What Pushes Back from Considering Materiality in IT?

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ABSTRACT

There are significant negative impacts from extracting, processing, maintaining, and ultimately disposing of the materials used to support information technology, as well as of producing the energy it uses, yet these negative impacts receive substantially less attention than discussion of the benefits or technical aspects of IT. This essay presents some ideas on the forces that either de-emphasize or even actively push against considering these impacts. They are grouped into three overarching categories: metaphor and utopian visions, economics, and disciplinary norms and practices of computer science. The essay concludes with some ideas for what might be done to counter these forces and increase the visibility of these impacts when appropriate, suggestions for further investigations, and a framing of these issues as a particular aspect of larger systemic and interlocking environmental, economic, and political problems.

CCS CONCEPTS

• **Social and professional topics → Sustainability**;

KEYWORDS

Materiality, sustainability, consumerism, e-waste, economics of computing, growth and post-growth

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1 INTRODUCTION

This essay presents some ideas on the cultural, technological, and economic forces that push toward minimizing the visibility and consideration of the materiality of existing and emerging digital technologies, in particular their environmental impacts, which include the use of raw materials in manufacture, as well as energy, land, water, pollutants, and e-waste, among others.

The impacts of information technology on material and energy use receive substantially less attention than discussion of its benefits or technical aspects. Consider as an example the Internet of Things (IoT). The number of IoT devices is growing rapidly, with projections by some analysts of 20 to 30 billion devices by 2020. (See for example reference [3] for a roundup of recent forecasts.) This sharp increase in the number of IoT devices, along with supporting infrastructure, will result in significant consumption of materials and energy and production of waste. Despite this, a recent United States Government Accountability Office report on IoT [21] has only a brief discussion (2 paragraphs out of a 70 page report) of the issue of electronic waste resulting from the increasing use of the IoT, and nothing on the consumption of raw materials and energy. A small assessment of the top 10 results of an internet search for "Internet of Things" shows a coverage that is quite skewed toward highlighting its potential positives with respect to materiality, and that for the most part ignores the potential downsides in terms of materials, energy, and waste — only 2 out of 10 of the results discussed any potential downsides with respect to materiality, and even within those 2, there were 5 to 10 times more mentions of potential positives than negatives.

Is this simply a result of highlighting where most of the attention of technologists, business people, consumers, and others is focused, or are there structural forces that more actively push toward minimizing the visibility and consideration of these downsides? We suggest that in fact there are such forces, and that they work together, reinforcing each other. The following three sections consider three overarching categories of forces that obscure the ecological costs of information technology: metaphor and utopian visions, economics, and disciplinary norms and practices of computer science.

2 METAPHOR AND UTOPIAN VISIONS

Lakoff and Johnson [10] discuss a key property of metaphors: the systematicity that allows us to comprehend one concept in terms of another necessarily highlights some aspects while hiding others.

One important metaphor for our purposes is that of "cloud computing," which conjures up images of something light and insubstantial, somewhere up in the sky — as opposed to other possible descriptions such as "huge warehouses full of energy-hungry servers." (Even the term "server farm," which of course is also a metaphor, may suggest images of bucolic agricultural endeavors, unless one thinks of factory farming.) "Cloud computing" highlights that the servers and their supporting infrastructure are located someplace else, and that users of the cloud need not concern themselves with how they are maintained, monitored, powered, cooled, and so forth; it tends to hide that they are even material at all.

The origins of the term "cloud computing" are disputed. One early and influential use was by Eric Schmidt, then CEO of Google, in a Search Engine Strategies Conference conversation in 2006 [19]:

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> It starts with the premise that the data services and architecture should be on servers. We call it cloud computing — they should be in a "cloud" somewhere. And that if you have the right kind of browser or the right kind of access, it doesn't matter whether you have a PC or a Mac or a mobile phone or a BlackBerry or what have you — or new devices still to be developed — you can get access to the cloud.

However, there are earlier uses of the term. Business plans from 1996, ten years earlier, use the term "cloud computing" in a way that would be familiar today [15]. The authors of those plans state that it was born as a marketing term, which suggests there may have been some awareness of the implications of the metaphor. This usage in turn drew on a convention, used by network design engineers, to loosely sketch the other networks that theirs hooked into as a rough cloud-shaped blob [17]. On the one hand, this convention represents a powerful design technique — abstracting away irrelevant details — but at the same time, it implies that these details, including the material implications of these other networks, are not relevant to the task at hand. (Also see Section 4 on "Disciplinary Norms and Practices of Computer Science.")

