# Sum, quorum, tether

## Design principles underlying external representations that promote sustainability

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We outline three challenges involved in designing external representations that promote sustainable use of natural resources. First, the task environment of sustainable resource-use is highly unstructured, and involves many uncoordinated and asynchronous actions. Following from this complex nature of the task environment, more task constraints and task interactions are involved in designing representations promoting sustainability, compared to representations that seek to make tasks easier in structured task environments, such as aircraft cockpits and control rooms. Second, external representations promoting sustainable resource-use need to motivate people to make decisions that sustain resources, and persist with this behavior, even though alternate behaviors are easier and commonplace. Third, external representations promoting sustainability also need to lower the cognitive load involved in sustainability decisions. This three-tiered function (meeting complex task constraints, providing motivation, lowering cognitive load) makes such representations challenging to design. However, some early prototype designs promoting sustainable resource-use have appeared recently, primarily addressing electricity use. Analyzing these digital prototypes, we outline three design principles they share, and show how these seek to address the complexities of the sustainability problem-space (complexity of task environments, goals, and representations). We then argue that at least two further cognitive scaffolds are required for effectively promoting sustainable resource use (action scripts, deconstruction). We close with some of the limitations of this approach to promoting sustainability, and outline future work.

**Keywords:** design, distributed cognition, external representations, motivation, sustainability, tragedy of the commons

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## 1. Introduction

There is an emerging consensus that humanity's current wasteful ways of living cannot be maintained, and humans need to use natural resources in a more sustainable fashion.

Given the extent of current consumption, much of the focus has been on lowering resource use, and treating lower usage as better sustainability. A variety of choices and actions (such as recycling and lowering electricity/water consumption) are presented to consumers as lowering consumption of natural resources. However, it is difficult to judge which of our choices and actions really support sustainable resource use in the long run, and by how much, as the information required to make this judgment is currently unavailable in a usable form (How much electricity/water do I consume? How much could I cut? How much do I contribute to sustainability when I recycle milk cartons?). Cognitive effort is thus required to identify sustainable actions and choices, and then, assuming that one is still motivated, to change one's behavior from current actions and choices to more sustainable ones. Further, increased cognitive effort is required to persist with these choices and actions day after day.

The lack of easily available and usable information supporting sustainable behavior is a significant problem. The very unavailability of usable information channels people away from sustainable resource use, and encourages them to persist with current wasteful behavior patterns, which are cognitively easier. It is not obvious that the individual's behavior is being channeled, since the channeling is a result of information being absent. As such, the cognitive load involved is hard to understand and address, compared to an action that is just cognitively difficult. To illustrate, if the option of using macros is available in a spreadsheet interface, it is possible for us to think why executing macros is difficult using the current interface, and how this operation could be improved. However, if we never know about macros (say, because the menu doesn't represent macros), and we always use the copy-paste function to do repetitive tasks, it would be difficult to think about the cognitive load involved in using macros, and how macros could be improved. More generally, if the world represents an action/cue, we can think about it in comparison with another action/cue. If there is no action/cue, we cannot generate that action/cue in real-time, and compare it with our current actions/cues.

There is also a second level of "invisible" information that adds to the cognitive effort in the sustainability problem — the lack of information about others' behavior. One person's sustainable choices can be neutralized by others' wasteful behavior, and there are currently no models or guidelines on how to best capture and represent a community's behavior, so as to support, or motivate, an individual's decisions.

In this paper, we analyze these two levels of cognitive effort involved in sustainability actions (personal, group), and the difficulties involved in characterizing the sustainability problem, even when using a framework such as distributed cognition, which was developed to describe complex socio-technical systems (Section 1). Section 2 describes the objectives of the paper (to make implicit concepts explicit and to develop a design narrative). In Section 3, we itemize some of the cognitive burdens associated with sustainable practice. Section 4 discusses how questions of cognitive load relate to the distributed cognition framework, and how this framework can help to address three key complexities (complexity of task environments, goals, and representations).We then present some design prototypes that seek to promote sustainable actions in the domain of electricity consumption (Section 5), and abstract out three features of these designs (sum, quorum, tether) intended to promote sustainable resource use (Section 6). Section 7 considers the implications of these ideas for distributed cognition. Section 8 outlines two other cognitive issues (action scripts, deconstruction) that are not addressed by current designs that promote sustainability. Section 9 discusses some of the major limitations of our approach, and how these could be addressed in future work.

There are currently no standard ways to evaluate the effectiveness of sustainability designs, as most designs are prototypes, and no usage data is yet available. In this paper, we seek to develop a conceptual framework for analyzing designs that promote sustainable resource use. In the next section, we provide a brief background on the objectives and the method of the paper, using an analogy.

## 2. Background on objectives and method

Old Roman bridges, built around 100 BC, are still used in parts of Europe and Asia. From a design point of view, these bridges are interesting for the following reason: *they were built without knowing anything explicit about building bridges.* Specifically, they were built without the explicit concepts of stress, strain, corrosion, aerodynamics, fluid dynamics, wind-speed, resonance, etc.

The Roman bridge builders did use some of these concepts while building their bridges, but in an *implicit* and intuitive fashion. However, once these implicit and intuitive concepts were made *explicit* (and external) by modern physics, their underlying physical factors could be tested separately, to develop and understand them under idealized conditions. These factors, thus optimized, could then be combined, to examine how different factors interacted in different situations. The results of these optimizations and combinations could then be applied to develop novel and challenging bridge designs, such as the Golden Gate Bridge across the San Francisco Bay.

This analogy, inspired by Kirlik (1998), illustrates that explicit knowledge of mechanisms is *not necessary* for developing new problem solutions or designs. However, explicit knowledge of mechanisms can help significantly in *extending* the novel solutions and designs to new and challenging areas. A similar point could be made using the example of projectiles such as arrows, spears and fire throwers, which were developed thousands of years before humans understood dynamics and mechanics explicitly. But once the explicit knowledge was developed, more sophisticated projectiles could be built, including rockets and jumbo jets.

This advantage of explicit knowledge frames the two objectives of this paper: make implicit design concepts explicit, and provide a design narrative. Our first objective is to make explicit some of the currently implicit concepts used by designers of representations/prototypes that seek to promote sustainability. We believe that developing such an explicit understanding of the implicit concepts (design guidelines) would help optimize and augment future designs, and help designers address more complex and challenging problems related to sustainability.

Since most of the representations we examine are based on information technology, we use an information and cognition-based approach to understand and capture these concepts. Importantly, we consider this as a first pass at capturing these concepts. We expect our proposals to be revised, tightened, sharpened, even rejected, based on whether and how designers use them, and based on new viewpoints and debate arising from the way these concepts are used in design. We do not seek to provide a top-down, comprehensive, and rigorous theoretical model of the factors that influence consumer behavior and sustainability. Any contribution the paper makes to theory will be through the use of the design guidelines by designers, to develop new artifacts. From the iterative building and testing of new artifacts that incorporate these design guidelines (combined with an understanding of user-behavior related to these artifacts), these theoretical concepts and guidelines would be ultimately either revised, tightened, or rejected. In this strategy, theory is developed by:

1. Seeding and evolving new designs using new concepts
2. Analyzing how the new designs are used
3. Applying this analysis to revise the design concepts, and develop new ones

This iterative theory-building strategy (where artifacts developed with the help of new concepts are used to 'poke' the real world, and the concepts are then refined based on the results) is part of the practice in human-computer interaction (for example: ubiquitous computing; Weiser 1993; embodied interaction; Dourish 2001), and in robotics (Brooks 1991). This strategy leads to the development of design guidelines that are different from the traditional (prescriptive and proscriptive) guidelines in social science. A good analogy to understand this strategy is the role played by controversies in science. Controversies act as the locus where critical activity is exercised and its norms established, applied, and modified (Dascal 1998). Entrenched beliefs, data, methods, interpretations, and procedures can be challenged in controversies, paving the way for the possibility of radical innovation. We expect our guidelines to lead to designs and concepts that generate a similar churning in the creation and use of external representations for sustainability.

The second objective of the paper is to develop a *design narrative*, where some of the sustainability design models discussed in environmental psychology and environmental economics (De Young 1999a; Ostrom 1990; 1999) are captured in cognitive terms using the distributed cognition framework. This new narrative serves two purposes. One, it tailors some of the existing knowledge in a way that can be easily used by designers. Second, this narrative, in conjunction with the artifacts it is derived from, allows sustainability design to move beyond some of the constraints identified by existing models of sustainability. For instance, Ostrom (1999), in reviewing her path-breaking work on community-based solutions that address the problem of overuse of common-pool resources (tragedy of the commons problem), argues that when individuals that use a common pool resource are held apart and unable to communicate either face to face, or via the type of signaling that is feasible in two-person situations, they overuse the resource. Some of the artifacts we examine in this paper specifically seek to block such overuse of common-pool resources in domains where users do not see each other, using new technology that does not require face-to-face communication. Ostrom's work also focuses on well-defined resources (De Young 1999b) and her proposals do not extend to cases where overuse of common-pool resources emerges from actors unable to gauge the extent of their consumption in relation to available resources. In most situations involving energy, resources are not well-defined, and actors do not know the extent of their use. The information technology applications we discuss seek to generate cooperative behaviors at the community level (similar to behaviors reported by Ostrom) in such complex and opaque situations, by creating perceptually salient ways of representing 'invisible' consumption and resources. Such artifacts need to exist before Ostrom's model of self-organizing communities can emerge in complex domains. These artifacts make information, as well as the tragedy of the commons, transparent. In keeping with Ostrom's model, as our discussion will outline, this structuring of invisible information is achieved using a form of self-organization.

