine in Wyoming, but the coal arrives exactly at the location of the power plant. Likewise food stuffs transported from the farm or from food processing centers must be targetable from a distance to specific supermarkets, and similar requirements of spatial resolution are present in supplying raw materials and parts to any manufacturing process. The intrinsic self-localization of solids (a brick placed on the ground retains its compact shape while a similar volume of water immediately spreads out in a thin sheet unless confined by solid boundaries as in a puddle or when self-localized in a channel) means that the transport path can be accommodated by a single narrow infrastructure zone. The aspect ratio of the travel surface of a major transcontinental highway is typically about 10^5. Transport corridors are thin presumably because infrastructure construction and maintenance costs energy. Given that targeted transport is a function of purpose, building wider-than-necessary infrastructure elements would represent a use of energy that corresponds to no human purpose, and hence would not be expected to occur.

11 Summary and conclusion

Certain fundamental physical requirements had to be met for large-scale systems of the kind that dominate technological energy consumption today to emerge. One of these, studied here, was the capability for rapid transport of large quantities of materials of limited deformability, such as coal, minerals, and other products, across large distances, i.e., advective transport of solids. The antecedents and path of development of today's multifaceted technology is often considered to lie in the bailiwick of historians (Basalla, 1989) and social scientists (Heilbroner, 1967), but one might expect that basic underlying functionality such as mass transport and energy supply would fall squarely within the bounds of the physical sciences. However, the mechanism of large-scale extraction of work from concentrated deposits of fossil chemical energy – the energetic basis of modern technology – is not entirely a problem of mechanics or thermodynamics.

Consumption of these energy sources had to await the emergence of human purpose, which (effectively) provided for an otherwise missing potential gradient between fossil energy sources and sinks. When Earth evolution produced a mechanism that could support such a transport mode, several further physical processes became possible that were also essential for the emergence of large-scale development of technology, including advection of complex payloads with persistent memory, displacement of these payloads independent of geophysical fluid flows and topographic slope, and spatially accurate delivery to fixed but arbitrary destinations. The example of solids transport illustrates how the study of the dynamics of the Earth system as it is today must have the flexibility to include not only the analytical tools of the classical hard sciences but also new dynamical principles arising from the presence of humans and technology as part of the Earth system.

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