Another term with metaphorical connotations is "ethernet," named after the "luminiferous ether" (or "luminiferous aether") [11], a hypothesized medium through which light travels. While the existence of the luminiferous ether was disproven by the famed Michelson-Morley experiment in 1887, the metaphor of an omnipresent, passive medium lives on in networking terminology, perhaps suggesting, as did the luminiferous ether, something almost invisible. The term thus highlights the ubiquity and convenience of the network while hiding its material manifestations as cables, routers, and other hardware.

A third example is "Moore's Law," which is the observation that the number of transistors in a dense integrated circuit doubles approximately every one to two years[1]. The word "law" implies that it describes a natural and inexorable phenomenon, i.e., invokes the metaphor of a law of physics. But it is hardly that — instead, it is an observation and a projection, and describes the result of huge investments in research and manufacturing plants, government policies, and so on, which are mostly invisible to the end users. In terms of highlighting and hiding, questioning the metaphorical "law" aspect of Moore's Law would make as much sense as questioning Hooke's Law.

The "agent" metaphor, as exemplified in early presentations such as the Apple Knowledge Navigator video and the Starfire concept video from Sun Microsystems, and now at least partially realized in systems such as Siri from Apple and Alexa from Amazon, centers on an intellectual rather than a material view of computation (even though there is a vast material apparatus underneath).

Finally, a curious metaphor is that of consuming media (and bandwidth) as eating. T-Mobile, for example, has a pricing offer entitled Binge On™ [20], which exempts all streaming data from any caps for that data plan. It would be strange to see a grocery store or restaurant advertisement that suggested that customers "binge on," but this seems to be more acceptable for streaming data. (We assume T-Mobile evaluated the perception of its trademarked slogan. Many of us would love to be able to eat as many desserts as we want with zero consequences. And if there is no material side of the IT infrastructure behind watching streaming data, what's the harm? Well, spending hours watching media on a handheld device may have its downsides … but these are less immediately obvious than the downsides of too many desserts.)

[1] Moore's original 1965 paper described a doubling every year for the next decade; in 1975 he revised his forecast to doubling every two years for the following decade. An Intel executive predicted 18 months, the period often quoted.

2.1 Visibility

Buildings full of servers are generally out of sight and out of mind, even without the highlighting and hiding arising from the cloud computing metaphor. Very likely most IT users have never been in one. There is also a disconnect between the physical infrastructure and personal use — it is also likely that most IT users don't know where their data is stored or requests are being processed (the privacy-conscious might at most know which nation the servers are in, given the different regulations); and of course one of the typical features of cloud computing is that the service provider can seamlessly shift the storage and processing to different locations.

The devices that users do own and see, such as smart phones or tablets as compared with desktop machines, have become smaller and smaller, which might suggest that the overall environmental footprint is decreasing. These devices are largely sealed as well — my phone, for example, is a thin, sleek black case with a glass screen, with no external suggestion of the tightly-packed chips, batteries, sensors, and so on that are inside the case.

2.2 Utopian Visions of Technology

Another force derives from utopian visions of technology. One notable example is Mark Weiser's vision of ubiquitous computing in which the technology "fades into the background" [22]. If something fades into the background, we are unlikely to be particularly aware of its implications, including its material ones. But Weiser's goal was broader: we not only need not be aware of the implications of the technology, but often we don't need to be aware of the technology at all. As the field of ubiquitous computing has evolved and we see computation embedded in walls, clothes, and so forth, the materiality to support it is often physically and intentionally hidden from the user. Indeed, this material disappearance is often considered evidence of good design.

The "agent" metaphor noted above, in particular in its early presentations such as the Knowledge Navigator and Starfire, is also another utopian vision. Yet another underlies an "information society" in which bits replace atoms — ignoring the material underpinnings of those bits [5]. Nicholas Negroponte in *Being Digital* [12, p. 2], as quoted in [5], for example, writes

> World trade has traditionally consisted of exchanging atoms. … This is changing rapidly. The methodical movement of recorded music as pieces of plastic, like the slow human handling of most information in the form of books, magazines, newspapers, and videocassettes, is about to become the instantaneous and inexpensive transfer of electronic data that move at

> the speed of light. ... This change from atoms to bits is irrevocable and unstoppable.