These two broad objectives are novel and have not been addressed in previous work. We hope the design narrative we develop in this paper will help bring existing research on sustainability and the tragedy of commons closer. This research is currently spread across various domains (such as economics, psychology, cognitive science and human-computer interaction). Importantly, we view this narrative as a first effort to integrate the distributed cognition framework with the community self-organization framework outlined by Ostrom, and to extend this integration to help designers understand and develop new information technology designs that seek to promote sustainability. Our discussion begins with an examination of the cognitive load involved in some common sustainability decisions.

## 3. Unsustainable cognitive load

Individuals can make a range of choices and actions that could lead to a more sustainable use of resources. These include lowering personal energy and water consumption, recycling, and moving to alternate energy sources. Other options include buying local products, reusing waste water, and harvesting rainwater. While these choices and actions appear straightforward, implementing these choices is not easy. The difficulty in implementation arises from both practical and cognitive considerations. In this paper we focus on the cognitive issues.

Consider the project of lowering one's personal energy consumption. This undertaking mostly involves actions under an individual's control, such as switching off appliances (lights, computer, air conditioner) when they are not in use, installing light bulbs that require less power, or washing clothes only in big loads. These actions contribute to lowering energy consumption. But the individual performing them usually has no idea how much energy she is saving, because currently the only way an average consumer can understand the effect of these actions is by tracking her electricity bill.

From a cognitive standpoint, the monthly bill is not well-fitted to the task of conserving electricity. The actions involved in lowering electricity-use require constant attention to the states of individual appliances such as lights and fans and heaters. Although many energy-saving actions must be performed each day, the results of these actions (feedback) are consolidated into a single bill at the end of the month, in a format (money) that is at best indirectly related to the individual actions. Further, the consumer would have to track this feedback across months to get a sense of the difference her actions have made. Usually this difference does not appear to be significant in terms of the money saved. There is no way of easily estimating how much electricity was saved by each action, and how much the action contributed to sustainability of natural resources. This is just one example of the cognitive load involved in making choices that reduce resource use.

More generally, making choices that promote sustainability brings with it the following cognitive burdens:

1. Increased attention: Every day, a number of world-states and individual actions need to be scrutinized from the standpoint of their impact on sustainability.
2. Increased processing: New or different actions must be generated, and executed consistently over time.
3. Uncertainty about outcome: The effect of those actions and choices is difficult to evaluate.
4. Uncertainty about others' actions: The overall effect of one individual's actions could be negated by the choices and actions made by others. The extent to which this is happening is difficult to evaluate.
5. Avoiding Relapse: The current ways of life are easier, well-known, available, and followed by everyone. On the other hand, it is difficult to generate and follow the new routines needed for sustainability. Further, since monetary savings are small, and the environmental benefit uncertain, there is no ready incentive or reward for such sustainability behaviors; persisting with this new and higher-cognitive-load regime is difficult. These factors create a strong 'pull-back' towards unsustainable behaviors, which needs to be resisted.

In combination, these burdens make the shift to sustainable resource use challenging, as the high cognitive load from these multiple sources requires ongoing vigilance, and the lack of feedback and incentive provides a poor climate for perseverance. Further, recent experimental results suggest that the motivation and the ability to control one's behavior is a finite resource that could be depleted by other effortful tasks (Hagger, Wood, and Stiff 2010; Baumeister, Bratslavsky, Muraven, and Tice 1998; Schmeichel, Vohs, and Baumeister 2003). Higher cognitive load and vigilance could act as effortful tasks that deplete one's motivation and self-control.

How could we make hidden information explicit, and reduce the cognitive load (arising from the above listed factors) in ways that would promote and maintain sustainable resource use? If we assume that designing external representations that mitigate these burdens is one possible way of accomplishing this goal (see Mazé and Redström 2008 for a discussion on why this may not be an optimal solution), what kinds of external information structures (*epistemic structures*, Chandrasekharan and Stewart 2007) would facilitate and encourage sustainable resource use for those interested in conserving?

## 4. Distributed cognition and three complexities

From a cognitive theory standpoint, these questions are best addressed within a distributed cognition (DC) framework (Hutchins 1995a; 1995b), as this theoretical framework was developed to study complex (usually technical and scientific) task environments, particularly environments where external representations are generated and used by groups of people. The primary unit of analysis in DC is a *distributed socio-technical system*.

A distributed socio-technical system consists of people working together to accomplish a task, as well as the artifacts they use in the process. The people and artifacts are described, respectively, as *agents* and *nodes*. Behavior is considered to result from the interaction between external and internal representational structures. A standard example of external representational structures in DC is the use of speed bugs in a cockpit (Hutchins 1995a). Speed bugs are physical tabs that can be moved over the airspeed indicator to mark critical settings for a particular flight. When landing an aircraft, pilots have to adjust the speed at which they lose altitude, based on the weight of the aircraft during landing for that particular flight. Before the origin of the bugs, this calculation was done by pilots while doing the landing operation, using a chart, and calculations in memory. With the bugs, these markers are set between two critical speed values (based on the weight of the aircraft for a particular flight). Instead of doing a numerical comparison of the current airspeed and wing configuration with the critical speeds stored in their memory or on a chart, pilots simply glance at the dial to see where the speed-indicating needle is in relation to the bug position. This external representation allows pilots to 'read off' the current speed in relation to permissible speeds using perception. They can then calibrate their actions in response to the perceived speed difference. The speed bugs (an external artifact) thus lower the pilot's cognitive load at a critical time period (landing), by cutting down on calculations, and replacing these complex cognitive operations with a perceptual operation. The setting of the speed bugs also leads to a public structure, which is shared by everyone in the cockpit. This results in the coordination of expectations and actions between the pilots. These two roles of the speed bug (lowering cognitive load and promoting coordination between pilots) are difficult to understand without considering the human and the artifact as forming a distributed cognitive system.

In a recent *Pragmatics & Cognition* special issue on distributed cognition, Schwartz and Martin (2006) argue that if distributed cognition is to become a general analytic frame, it needs to handle more aspects of cognition than just this type of highly efficient problem solving. Sustainability decision-making is a natural domain to extend the application of DC, as the problem of sustainable resource use is similar to the cockpit example, and other problems traditionally studied by DC

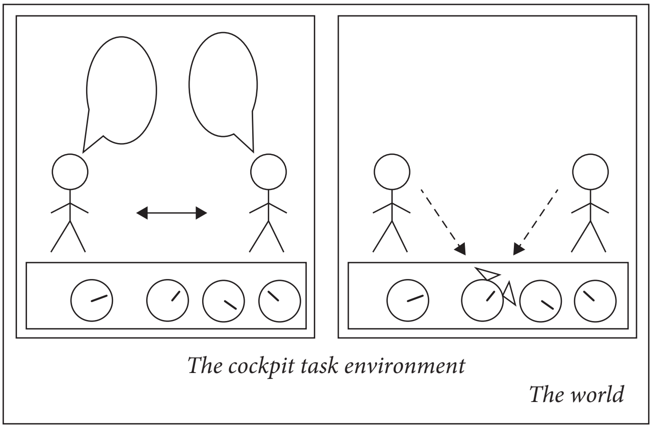


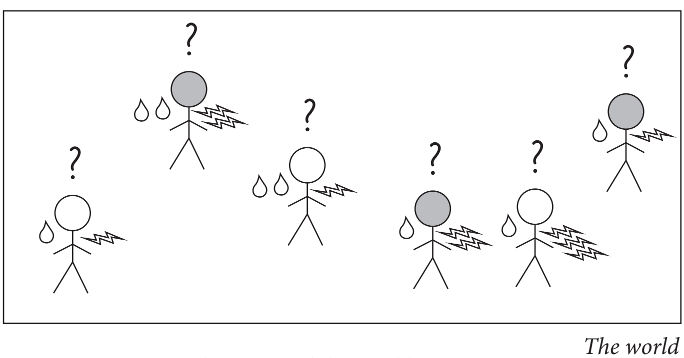

**Figure 1.** The task environment in the speed bug example. The left panel shows the task before the speed bug representation was designed. The pilots do computation in their heads, and coordinate with each other, and the dials. The right panel shows the task after the speed bugs (the triangles on the dials) were designed. Notice that the cockpit environment is boxed off from the world.

(Hutchins, 1995b). It also involves groups of people and artifacts, with tasks that are stretched across time and space. However, compared to the task environments traditionally studied by DC, the sustainability problem is more complex, as is the design of external representations required to address it. The complexity is threefold and stems from complexities of task environment, goals, and representations:

- Complexity of Task-environment: Unlike the case of landing an aircraft, in the sustainability problem there is no structured task or task environment, with synchronous actions connecting individuals or groups. There are only general goals, such as lowering electricity/water consumption. These general goals are spread across groups of people who share a resource network, but don't share a tightly integrated task environment. They don't see each other, they work in different settings (such as different homes), at different times and using different appliances.
- Complexity of Goals: Users within a community sharing a resource have conflicting interests. For instance, some users (say large shareholders of energy companies) would not be committed to sustainable resource use, and may even actively seek to sabotage this goal. Users's goals are also not the same across all locations. For instance, when there is a limited amount of a resource (such as water and electricity in less industrialized countries), the sustainability goal becomes sharing a limited resource, rather than an across-the-board minimizing of resource use, which in industrialized countries is equated with sustainability.

This situation brings in the problem of the tragedy of the commons (Hardin, 1968; Ostrom, 1999), where the actions of some people in the group are based exclusively on their self-interest, leading to a resource getting depleted rapidly. This can happen even when it is clear to these people, and to everyone else, that this is not in the group's interest, or even, ultimately, in their own interest.

– Complexity of Representations: Moving to sustainable resource use requires motivation, as users need to move from existing behaviors that are easy, to more difficult sequences of actions that support a broader and communal goal. This problem of motivation is closely connected to feedback. For instance, in the case of a person seeking to lower electricity use, it would be easier to persist with her resource-saving actions if she gets real-time feedback (how much less am I using now) and feedback across time-periods (how much less did I use this week/month/year). The feedback might be still more motivating if the user knew that her community's actions were also contributing to the broader goal of sustainability (how much is everyone else using). To support these different levels of feedback-based motivation, the epistemic structures that support sustainability need to change dynamically. They should display information across multiple time-periods (changing in real-time, as well as capturing history in a cumulative fashion), and register feedback to actions executed at both at the individual and community levels. These two levels of information should also be easy to comprehend. To address the uncertainty involved in community behavior, the real-time and longer-term variations in the representations would need to be accessible to everyone drawing resources from the same network (say electricity/water line).




*The sustainability problem space*

**Figure 2.** The sustainability problem space. The drop beside the agent indicates water consumption, the lightning indicates electricity consumption. The question mark indicates that each agent does not know their own consumption. Note that there is no boxed off task environment here.

Traditionally, distributed cognition (DC) has not addressed problems involving unstructured task environments. In unstructured task environments, where agents do not share a space and artifacts, they execute actions asynchronously. Unstructured problem-domains have been studied in relation to design (Voss, 1988; Schunn, McGregor, and Saner 2006) but the studies mostly involve single learners, and do not involve distributed systems or distributed cognition. Further, DC has not studied groups operating in disparate, but resource-sharing, environments. The framework also does not address preference/choice judgments in large groups of people with potentially conflicting interests. Finally, DC is a descriptive framework for the analysis of a task domain: it does not provide any guidelines on designing the external representations themselves. In particular, DC provides no guidelines on designing external representations that seek to motivate by incorporating, in this case, both global and local information that can change dynamically in response to user actions.

DC has mostly studied decision-making in structured domains such as aircraft cockpits (Hutchins 1995a) and naval ships (Hutchins 1995b), where lowering cognitive load in a well-understood task is the primary objective. In such domains, the lowered cognitive load from an epistemic structure has a 'self-revealing' nature, and this lowering of cognitive load acts as a clear incentive to use the new external representations. Task analysis in these domains seeks to change the representational environment, so that a decision that is currently complex becomes easier from the standpoint of cognitive load (Hutchins 1995a). Since the advantage provided by the new system is transparent, and usually results in a lowering of cognitive load for the individual or group, the new action sequences are adopted quickly.

Given the three complexities above (complexity of task-environment, goals, and representations), the sustainability domain is more challenging than the usual domains studied by DC. Designing new epistemic structures for this task domain is accordingly harder. However, there have been a range of recent efforts in this direction, and some novel representations have been developed that partly address the three complexities of the sustainability problem (complexity of task-environment, goals, and representations). In the following section, we will examine some of these solutions in detail. Similar to the cognitive analysis of early direct manipulation interfaces (Hutchins, Hollan, and Norman 1986), we will try to tease out features of these representations that promote sustainable resource use.

We note here that the designers of the prototypes treat motivation as an unanalyzed and single design constraint. Since our objective is to identify broad cognitive principles for design purposes, we will follow this (rather simplistic) stance. However, we acknowledge that the interactions between motivation and decision-making can be extremely complex (Fishbach, Zhang, and Trope 2010; Shah and

Kruglanski 2003; Higgins 2000). There is also the added complication of motivation being a finite resource, and the possibility of control as well as cognitive load depleting it (Hagger, Wood, and Stiff 2010; Baumeister, Bratslavsky, Muraven, and Tice 1998; Schmeichel, Vohs, and Baumeister 2003). The designs that seek to lower cognitive load address the latter interaction (but in an intuitive fashion). In future work we plan to address in detail how such interactions play out in this domain, particularly in relation to external representations.

## 5. Early prototype applications

In this section, we will describe design prototypes that lower cognitive load for individuals, and then move on to consider designs that target groups. Most of the artifacts we discuss relate to electricity consumption, and they lower cognitive load by making information more transparent. However, each of these artifacts represents information differently, and the scope of each artifact is different. While most of these designs are based on electricity use, the underlying design principles could be extended to water use, and to some extent, recycling. (See Acknowledgments for the sources of these designs.)

### 5.1 Personal level applications

***The Energy-aware Clock***: This design represents the energy use in a home, as graphs on a clock display. Yesterday's graphs fade away slowly, and today's consumption is drawn on top of previous days' consumption, making it easy to compare your energy use for several periods. The clock is wirelessly connected to the home's energy meter, and can be moved to any location within the home.

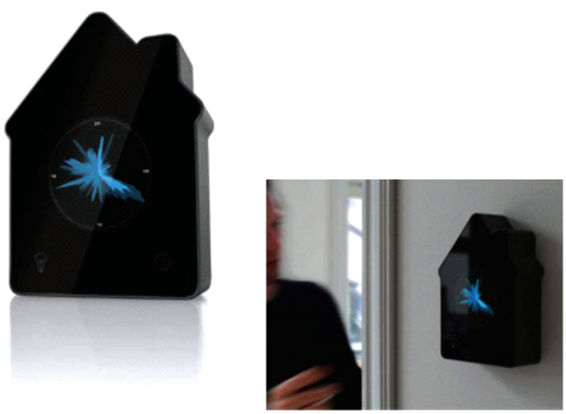


**Figure 3.** The energy clock

This design makes information on energy usage explicit, and provides instant feedback on the energy saved by an action. It tracks and displays three kinds of information: switching on of individual appliances, current energy use of the home taken as a whole, and today's energy use as seen in comparison with recent use. The variation in the display across days can help to motivate still lower energy use. An option to display the energy saved using a broader perspective, such as lowered CO2 emissions or environmental degradation, could provide even better motivation.

**Figure 4.** The energy plant

A related design is the color-changing Energy Orb, which indicates high energy-usage by glowing red, and low usage by glowing green. It can also be configured to display real-time energy price information.

There is some indicative evidence that consumption can be reduced by making information about use patterns visible. A pilot monitoring project reported that homeowners who regularly consult their electricity usage online showed an average reduction in usage of 9.3% (PA Consulting 2010). In the same report, a meta-analysis attributed an average of 5.1% energy savings to the use of energy management systems (PA Consulting 2010).

***The Energy Plant***: This is a digital display of a plant, wirelessly connected to your power meter. Every month, a seed sprouts and starts growing in the display; its growth is based on your power consumption. The plant grows fast when the energy consumption is low, and withers when the consumption is very high. Encouraging the plant to grow entails keeping consumption down.

The Energy Plant presents an interesting real-time representation of the monthly electricity bill, but using a format that is much more intuitive. Its time-period is broader than what is captured by the clock and the orb, and it aims at a motivational element (keeping the plant alive) that is missing in the clock.

A similar design which also aims to motivate the user is the Flower Lamp, which opens up when less energy is used, and closes its petals to form a cylinder when more energy is used. A related design from the domain of recycling is the composting pot with a plant. The survival of the plant depends on the user's composting actions.

***The Power-aware Cord***: While the energy clock and the energy plant indicate the overall power usage, they are not very helpful in understanding the level of power usage within an individual appliance and across appliances. The power-aware cord exhibits the (currently invisible) power consumption by an appliance as glowing pulses, and flow/intensity of light. It displays how much power an appliance is taking when it is not in use. It also helps the user compare different levels of power usage by an individual appliance (such as the rise in power usage when the volume of a stereo is raised) and between appliances (between, for instance, the level of power used by a microwave and that used by an electric kettle for boiling a glass of water).