It is worth emphasizing this last sentence. It claims that there is an irrevocable and unstoppable change from atoms to bits: the material vanishes.

All of these metaphors and visions — cloud computing, ethernet, agents, the utopian vision of an information society in which bits replace atoms, and Weiser's vision of ubiquitous computing as technology that fades into the background, have substantial currency in the popular and business cultures — and consequent impacts on how visible is the materiality of IT.

3 ECONOMIC ISSUES

There are also a constellation of economic issues that push back from noticing materiality in IT, or that at least imply that it is appropriate to ignore it.

3.1 Price Signals

Prices are strong economic signals, and for IT they often imply that it is appropriate to downplay its material impacts.

For bandwidth and storage, the price signal is often to ignore materiality, even though increasing the amount of data transmitted, the bandwidth, or long-term storage on servers may require additional infrastructure. (The individual contribution of each person's use will be small, but in the aggregate the contributions are large.) Regarding data transmission and bandwidth, hardwired connections to businesses, institutions, and homes are usually priced based on a bandwidth cap alone — there is no cost difference for receiving or transmitting a smaller or larger amount of data. (Behind the scenes, the service provider might throttle the bandwidth of users who go over a cap, for example because they are running a server — however, we hypothesize that this is not something typical users consider.) For cellular data, plans often do include either a maximum data allotment, or else unlimited data but with slower speeds after a certain amount; and this cap is more strongly advertised. Consumers often do tailor their usage to these limits [16].

The cost of storage has of course plummeted over the years, but storage does have a physical manifestation. For storage on a personal device, there is a hard limit and corresponding price signal — exceeding its storage will require buying a new device, moving data off onto a thumb drive or onto a server, or whatever. Similarly, purchasing cloud storage will come with a particular cost for a given amount. There is also a price signal from processor speed, screen resolution, and other hardware questions: if I want a faster laptop I need to buy it. Yet even here the price signal doesn't tell the whole truth, since the cost does not reflect many of the negative environmental impacts of production and disposal of digital devices and infrastructure (or negative externalities, in the language of economics).

In considering the effects of price signals, it is also useful to highlight differences between the developed world and the Global South. For example, since memories are typically smaller on mobile phones in the South, many users there already manage the content on their phones more carefully. And given the relative cost of cellular data compared with income, users are usually much more careful about usage.

3.2 Consumerism and the Role of Advertising

There is a powerful culture of consumption and rapid obsolescence around electronic devices, with pressures to have the latest devices, including as part of one's self- and public image.[2] This is accompanied by a throw-away mentality that often makes older devices almost worthless — but still needing disposal. Smart phones and other personal electronic devices are also highly addictive. This problem is seeing increased attention, both in general and for particularly problematic situations, such as texting while driving, parents at playgrounds [8], and students in classrooms or while studying, among many others. The focus of this attention is primarily on the impacts for social interaction, self-image and self-esteem, safety, child development, effects on learning, ability to think deeply and in a sustained fashion about a problem rather than constantly multitasking, and the like. These are all important concerns. But the significant material and energy impacts of this pervasive use are often ignored, even though that is a result as well.

A closely related issue is how software and services are paid for. Many consumer services, such as search, personal email, social media, news, and others, are paid for by advertising and by accumulating personal information about the end users, rather than by direct payments by the end users. This advertising, and the results of marketing schemes powered by the user data, in turn feeds into and reinforces consumerism. This results in a powerful set of price and social signals to consume lots of these services: more use implies more advertising revenue and more Big Data about user activities, interests, and preferences, thus motivating companies to encourage consumption. For example, Facebook devotes a huge amount of effort toward hooking its users in, to maximize user time on the site (and thus requiring more data centers) — the addictive nature of smart phones and other personal electronic devices noted above is not entirely an accident. In promoting gmail, Google advertises "never delete another message — just archive it!" And on and on.

Note that the gmail slogan pushes back against considering the materiality of saving all that email; it doesn't just say to ignore it. The implication is that you are being archaic by worrying about how much storage email consumes or how much processing is needed when you search an enormous email archive, and are probably going to delete something you'll eventually want if you don't just archive it.