Currently, the information on how much energy is used by a device is mostly hidden. For instance, the little LED light on the TV or the computer shows that the device is on. However this light does not give any indication of how much power the appliance is using. It is also very difficult to compare across appliances in terms of the power used. The aware-cord design makes this information transparent. The light pulses provide a subjective sense of the power usage, and the movement

**Figure 5.** The power-aware cord

of light also highlights what is on, and provides a cue to switch off things that are not in use.

***Power Explorer***: The Power explorer is a mobile phone video game connected to the home power meter. Winning in the game involves lowering energy consumption in the home. The game makes energy efficiency fun, and allows you to explore your home from an energy-efficiency perspective, making changes to your energy profile using the game as a proxy.

Besides making energy information explicit, this design combines motivation and mobility. It also brings together the game world and the real world in a unique fashion, recasting the sustainability problem as a local challenge. The design may be fruitful in encouraging the young age group, particularly children, to shift to sustainable resource use. A related project in the recycling domain is the Bottle Bank Arcade, which displays points for bottles dropped into the right slots, making recycling similar to an arcade game.

The applications we reviewed in this section focus on providing information about individuals' energy use, helping them make decisions that support sustainable resource use. Access by individuals to their own electricity data, and eventually natural gas and water data, through the Green Button initiative (greenbuttondata.org/greenabout.html) are spurring a new class of application (Han, 2012). The kinds of design principles made explicit here could prove useful in developing this emerging class of application. In the next section, we consider applications that provide information on energy use by groups of people.

### 5.2 Group level applications

***Comparison Bills***: The power explorer exploits the competitive spirit at the personal level. There are also efforts to expand the competition idea to the local community. This includes electricity bills (piloted in California) that show your energy consumption in comparison to your neighbors' consumption and in comparison with average consumption. Your consumption is then tagged with smiley and frowning faces, depending on how your efficiency compares with others' consumption. In this approach, privacy is maintained, since only relative energy consumption is displayed, and not absolute energy consumption. A similar experiment is BOEL, a web interface that presents daily electricity consumption figures to homeowners, and also to neighbors. The idea is to promote joint savings, and foster competitive energy saving behavior among neighbors.

This design tries to address the uncertainty over the community's behavior, while also attempting to motivate using peer pressure. Since the information is presented on a bill or the web, it is not always on; so it does not provide instant feedback on user actions. It thus forgoes the motivation possibilities provided by the personal-level artifacts.

***Symbiots***: Symbiots are a conceptual class of designs that extend the kind of feedback provided by Comparison Bills into the neighborhood. In the Symbiots project, when people in nearby households, buildings or neighborhoods reduce energy consumption below a threshold, some of the excess energy is employed to surface playful and provocative forms within the local landscape. Examples include street cinema, street lights that spotlight individual houses based on energy efficiency, and fountains (Bergström, Mazé, Redström, and Vallgårda 2009). Another project, which one might also regard as a Symbiot, is the Green Haze over Helsinki, where lasers were used to draw a highly visible green cloud in the sky, which was projected into the smoke emitted by the Helsinki power plant. The cloud grew bigger as electricity use was reduced across the city, leading to a successful "unplug" event, in which 4000 residents collectively saved 800 kVA (Evans 2008).

The Symbiots system is intended to address the uncertainty over community behavior, and includes a motivation element similar to the case of the energy plant. Conservation behavior is 'tethered' to a representation embedded in the community, which takes nourishment from the community's energy management. Symbiots also present the possibility of people not already committed to sustainability being drawn into energy-saving behaviors, based on a possible favorable reaction to the Symbiots.

***SmartSwitch***: This is a switch that becomes harder to turn on when the energy consumption is above a target. The target can be based on an individual's consumption, the neighborhood's consumption, the load in the grid, or ambient light.

This design combines the individual and group levels, and is different from most of the above in that it actively tries to discourage consumption, both literally and symbolically. A similar design is the ECO gas pedal, which presses upward when it senses that the driver is speeding up too quickly.

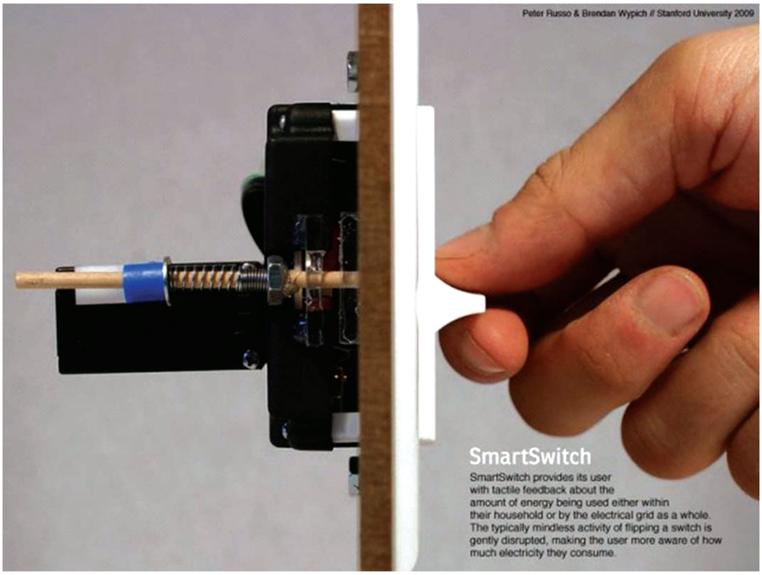



**Figure 6.** The smartswitch

***The Copenhagen bike meter***: In a domain different from electricity consumption, the city of Copenhagen has installed a meter in front of city hall that counts the bikes that pass. It provides numbers for bikes passed today, and bikes that have passed this year. Cyclists on the bike lane are registered by a 'sensor line' in the asphalt a few meters in front of the counter. A SIM-card in the counter sends the information to the City of Copenhagen's Center for Traffic. This representation also addresses uncertainty over other people's behavior, and has an element of motivation, as a large number of bikes on a road (accurately measured) could motivate non-bike users into using bikes.

Most of the applications reviewed in this section deal with electricity use. However, recent prototypes extend this approach to other resources, such as water, gas, waste-recycling and public transport (Froehlich, Findlater, and Landay 2010; Cohn et al. 2010; Campbell et al. 2010). Our analysis below is based on the applications presented in this section, but we believe the identified design principles extend to these other resources as well.

## 6. Sum, quorum, tether

What common features underlie the above examples of external representations that promote sustainable resource use? At least three design principles can be identified, which we term *Summation of actions*, *Quorum-sensing*, and *Tethering of actions*. We discuss these in detail below.

### 6.1 Summation of actions

Almost all the above prototypes provide integrative feedback, where the representations present a summation of actions (a related concept is 'aggregation'; see Ostrom 1999). For instance, the clock, the plant and the video game present electricity-use information in snapshots, summing the actions the user has taken over a period of time. The SmartSwitch, Symbiots, and the bike meter extend this summation to the actions taken by a community of users. These summations prevent the user from losing track of her actions over time (dissipation), and also help track user actions and results across periods of time. The summations thus lower the user's uncertainty about the outcome of her actions, as without the summations it would be difficult to know the extent of the effect of her actions. By providing information about multiple appliances at a single point, the summative structures also lower the load on attention.

Further, the summations generate a record of user actions, which can be referred to, and further actions can be built on top of these records. For instance, devices in homes can be networked to create large-scale maps of resource use, which may eventually be used to create smart energy grids that allocate supply based on demand. The summations provided by in-home displays also could prevent

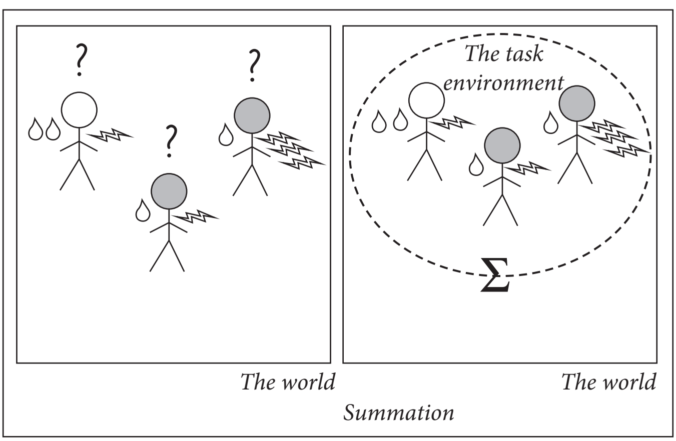



**Figure 7.** The sustainability problem-space before and after the personal-level summation structures are designed. The sigma represents the summation. The agents can now track their own consumption. Note that the summation structure leads to a dotted circle, which is a rough approximation of the task environment box. This indicates that the agents' actions could now be interlinked approximately through the summation.

relapses into wasteful behavior, as behavior can be anchored to a baseline achievement. Current designs do not relate summations to a target goal, such as an ideal usage level for a home for two people. Such targets may provide more motivation to persist with a low-resource-use behavior pattern.

### 6.2 Quorum-sensing

In the community level prototypes discussed above (Community Bills, Symbiots, Green Haze over Helsinki, and the Copenhagen Bike Meter), assorted actions, by diverse sets of unrelated people, are made explicit using a summed representation, which everyone can perceive. The fact that everyone can perceive it lowers uncertainty about others' actions. These public representations also provide two types of motivation. The first is a motivation to persist. Public representations create a public record of resource-use levels, and this record encourages people to continue their energy-saving actions (i.e., prevent relapse), so as not to lag behind the resource saving levels they/others have achieved. The second is a motivation to join, where the public representations act as an invitation for non-participants to join the energy-saving initiative. The personal level artifacts mostly supply motivation to persist, though they may also inspire close family members and friends to start their own energy-saving initiatives. The group-level artifacts support both types of motivation. The general principle here is that actions that support sustainable resource use, when summed as a representation, act as psychological thresholds. These thresholds motivate even more sustainable resource use.

'Quorum-sensing' is our metaphor to capture this threshold-based motivating feature of summations. It comes from behavioral biology, where the term refers to chemical representations generated by organisms such as bacteria. If a bacterium attacks a host alone, it will be overcome by the host's immune system. But if the attack is by a sufficiently large colony of bacteria, the immune system can be overpowered. To assemble this critical quorum, individual bacteria secrete molecules known as auto-inducers into the environment. The auto-inducers accumulate in the environment, and the individual bacteria in the colony constantly sense the concentration of this chemical. When the auto-inducer levels reach a threshold, the entire colony senses this threshold, and moves into action (Waters and Bassler 2005). The quorum-sensing strategy allows organisms to optimize their performance and effort in unstructured decision-making environments, where participants are spatially dispersed, and execute their actions at different times. The sustainability problem-space has the same features. A popular design that exploits the quorum sensing structure is an electronic coupon (such as Groupon) that leverages internet groups: the coupon becomes active for everyone when a certain number of people sign up for it.

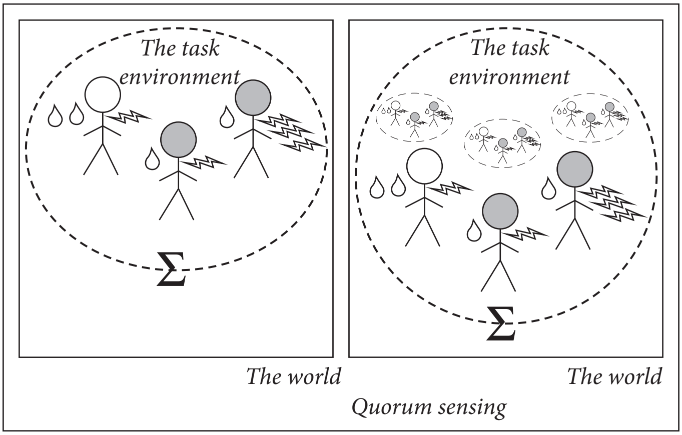



**Figure 8.** The sustainability problem-space before and after the group-level summation structures are designed. The smaller circles with people indicate that each agent now has a representation of the actions of the group, of which they are a part.

The notion of quorum sensing is an apt metaphor for how external representations allow individual energy-saving actions to be summed together into a public record, and sensing of these records by everyone then triggers more coordinated actions at the group level. These coordinated actions then cross thresholds the individual actions could not cross by themselves. Interestingly, the quorum-sensing metaphor can also be used to capture some of the designs for purely individual use, such as the energy clock and energy plant, which summate the user's actions across different time-periods. The quorum being sensed here is the individual's own actions, which are dispersed across time and space. The summation brings these actions together under a single representation, which could then trigger new decisions or actions, such as a conscious effort to save more energy.

## 6.3 Tethering of actions

In some of the representations described earlier, people's energy-saving behavior nourishes an external structure, such as the energy plant that survives on your saved energy (a whimsical representation at the personal level), and Symbiots (playful structures at the community level). These elicit encouraging displays, which reward participation. In the case of the energy plant, the tethering is exploiting general metaphors of flourishing. We associate a flourishing plant with a good result, and it's clear to us that the intent of the designer is to connect that good result with a lowering of energy consumption. These displays are 'tethered' to the behaviour of groups, which are in turn built on top of the summation of individual actions. Tethering seeks to address the repetitive nature of resource-saving actions, providing reminders and motivation elements to maintain current behavior. In the current community-level prototypes we describe, the tethered structures lower uncertainty about others' actions, and thus motivate actors to persist with their actions based on the knowledge that others are similarly contributing.

However, follow-on prototypes based on the principle of tethering could motivate *novel actions*. For instance, imagine a pond in a community that practices rainwater harvesting. The harvested water feeds into the local aquifer, which supports the pond. The pond is thus tethered to the community members' rainwater harvesting actions. But the level of water in the pond is also an indicator of the level of water that has been captured by households and stored underground. A brimming pond would then encourage one style of water usage by individual households, a half-full pond would encourage quite another. Such a tethering structure also offers a promising direction in solving the tragedy of commons problems that arise with such public resources. This is because the representation also creates a framework to develop grass-root institutions (say a village committee that monitors the level of the pond and recommends usage patterns), which have been shown to be effective in addressing the tragedy of commons problem (Ostrom 1990; 1999).

An interesting element of such a tethered structure at the community-level is its possibility to motivate, and specifically, its ability to attract non-participants to the sustainability initiative. The pond is an indicator of the success of rainwater harvesting, but not just for people who harvest rainwater, but also for anyone who sees the pond and comes to know that the community practices rainwater

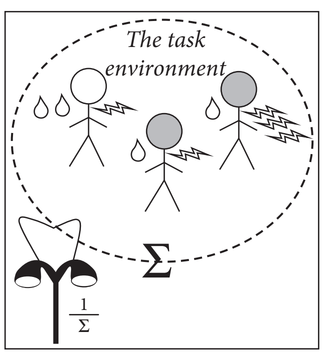



**Figure 9.** The sustainability problem-space after the tethering structures are designed. The streetlight survives on the power saved by the agents. Its brightness is an inverse function of the power consumption (1/sigma).

harvesting. The pond could thus recruit more participants to rainwater harvesting. The outdoor forms of Symbiots similarly seek to generate this attraction effect.

That said, for any such recruitment to occur, it is crucial that passersby be made aware of the purpose of the Symbiot. Without context, a Symbiot light show would simply look like a light show to the uninitiated. A tethered representation is not motivating in and of itself. Any tether requires context to be interpreted correctly. Without context, a passerby might never make the connection between the public display and levels of consumption. Without some kind of specific information (a street sign), there is nothing that would lead a passerby to suspect that the Symbiot has a specific reason for triggering. In the language of pragmatics, appealing to Dascal (2003), and abstracting beyond linguistic pragmatics, one might distinguish between cues (that signal whether the *computed* purpose of an artifact is a satisfactory candidate for its *intended* purpose) and clues (that help determine the best candidate for an artifact's intended purpose). An energy orb, or an energy plant, are both sufficiently unusual in a house-hold setting to provide *cues* to a visitor that these artifacts are not merely decorative, but convey information. As such, they may invite further inquiry on the part of the visitor, in a way that Symbiots might not. However, they do not provide obvious *clues* as to their purpose. In the case of personal level artifacts this may not matter. The person who buys these artifacts and uses them already knows their purpose. However (as alluded to in the pond example, above) designing-in *clues* to the artifact's purpose provides a valuable secondary function: to attract and engage non-participants.

Clues to purpose are not absent from all of these designs. The purpose of the energy-aware-cord, for instance, will probably be apparent to most people who see it. The onlooker is cued to a novel purpose by the fact that the energy-aware-cord behaves in a way that is different from the normal behaviour of cords. The non-standard behaviour of the energy-aware-cord calls attention to itself. This provides a cue that additional information is being conveyed.

The *clue* to the nature of that purpose is the fact that the information is displayed on the cord itself. The fact that the information is physically associated with the resource (electricity) enables the viewer to make the correlation between electricity level and cord brightness. The advantages of providing both cues and clues to an object's purpose suggest two additional (though modest) design principles:

1. The device should call attention to itself in a way that suggests that information is being conveyed, inviting further inquiry.
2. For easy identification, the information should be physically associated with the resource being measured, as with the plant-in-a-compost-pot. This is an idea we elaborate on in the next section.

## 7. Looking back at distributed cognition

In Section 1, we argued that the task environment in the sustainability problem has three complex properties (complexity of: task-environment, goals, and representations) that are not addressed by the distributed cognition framework in its current state of development. Our analysis shows that recently developed external representation prototypes (that use external representations to promote sustainable resource use) are based on three design principles (sum, quorum, and tether). How do these principles address the three complexities of the sustainability task environment we outlined in 4, and how do they fit with the distributed cognition framework?