To connect with the themes noted above, Eric Schmidt in the interview cited in Section 2 states: "And so what's interesting is that the two — cloud computing and advertising — go hand-in-hand." Indeed.

3.3 Unending Growth?

More broadly, our overall economic system is currently predicated on unending growth. The IT industry has linked itself strongly to this ethos, with some particular manifestations being the constant need for novelty, the accompanying throw-away culture around

[2] In this essay we focus primarily on the economic side of consumerism. A direction for future work is a broader consideration of consumerism as culture. For example, Section 2 mentioned the metaphor of consuming media and bandwidth as eating — except that binging on media is more socially acceptable than binging on food. What does this say about the culture of consumption for IT more generally?

consumer electronics, and the glorification of disruption. Yet, mathematically, growth that requires material resources cannot continue forever in a finite world.

One response to this is the idea of decoupling: despite the limitations of the physical world, we can still have unending economic growth because we can separate growth from the use of materials. Note that making this work requires absolute decoupling (using less stuff in total), not just relative decoupling (using stuff more efficiently but still using more of it). An in-depth discussion of decoupling is beyond the scope of this essay — but to date there has been no evidence of absolute global decoupling [7], the relevant sphere given our globalized economy in which material flows occur. While the efficiency of many processes has improved (relative decoupling), overall consumption has continually increased once one controls for recessions (no absolute decoupling). Moreover, efficiencies can often lead to a rebound effect, in which efficiencies result in greater consumption. All this is not to say that using materials and energy more efficiently is unimportant — to the contrary, it is incredibly important. But without absolute decoupling, such efficiencies won't let us cling to the goal of endless growth. See Jackson [9] for more on this issue and additional references.

To connect this with our theme of what pushes back from considering materiality in IT, a belief in unending economic growth in a finite world seems to require suspending considerations of its material aspects, and either belief in absolute decoupling or simply ignoring the issue.

Finally, Moore's Law bears mention in this regard as well as with respect to metaphor. Moore's Law appears to be coming to an end — which is often described as a crisis. Is it really a crisis if exponential growth comes to a halt? Is the IT industry that addicted to growth?

4 DISCIPLINARY NORMS AND PRACTICES OF COMPUTER SCIENCE

Even the basic intellectual commitments of computer science in many cases involve ignoring the materiality of computation, abstracting away the physical manifestations to concentrate on information and computation.[3] Similar to the use of clouds in network diagrams, this represents a powerful intellectual move, allowing us to concentrate on key aspects of the phenomenon and ignore irrelevant ones.

Of course, work for the practicing programmer or designer is usually not so tidy. As Paul Dourish puts it in his book *The Stuff of Bits: An Essay on the Materialities of Information* [5, p. 6], "Programmers understand the ways in which digital structures can resist their will, every bit as much as clay, wood, or stone." The vast majority of experienced programmers at some point or other will have needed to address issues of efficient use of memory, which is ultimately a consequence of the realization of the computation on a physical device. Similarly, skilled web designers often need to consider download speeds for different possible layouts and contents. As a third and perhaps less familiar example, for applications that can tolerate inaccuracies, programmers can sometimes trade off energy use and accuracy, that is, reducing the energy consumption of a given program at a cost of lower accuracy. More typically, however, the results of more efficient use of memory or bandwidth or processors is simply to do more, rather than to save materials or energy. (This is the rebound effect mentioned in Section 3.3.)

Returning to the theme of abstraction in computer science, in many cases researchers develop tools and systems that encapsulate the concerns with storage and energy use (i.e., with materiality). Most high-level programming languages, for example, provide automatic storage management, so that programmers generally need not concern themselves with explicitly freeing data that is no longer used (although they must still consider good representations to better make use of memory for data that *is* in use, and sometimes must remember to avoid keeping around a reference to data that is no longer needed). Similarly, one topic of recent research has involved developing programming language support for making tradeoffs between energy use and accuracy [13, 18]: thus not erasing the tradeoff, but making it more convenient to make.