There is no direct one-to-one mapping between these three design features and the three complexities we have identified. These design features do address some aspects of the three complexities, but not all. In the following section, we outline how these design features address some of the complexity issues. One of the central ideas of distributed cognition is that external representations allow a perceptual 'reading off' of information, thus supporting a bypassing of complex internal operations (Hutchins 1995a). Given its descriptive nature, the DC framework does not elaborate on the relationship between this reading off and the structure of the task-environment, or the biological mechanisms that underpin this reading off (see Chandrasekharan 2009; Chandrasekharan and Osbeck 2010 for a possible mechanism). One way to view the summation property, which is


**Figure 10.** Recycling bins in Barcelona

supported by almost all the prototypes we discuss, is to consider it as providing this reading off feature: the summation seeks to generate a perceptual structure that accumulates actions and their effects, allowing them to be read off at one go. This accumulation, particularly in the group-level applications, has the effect of addressing the first complexity: the asynchronous and unstructured nature of the task environment in the sustainability problem. The summation captures the users' asynchronous actions that are spread over many locations, and makes this information available in a perceptually readable fashion to all members of the group. This group summation also partly addresses the second complexity, as it lowers the uncertainty over others' actions and goals.

The way in which summation addresses the first complexity suggests that there could be a relationship between the nature of the task environment and the emergence of the summation solution. In structured task environments such as aircraft cockpits, feedback is usually needed in real-time, so external representations such as the speed bug connect user actions (joystick movements) to system states (aircraft speed/altitude), almost one-to-one, allowing them to be coordinated efficiently in real-time. In unstructured and asynchronous task environments, such one-to-one mappings are not possible; neither are they desirable, as one-to-one mappings would block the emergence of information structures fluid enough to be used by all members of the community. Dynamic and asynchronous summations such as quorum-sensing evolved to adapt to the constraints of such unstructured task environments. It is interesting that this adaptive strategy first developed at the cell-biological level is now emerging in designs that address the sustainability task environment, which is also unstructured and asynchronous (see Ostrom 1999 for a broader discussion of this point in relation to complexity theory).

The perceptual reading-off property (provided by summations) addresses the third complexity as well, particularly providing motivation. A good example is a cola-recycling bin, which is shaped like a giant cola bottle, and brings together many users' recycling actions. It provides instant perception of, and motivation for, the bottle recycling action. A more nuanced example, involving the use of a form of tethering to provide motivation, is the effort to scale the plant-in-a-compost-pot model to apartment complexes. One possibility here would be: all tenants in the apartment complex contribute their organic waste to an on-site composting system, and compost from the system would be used to maintain a roof garden (a form of tethered representation) for the building, whose produce would be sold to the tenants at a discount. In this closed-loop implementation, composting actions are tethered to the garden and its produce, and the integrated effect of composting actions can be read off from the state of the garden and its produce.

Now, by contrast to the roof garden, consider a different kind of implementation with similar closed-loop features: methane from the composting system is used to heat water in the building, and the compost is sold to a farmers' cooperative outside town, whose produce is sold back to the apartment tenants.

While heating water has better efficiency compared to growing plants on the roof, the water heater is less obviously tethered to the tenants' actions, as the effects of heating water+selling compost are fragmented, and cannot be read off readily. Unlike the roof garden, the water heater is not tethered to the composting actions in an integrated way. The hot water produced by the heater is used in an intermittent and dissipative fashion, and thus does not track the actions taken by the tenants in an integrated format. The produce, similarly, is removed from the perceptual loop of the community, as it grows somewhere else, and does not track the tenants' actions. So there is no constant, readily readable, one-shot feedback for the community's actions. This means both tethering and the perceptual reading-off need to be combined to address the motivation problem.

The above example suggests that the cognitive distance between user actions and tethered representations should be very low for tethering to be effective. However, this distance, and the perceptual reading off involved, is quite nuanced in the sustainability problem. This is best illustrated using the energy plant example. The plant summates the use of electricity in a house, and represents the *lowering* of electricity usage as *growth* in the plant. From the perspective of designing a representation that supports perceptual reading-off of the effects of a user's actions, the cognitive distance would be lower (require less transformations) if the lowering of electricity usage is represented as a lowering in the representation, say by a line dipping in a graph that charts consumption across time (as used by the energy clock). However, such a cognitively-close representation does not provide the same level of motivation as the plant (which, in fact, is a later design from the same group that designed the clock). The energy plant's output is tethered to a more inspiring representation: a plant that grows as consumption shrinks. Thus, the tethering feature sometimes requires violating the standard direct mapping principle in interaction design (where, for instance, lowering usage is represented by a lowering line and growing usage by a growing line). Direct mappings that lower the cognitive distance between user action and the tethered representation may not always be optimal in the sustainability task environment.

This discussion is preliminary, and it only broadly outlines how the identified design principles relate to distributed cognition. Understanding how exactly the three identified design features (in combination) address the three complexities requires a more detailed analysis, which we hope to undertake in future work.

In this paper we have applied DC as a framework to analyze design interventions that ease the performance of tasks that promote domestic energy conservation. However, this is only one of many task domains that make up the field of sustainable practice. The approach taken here for energy conservation could be applied to a variety of other task domains that are often classed as related to sustainability, such as water use and recycling.

That said, what is meant by sustainability depends on context. In an off-the-grid house, reducing energy may have no effect on sustainability. In some cases, a technological intervention may uphold one path to sustainability while neglecting another. For instance, over its lifetime, an electric car might produce no exhaust, but rely primarily on coal-fired electricity plants, as well as consign spent batteries to landfill. Those contradictions will not be resolved here. But we would like to note that these kinds of considerations add to the cognitive complexity of designing a sustainable civilization and the artifacts and practices that constitute it. Ideally, a new practice or device should be non-toxic *and* energy-efficient *and* fully recyclable (McDonough, 2002). In particular, the need to satisfy many such design requirements at once adds to the cognitive complexity of the design process, and creates a need for new tools to tame design complexity.

## 8. Beyond sum, quorum, tether: Re-usability engineering

The external representation prototypes (and the design principles they use), appear promising, but these structures seek to restructure behavior purely by representing information in new ways. This information-driven strategy neglects at least two cognitive components of the sustainability problem. We will examine these below. Both of them involve building action structures in the environment, which seek to alter mental and social models, and thereby encourage actions that promote sustainability.

The first cognitive component that is missing is a 'script' (Schank and Abelson 1977) in which users go into a sustainability space and execute a sequence of actions that promote sustainable resource use, much like the sequence of actions people follow in a restaurant, or a bank, or a clinic. Such scripts (similar to ones described by Schank and Abelson 1977) would turn actions that promote sustainability into routines that are valued by the community. For recycling, building this script would require first setting up a recycling space. An example would be a set of walk-through cubicles in apartment complexes, arranged in sequence. Each cubicle would have a reverse vending machine, accepting just one type of material for recycling. Each machine credits the deposited materials to the user's smart card. The credits can be redeemed at a mall or elsewhere. Such a space, and sequenced actions, would help users build a recycling routine similar to the shopping routine, allowing them to step through each machine slot, executing recycling actions. Currently, there is no such recycling routine or space. There is a garbage-dumping routine and space, which involves putting all your garbage into one bag, going to a set of overflowing boxes sitting outside the complex, and dumping your bags in the garbage container for the truck to come and pick up and dispose of. Recent work has shown that such messy arrangements can lead to the spreading of disorder (Keizer, Lindenberg, and Steg 2008). There is no incentive for extensively sorting your garbage for recycling, so it is either enforced by the city, in which case it is resented, or only conscientious people do it. Building a recycling space, making it part of housing, and returning credits, would make recycling a routine with explicit value, both for the individual participant and the community. In downtown Barcelona, there is no garbage pickup. People instead take their garbage and recycling to a nearby line of bins. They start at one end, and as they proceed from bin to bin, they throw their recycling in each bin as appropriate. Bins are always lined up in the same order, making it easier for blind people to identify the bins (Camprubi 2010). It's not as carefully controlled as what we have described, but it is suggestive. Similar scripts could be developed for electricity/water usage, both of which are currently recorded by meters hidden away in corners of the living space. One approach is to make these meters public artifacts that display a person's values and life routines. For instance, certain German households have their water meter in the living room for guests to see (Suzuki and Dressel, 2002).

A second cognitive aspect of the sustainability problem that is not addressed by external representations is humans' focus on the construction of artifacts, and a resulting high positive value accorded to construction in our mental and social models. Building activity is central to humans' evolutionary niche, and such activity is highly valued by human society. Maintenance, and activities such as recycling, are generally accorded subsidiary roles in the social hierarchy. This bias possibly comes from an era where nature deconstructed humanity's efforts routinely, and not much attention needed to be paid about how things degraded. However, now we are at a point in our evolutionary history where the products of our construction activity threaten to swamp the entire planet. The recently identified continent-sized patch of plastic in the Pacific Ocean (the Great Pacific Garbage Patch) is an early indicator of what the future would look like if we continue in this trajectory, without developing mechanisms to systematically degrade and reuse our construction output.

From a cognitive standpoint, we believe that lowering our focus on construction, and widening our mental and social models to include deconstruction activity, would help address the trash and resource-scarcity problems. For instance, we have prizes (such as the X-prize) for building new inventions, but no prizes for efficiently dismantling artifacts, especially artifacts that create environmental problems, such as nuclear reactors and other devices that emit radiation. More broadly, we need to strive to change the mental/social model where construction is celebrated, and deconstruction is relegated to the sidelines. This would not be easy, since our beliefs about the appropriateness of focusing resources on construction, rather than de-construction, are already fixed, and of long-standing. Some philosophers take the view that it impossible for people to change beliefs that are already fixed. However, there is evidence that beliefs can be altered by re-framing them (Dascal and Dascal 2004).

How, then, could we widen this mental/social model? One way would be to highlight deconstruction activities in the media, as seen in program 2801 of *This Old House* (The Weston Project, Part 1), where a house is shown to be taken apart piece by piece by a deconstruction crew, who are able to reclaim much of the material in the house and repurpose it. Public awareness of the possibility of deconstruction, however, may not, in itself, be sufficient. Another, more long-term approach would be to change influential institutions so that they promote deconstruction activity, making it a greater part of common practice, and thereby making it valued. For instance, most of our universities have engineering schools that are focused on assembling and manufacturing complex artifacts, a valued and respected activity. A plausible institutional change would be to develop deconstruction/re-usability engineering departments within these engineering departments that would develop ways of efficiently disassembling artifacts so that they could be reused optimally. This would enlarge the domain of engineering, and make the practice of disassembling valued and respected as well. Each industry could then have its own deconstruction departments. Practical experience with deconstruction would, in turn, inform the design of products in ways that allow them to be easily disassembled.

This example is suggestive of the ways in which our institutional and resource frameworks are almost entirely oriented towards construction. A systematic examination of this bias could open up valuable spaces for redesigning our institutions, and better allocation of our resources.

External representations, and their designers, may contribute to such a shift in mental and social models, but external representations by themselves cannot drive this institutional shift. What is required are case studies and clear analysis of how institutions shape cognition and mental models, and how the redesign of institutional frameworks could reshape our cognitive models to support the sustainability effort. The emergence of departments of sustainability science on university campuses (Sherren, Klovdahl, and Robin et al. 2009) provides one such avenue for study. Within engineering in particular, the evolution of usability engineering as a discipline, and the incorporation of usability as a business principle by most organizations, is the closest analogy/template we have of such a wide change in practice and of institutional/organizational design. Usability may thus be the best stepping stone towards reusability.

## 9. Limitations of our approach

Our analyses of external representations that promote sustainability make use of a set of assumptions (some of which come from the prototypes), which limit the wider applicability of the identified design guidelines. We group these assumptions under two categories and make them explicit in this section, so that they can be addressed in later designs and analyses. We are grateful to two anonymous reviewers and the editor for pointing out some of these assumptions.

### 9.1 Tragedy of the commons

Almost all the designs we discuss are based on two implicit operational assumptions. One is that there are some consumers who would like to lower their resource usage, and some others who could be motivated to lower their usage. A second assumption is that lack of information is one of the central reasons that these two classes of consumers engage in wasteful behavior. These operational assumptions try to circumvent the tragedy of the commons (TC), which, in the environmental context, is characterized by De Young (1999b) as below: "individual rational behavior (i.e., acting without restraint to maximize personal short-term gain) can cause long-range harm to the environment, others, and ultimately oneself".

TC is a very complex problem that spans economics, behavior, and the design and use of governance systems (Ostrom 1999). The prototypes we review all seek to solve this problem using external representations that present information about individual and community usage in novel ways. It is unclear whether external representations by themselves can help solve the TC problem. For instance, McKenzie-Mohr (2000) presents a case study of water conservation where households were either sent an information packet (an external representation) about conserving water, or they were visited by a cyclist who discussed water conservation with tenants. Compared to baseline measurements, observation of residents indicated that those householders who were visited by cyclists decreased watering by 54%, whereas those in the information-only control group increased lawn watering by 15%. Similarly, a study on hotel towel reuse (Goldstein et al. 2008) showed that reuse did not go up with standard environmental messages ('save resources'), but reuse went up significantly when the message was framed in the context of peer group behavior ('the majority of guests in this room reuse the towels'). Relating this result to the prototypes we discuss above, the information they present are not all framed in the context of peer behavior, and even if this could be done, it is unclear what the peer-group would be for the presented information.

The two assumptions we outline above allow the designers to start the design process without analyzing the TC problem, nor by postulating a specific set of users, and targeting the design to a specific problem they face. While this operational move is needed to get the design-and-optimize strategy going, there are many issues that arise even if we grant these assumptions. We discuss these below.

1. The summations may actually lead to these ideal users consuming more, either when they see the overall consumption coming down, or when they notice that the average individual consumes a lot more than them. One can assume that these ideal individuals are conscientious, and such a relapse will not happen, but this assumption will not hold when trying to scale the applications to the wider population. The design and the scaling processes thus would need to take into account this problem explicitly.
2. It is unclear whether summations of group behavior would have the desired effect on individual behavior. However, this is an empirical question, and we need to create the summations to test this proposal and fine-tune the summation idea based on the results.
3. The comparisons between households may be unfair (for instance, one household may have a patient who needs intensive care), and this would raise the cognitive/emotional load of users in such households.
4. The comparisons could also lead to arms-race type behavior where groups of users opposed to lowering resource use (say energy company shareholders) raise their consumption to negate the savings generated by other users.
5. Users could perceive the tethered representations in neighborhoods negatively, and thus the representations may not lead to the community behavior sought; there may even be concerted efforts to increase consumption so that the tethered representations are shut down.
6. The proposed designs do not take into account what is known about TC, particularly the work on the emergence of governance systems by Ostrom, who suggests that "instead of thinking of overcoming or conquering tragedies of the commons, effective governance systems cope better than others with the ongoing need to encourage high levels of trust while also monitoring actions and sanctioning rule infractions." (Ostrom 1999). The designs do not address the problem of trust, and assume that transparent representations (of community behavior) will raise trust levels automatically. The designs also do not address how they could be extended to develop governance systems, rules and sanctions, which would be required while scaling the sustainable behaviors to the wider population.
7. The proposed solutions are all general, and do not seek to support local constraints and gradual refinement of the representations, nor as learning by the

stakeholders; these are important components of the self-governing systems identified by Ostrom.

8. The proposed designs do not take into account the user's context in a systematic way, and future prototypes would need to be redesigned to accommodate context elements. Our analysis of the prototypes also do not systematically take into account context elements, and how the information presented by the prototypes could be made relevant and motivating to users in many different contexts. We hope to address this aspect in future work.

Some of these limitations could be addressed by revised designs that are based on user feedback and behavior changes. These designs, and the user-information they are based on, may provide deeper insights into the TC problem in general, and new ways of tackling it. Some of the other issues (such as developing governance systems) require paying attention to existing models of sustainability (such as Ostrom's) and integrating them with the distributed cognition framework.

### 9.2 Motivation

As we noted at the end of Section 4, the prototypes are not based on a detailed and comprehensive understanding of the motivation literature, and do not take into account the many possible interactions between motivation and decision-making, as well as interactions between motivation, control and cognitive load. These interactions can be very complex. As an example of this complexity, a recent study found that motivation is augmented by the process of making the decision, the feasibility of the participant's goal, the emotions she anticipates, and her perceived control over her behavior (Bagozzi, Dholakia, Basuroy 2003).

Another study found that implementation intentions improve recycling behavior (Holland, Aarts, Langendam 2006). McKenzie-Mohr (2000) observes that when there is low motivation to engage in a sustainable behavior, it can be improved with incentives (see Gardner and Stern 1996) or commitment strategies (Katzev and Wang 1994). McKenzie-Mohr also points out that it is more difficult to alter and maintain repetitive behavior changes, compared to one-time changes in behavior (Kempton, Darley, and Stern 1992; Kempton, Harris, Keith, and Weihl 1984). Finally, including many such representations in the household may lead to users shutting the representations out of attention, and coasting along with some default behavior. There is also the related problem where a user is unsure which representation to attend to during a given task, and this higher cognitive load can lead to lack of motivation, particularly given the findings on motivation as a finite resource (Hagger, Wood and Stiff 2010; Baumeister, Bratslavsky, Muraven and Tice 1998; Schmeichel, Vohs, and Baumeister 2003).

It is unclear how these interactions with decision-making will play out in conjunction with the developed prototypes, which have not been tested extensively in the field. However, given the general HCI strategy of develop-test-redesign, we expect these interactions to be taken into account by later versions of the prototypes.

## 10. Conclusion

We examined the problem of designing external representations that help lower resource use, and the limitations of using the distributed cognition framework to address this problem. Based on an analysis of a set of prototypes that promote sustainable resource use, we extracted three design principles (sum, quorum, tether), and showed how they help extend the distributed cognition framework to unstructured task environments. We also looked at how these address some of the cognitive complexities of the sustainability problem space. In the penultimate section, we examined two further advances needed for promoting sustainability — developing sustainability routines, and revising mental/social models that currently accord higher value to construction and lower value to de/reconstruction activity. We concluded this section with two proposals, namely that these guidelines need to be augmented in two ways: by developing action spaces and scripts for sustainability, and also by developing institutional frameworks that promote deconstruction. In the final section, we outlined some limitations of the prototypes and of our analysis, paving the way for revised designs and theory that take these limitations into account. We hope that these guidelines will lead to the design of better cognitive and social systems that advance the cause of sustainability.