There are other relevant disciplinary norms and practices — nowhere near as fundamentally rooted in computer science, but still worth calling out. Preist, Schien, and Blevis [14] identify and consolidate features of the dominant design paradigm for interactive devices into what they call the "cornucopian paradigm," which includes such features as the expectations of instant response, huge variety, and anytime and anywhere access. As they point out, while in many ways these expectations result in features that are desirable for users as individuals, they can also result in significant negative impacts at a societal level. As another example of disciplinary practices, even in the HCI sustainabity community up until recently the material side of cloud and other digital infrastructure has received significantly less attention than that of the devices that users see and use, despite its having a similar or even larger environmental footprint [14]. To what extent this is due to metaphor (Section 2), lack of physical visibility (Section 2.1), or other possible causes, is an interesting and open question.

5 WHAT COULD BE DONE?

This section outlines some ideas for what might be done to counter the forces that push back from considering materiality in IT, and when appropriate to increase the visibility of the negative impacts in terms of materials, energy, and waste. While the focus of this essay is visibility, there are also a few thoughts in this section on how increased visibility might translate to mitigations.

Of course, increasing visibility is not always desirable. It seems entirely appropriate to keep our dirty laundry (real laundry, that is, not the metaphorical kind) off in the laundry room or a closet and not in the living room. As a quite different example, Section 4 notes that in many cases computer scientists abstract away the physical manifestations to concentrate on information and computation. On the other hand, making some phenomenon visible can be useful if doing so surfaces important considerations. (The considerations might be important for any number of reasons, including moral, environmental, economic, or engineering ones.) Given the very large impacts of information technology in terms of raw materials, pollutants, energy, and waste, this may be one such case.

In general, approaches include education, developing new technology to support visibility, economic measures, and implementing new laws and regulations. This visibility is not an end in itself: we

[3] Consider the alternate term "informatics" for the discipline, which emphasizes information over physicality.

want to lessen the negative impacts of IT. These ideas should thus be seen as one possible component of an overall strategy, for example the Sustainable Interaction Design approach described in Blevis's original paper [2] and extended in a range of more recent work, for example [14] on considering cloud and other infrastructure.

5.1 Education

Educational approaches will often be the easiest to implement. There could be general educational campaigns, for example, that call attention to the material and energy impacts of the server and network infrastructure that backs cloud computing, or of hours spent on social media. While these may raise awareness of the issue, it may be difficult to translate this awareness to action due to the lack of coupling between the intervention (say a public service announcement) and the behavior (say posting a social media item). Approaches that have a tighter coupling seem more likely to increase awareness and potentially to have an effect. For example, particular applications could be instrumented with material and energy meters that increment whenever the user is doing some action (or perhaps is about to start some action).

Rather than focusing on the material and energy use directly, another approach would be to seek to make visible the server and networking infrastructure activated by a request, in a way that counters the light-and-airy implications of the "cloud" metaphor. An advantage of this approach is that it has a tight coupling with the action but doesn't involve nagging (at least directly), and might help to inform the mental model that users have of what goes on with the servers and networks behind their activities.

There is an extensive body of HCI research on making behaviors (and the results of behaviors) visible, and any work in this direction should draw on those ideas and lessons learned. In particular, instrumenting applications with material and energy meters is similar to many projects in the earlier phases of sustainability HCI research; and it is not clear that these approaches have worked that well in the end. Other lessons from that literature are the limitations of appeals to change personal behavior [4], as opposed to systemic or political change.

A targeted educational approach would focus on the education of interface designers, software engineers, hardware engineers, and others, bringing in consideration of the materiality considerations of the technologies they are developing. As discussed in Section 4 on the disciplinary norms and practices of computer science, abstraction (including abstracting away material aspects) represents a powerful intellectual and design technique; but at the same time, actual practice is rarely so tidy. So just as software engineers must often concern themselves with the limitations of actual available memory, perhaps education could include guidelines on when considering these materialities is also important.

5.2 Technology Development

On the technology front, many of the visibility techniques mentioned in connection with education to make materiality more visible will also require supporting technology, for example interface changes.

Section 4 mentioned research on programming language support for making tradeoffs between energy use and accuracy — so allowing some of the benefits of reasoning with higher-level abstractions while at the same time being able to consider the consequences for energy use of tradeoffs. There could be similar efforts to make the energy use by servers visible while still using higher-level abstractions (either in debug mode for developers, or for helping instrument end-user applications).

5.3 Economic Models, Laws, and Regulations

Section 3.2 notes the central role of advertising and Big Data in paying for search, social media, and other services, and how the logic of this economic system rewards having users spend as much time as possible using the different services. An alternative for funding these services without this logic is government or other societal support (such as co-ops, volunteers, etc.) as a part of a "civic commons" infrastructure. Another is corporations that provide the services on a pay-per-use basis, perhaps using a "utility" rather than a "content" model (in analogy with the debates over net neutrality).

Prices as economic signals often imply that it is appropriate to ignore, or at least not fully consider, the material impacts of IT (Section 3.1). Taxes or fees could change this. A goal could be that prices more accurately account for the full life cycle costs of information technology, with revenues going to mitigations of different kinds. More accurately accounting for life cycle costs ("let prices tell the truth") has a strong appeal within the currently prevailing worldview, in which economics plays a foundational role. However, one can certainly imagine other societies in which the economy is subservient to other systems (the natural environment, the social world), and in which the goal of such taxes and fees is to help put bounds on activities that have larger downsides than society as a whole wants to bear, rather than thinking of this entirely in economic terms. In such a society, such taxes for example might be set considerably higher than would be done simply to have them better reflect full life cycle costs, and be part of a larger coordinated strategy to enable humanity to live more lightly on the earth (other components being education, and even attempts to shift culture). We return to this theme in the conclusion (Section 6).

These issues are related: having services such as search and social media be "free" (i.e., supported by advertising) erases price as an economic signal that is visible to the end user.

Finally, regulations about such issues as proper disposal of e-waste could be another way to make the issues more visible, for example by labeling new products with information about their eventual disposal, or building fees for disposal into the price of new products.

6 CONCLUSION AND DIRECTIONS FOR FUTURE WORK

This essay has presented some preliminary ideas on the forces that push toward minimizing the visibility and consideration of the materiality of digital technologies, in particular their environmental impacts. All of the topics noted here would benefit from exploration in much greater depth.

One direction for future investigation is understanding the mental models that people have of information technology, both of the devices they have personally and also of the server and networking infrastructure that backs them. In Section 2 we suggest that the cloud computing metaphor conjures up images of something light and insubstantial, somewhere up in the sky. What mental models do people have of the devices and infrastructure? What is the impact of the cloud computing metaphor on these mental models? Do the models adequately represent the material side?

Do the three overarching categories used here (metaphor and utopian visions, economics, and disciplinary norms and practices of computer science) capture the range of forces, or are there others? Within each category, certainly additional forces could be identified and investigated empirically. We want to highlight the economic forces in particular as central and needing much additional investigation, as well as the questions of unending economic growth and the oft-proposed decoupling of economic from material growth (which here is suggested to be an illusion). This recommendation echoes a call made by Ekbia and Nardi [6], who make a key point: "Computing and political economy are much more intertwined than current discourse in HCI admits. Our contention is not that HCI researchers and practitioners are unaware of the relationship between economy and technology; rather, that this does not typically figure in any deep way into our theories, practices, and designs. ... Researchers tend to focus on the cultural aspects of technology at the expense of the more material and economic facets." This focus on the cultural (immaterial) facets, and corresponding lack of attention to material and economic facets is also a current disciplinary practice — not fundamental, in contrast to the basic intellectual commitments of computer science — but nevertheless a current part of practice.

This essay is primarily written from the perspective of the developed world. How do these issues play out in the Global South? For example, connectivity is often a challenge there, so assumptions of seamless integration with cloud services break down; but on the other hand, the material side of the cloud may be even less visible than in the developed world. We have also touched on the issue of recycling or disposal of e-waste — and it is often in the Global South that this recycling or disposal happens.

Finally, there should be much more work on specific policies and other approaches to what can be done. Again, visibility is not an end in itself: we want to lessen the negative impacts of IT. While increased visibility may help with this, the results from such interventions by themselves will be quite limited in comparison with what actually needs to be done to live within the earth's limits. The dark side of IT's materiality is due in part to particular characteristics of the technology, industry, and discipline, but is also a manifestation of integrated and systemic environmental, economic, and political problems, which need to be addressed in a similarly integrated fashion [1]. Thus, one framing of the directions outlined in this essay is: suppose that we accept this overall analysis of integrated and systemic problems in the environment, economy, and democracy. In a different society in which the economy is subservient to other systems (the natural environment, the social world, democratically elected government), and in which there is a larger movement to enable humanity to live more lightly on the earth and within its limits, what is a proper role for IT technology, industry, and research? And how could we get there?

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