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## References

Bagozzi, R.P., Dholakia, U.M., and Basuroy, S. 2003. "How effortful decisions get enacted: the motivating role of decision processes, desires, and anticipated emotions". *Journal of Behavioral Decision Making* 16: 273–295.

Bergström, J., Mazé, R., Redström, J., and Vallgårda, A. 2009. "Symbiots: Conceptual interventions into urban energy systems". *Proceedings of the Nordic Design Research Conference, Engaging Artifacts*, Oslo, 2009.

Campbell, T., Larson, E., Cohn, G., Froehlich, J., Alcaide, R., and Patel, S.N. 2010. "WATTR: A method for self-powered wireless sensing of water activity in the home". *Proceedings of UbiComp 2010*, Copenhagen. ACM, New York, 169–172.

Camprubi, D. 2010, February 11. "Barcelona's innovative public recycling containers". *PSFK*. Retrieved from: http://www.psfk.com/2010/02/barcelonas-innovative-public-recycling-containers.html.

Chandrasekharan, S. 2009. "Building to discover: a common coding model". *Cognitive Science* 33: 1059–1086.

Chandrasekharan, S. and Stewart, T.C. 2007. "The origin of epistemic structures and proto-representations". *Adaptive Behavior* 15: 329–353.

Chandrasekharan, S., Osbeck, L. 2010. "Rethinking situatedness: Environment structure in the time of the Common Code". *Theory & Psychology* 20: 171–207.

Cohn, G., Gupta, S., Froehlich, J.E., Larson, E., and Patel, S.N. 2010. "GasSense: appliance-level, single-point sensing of gas activity in the home". *Proceedings of the 8th International Conference on Pervasive Computing.* Berlin: Springer, 265–282.

Dascal, M. 1998. "The study of controversies and the theory and history of science". *Science in Context* 11(2): 147–154.

Dascal, M. 2003. "*Interpretation and Understanding*". Amsterdam: John Benjamins, http://public.eblib.com/EBLPublic/PublicView.do?ptiID=622708.

Dascal, M. and Dascal, V. 2004. "De-fixation of belief". In F. Gil, P. Livet, and J. Pina Cabral (eds.), *O Processo da Crença*. Lisboa: Ediora Gradiva, 321–353. Translated into Portuguese by Fernando Gil.

De Young, R. 1999a. "Environmental psychology". In D. E. Alexander and R. W. Fairbridge (eds.), *Encyclopedia of Environmental Science*. Dordrecht: Kluwer Academic Publishers, 223–224.

De Young, R. 1999b. "Tragedy of the Commons". In D. E. Alexander and R. W. Fairbridge (Eds.), *Encyclopedia of Environmental Science*. Kluwer Academic Publishers, 601–602.

Dourish, P. 2001. *Where the Action Is: The Foundations of Embodied Interaction*. Cambridge, MA: The MIT Press.

Evans, H., 2008. "Nuage Vert". *Cluster Magazine*. Special Issue: Transmitting Architecture 7. Torino.

Fishbach, A., Zhang, Y., and Trope, Y. 2010. "Counteractive evaluation: Asymmetric shifts in the implicit value of conflicting motivations". *Journal of Experimental Social Psychology* 46: 29–38.

Froehlich, J., Findlater, L., Landay, J. 2010. "The design of eco-feedback technology". *Proceedings of the ACM computer-human interaction (CHI) conference*, Atlanta ACM. New York: 1999–2008.

Gardner, G.T. and Stern, P.C. 1996. *Environmental Problems and Human Behavior.* Boston: Allyn and Bacon.

Goldstein, N., Cialdini, R.B., and Griskevicius, V. 2008. "A room with a viewpoint: Using social norms to motivate environmental conservation in hotels". *Journal of Consumer Research* 35: 472–482.

Hagger, M.S., Wood, C., Stiff, C., and Chatzisarantis, N.L.D. 2010. "Ego depletion and the strength model of self-control: A meta-analysis". *Psychological Bulletin* 136: 495–525.

Han, L. 2012. "Green Button Program: An Analysis of Business Opportunities". Retrieved from: http://www.erb.umich.edu/Research/InstituteReports/11-12/RenewableEnergy Scholarship -LawrenceHan-Green-Button.pdf

Hardin, G. 1968. "The Tragedy of the Commons". *Science* 162: 1243–1248.

Higgins, T. 2000. "Making a good decision: Value from fit." *American Psychologist* 55: 1217–1230.

Holland, R.W., Aarts, H., and Langendam, D. 2005. "Breaking and creating habits on the working floor: A field-experiment on the power of implementation intentions". *Journal of Experimental Social Psychology* 42: 776–783.

Hutchins, E.L., Hollan, J.D., and Norman, D.A. 1986. "Direct manipulation interfaces". In S.W. Draper and D.A. Norman (eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction*. Hillsdale, NJ: Lawrence Erlbaum Associates, 87–124.

Hutchins, E. 1995a. "How a cockpit remembers its speeds". *Cognitive Science* 19: 265–288.

Hutchins, E. 1995b. *Cognition in the Wild*. Cambridge, MA: The MIT Press.

Katzev, R. and Wang, T. 1994. "Can commitment change behavior? A case study of environmental actions". *Journal of Social Behavior and Personality* 9: 13–26.

Keizer, K., Lindenberg, S. and Steg, L., 2008. "The spreading of disorder". *Science* 322: 1681.

Kempton, W. Darley, J.M. Stern, P.C. 1992. "Psychological research for the new energy problems". *American Psychologist* 47: 1213–1223.

Kempton, W., Harris, C.K., Keith, J.G., and Weihl, J.S. 1984. "Do consumers know what works in energy conservation?". In J. Harris and C. Blumstein (eds.), *What Works: Documenting Energy Conservation in Buildings*. Washington, D.C.: American Council for an Energy Efficient Economy, 429–438.

Kirlik, A. 1998. "The design of everyday life environments". In W. Bechtel and G. Graham (eds.), *A companion to Cognitive Science*. Oxford: Blackwell, 702–712.

Mazé R. and Redström, J. 2008. "Switch! Energy ecologies in everyday life". *International Journal of Design* 2: 55–70.

McDonough, W. and Braungart, M. 2002. *Cradle to Cradle: Remaking the Way we Make Things*. New York: North Point Press.

McKenzie-Mohr, D. 2000. "Promoting sustainable behavior: an introduction to community-based social marketing". *Journal of Social Issues* 56: 543–554.

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.

Ostrom, E. 1999. "Coping with tragedies of the commons". A*nnual review of Political Science* 2: 493–535.

PA Consulting. 31 March, 2010. Cape Light Compact Residential Smart Energy Monitoring Pilot Final Report. Madison, WI. Retrieved from: http://www.capelightcompact.org/library/2010/08/3.31.10-Residential-Smart-Home-Energy-Monitoring-Final-Evaluation-Report.pdf.

Schank, R.C. and Abelson, R. 1977. *Scripts, Plans, Goals, and Understanding*. Hillsdale, NJ: Earlbaum Associates.

Schmeichel, B.J., Vohs, K.D., Baumeister, R.F. 2003. "Intellectual performance and ego depletion: Role of the self in logical reasoning and other information processing". *Journal of Personality and Social Psychology* 85: 33–46.

Schunn, C.D., McGregor, M., Saner, L.D. 2006. "Expertise in ill-defined problem solving domains as effective strategy use". *Memory & Cognition* 33: 1377–1387.

Schwartz, D. and Martin, T. 2006. "Distributed learning and mutual adaptation". *Pragmatics & Cognition* 14: 2 313–332.

Shah, Y.J. and Kruglanski, A.W. 2003. "When opportunity knocks: Bottom-up priming of goals by means of its effects on self-regulation". *Journal of Personality and Social Psychology* 84: 1109–1122.

Sherren, K, Klovdahl, A.S., Robin, L., Butler, L., and Dovers, S. 2009. "Collaborative research on sustainability: Myths and conundrums of interdisciplinary departments". *Journal of Research Practice* 5(1): 1–29.

Suzuki, D. and Dressel, H. 2002. *Good News for a Change: Hope for a Troubled Planet*. Toronto: Stoddart Publishing.

This Old House, 2 October, 2008. "Season 30: The Weston Project". Part 1. Program 2801. Retrieved from: http://www.thisoldhouse.com/toh/tv/house-project/show-descriptions/0,,20198092,00.html#

Voss, J.F. 1988. "Problem solving and reasoning in ill-structured domains". In C. Antaki (ed.), *Analyzing Everyday Explanation: A Casebook of Methods*. London: SAGE, 74–93.

Waters, C.M. and Bassler, B.L. 2005. "Quorum sensing: Cell-to-cell communication in bacteria". *Annual Review of Cell and Developmental Biology* 21: 319–346.

Weiser, M. 1993. "Some computer science problems in ubiquitous computing". *Communications of the ACM — Special Issue on Computer Augmented Environments: Back to the Real World* 36(7): 75–84.

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