# Collaborative Filtering and Carbon Footprint Calculation

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*Abstract*—**An increasingly common way for people to measure and understand their individual environmental impact is by using an online carbon footprint calculator. Although a wide variety of these calculators are available, the vast majority shares the same form of user interaction and calculation methods, limiting the reach of these tools and introducing a number of problems for informing users of their environmental impact. We find that the interaction afforded by popular calculators—in addition to considering only a limited number of impact factors at a single instant in time—treats a person's carbon footprint as an individual matter, rather than drawing attention to the interconnectivity and wider impacts of footprints across the person's broader community. To address these problems, we present the Better Carbon calculator, which uses collaborative filtering and location-based calculation to provide an individual footprint estimate while simultaneously affecting and improving the estimates for other people in a user's community.**

***Index Terms*—carbon calculator, carbon footprint, collaborative filtering, estimating individual impact, environmental sustainability.**

## I. Introduction

As environmental sustainability becomes a more important social value, people are increasingly interested in ways to measure their personal impact on the world around them. Understanding the environmental effects of their everyday activities can allow people to alter their behavior to be more sustainable, making more informed choices about their purchasing, transportation, and overall lifestyle. Carbon footprint [1]—the total amount of carbon dioxide directly and indirectly caused by an activity or accumulated over the lifetime of a product—is an increasingly popular method of measuring environmental impact. The term derives from the idea of an ecological footprint [2], an estimated measure of how large an area of land is needed to produce all the natural resources a person uses—to sustain that person's consumption. Though the ecological footprint has been extensively critiqued (e.g., [3,4]), the idea has found traction among many audiences, perhaps in part due to how capturing sustainability in a single number may facilitate discussion and understanding of relative environmental impacts. Despite being measured as a weight of invisible gases produced each year, carbon footprint nevertheless serves as a quantifiable measure that people can use to compare and discuss their effects on the environment.

One of the most common ways for a person to measure their individual carbon footprint is to use one of many online carbon footprint calculators. These calculators are websites that allow users to enter information about their lives, such as what type of car they drive, what size home they live in, and how often they travel by plane. This information is then used to give people a rough estimate of their carbon footprint by adding together the average amount of carbon dioxide (or carbon dioxide equivalents when including other greenhouse gases) produced by the reported measure of a particular activity. For example, driving a car 1000 miles produces around 0.7 tons of carbon dioxide equivalents ($tCO_2e$), while heating a small home for a year produces around 1.8 $tCO_2e$. Users can compare their carbon footprints as estimated by these calculators with an established baseline (such as the U.S. average) to get a sense for how sustainable their lifestyles are.

However, the design of current calculators introduces a number of limitations. In addition to considering only a limited number of impact factors, these calculators treat a person's carbon footprint as an individual matter, rather than drawing attention to the relationships between footprints across the person's broader community. Thus we introduce the Better Carbon calculator, a novel carbon footprint calculator in which an individual's estimated footprint alters the estimated footprint of their local community through the use of collaborative filtering [5-7]. In this way, the system adds a community component to carbon footprint estimation not present in other calculators, while also being more extendable and easier to use. By treating carbon footprint as a more social, collaborative calculation, Better Carbon helps convey the need for people to work together to live sustainably.

## II. Related Work

Although considering environmental impact in terms of a carbon footprint is becoming increasingly common, there is still debate over the meaning and usage of the term [1]. Indeed, previous work comparing the estimates provided by online carbon calculators [8] has found these systems to be inconsistent, as well as lacking transparency about how the calculations are performed. We extend such research,

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considering and advancing the mode of interaction afforded by these calculators, rather than the accuracy of their estimates.

Other previous research has looked at new and improved ways of calculating a person's carbon footprint. For example, The Consumer Footprint Calculator [9] uses patterns of consumption to model people's carbon footprints, while Co2Green [10] automatically estimates carbon footprint based on financial transactions, allowing people to determine their footprint while using tools for tracking their spending. Other projects have looked at calculating environmental impact using measures other than carbon footprint, such as Watts of power used (www.wattzon.com). However, this prior work has not considered the use of online sociality to improve such systems.

Social connections are playing a larger and larger roll in discussions about increasing sustainability. Mankoff et al. [11] describe how online social networks can be used to motivate people to decrease their ecological footprints, and sites such as TreeHugger (www.treehugger.com) enable communities of like-minded people to access and share content about how to live in more sustainable ways. Other work has looked at ways to enable the community to contribute to knowledge about environmental impact. For example, GreenScanner [12] uses community-generated reports to provide environmental impact information on household products, letting the community both use and contribute information. Such projects demonstrate the increasing interest of the research community in enabling the move from individual action to collective action in reducing environmental impact (e.g., [13,14]).

## III. Limitations of Current Carbon Calculators

There are numerous available online carbon footprint calculators that allow users to estimate their environmental impact (e.g., [15-19]). Nevertheless, the vast majority of popular calculators share the same basic mode of user interaction. In these systems, users answer a series of questions about their personal lifestyles and then are told their individual carbon footprint based only on those answers, along with ways to offset and reduce their greenhouse gas emissions.

This question-answer mode of interaction creates a number of limitations for online carbon calculators. For example, most calculators have a restricted scope, considering only a limited range of impact factors—categories that contribute to a user's carbon footprint estimate. Although most calculators include the three main sources of carbon emissions (ground transportation, air travel, and home energy) and some consider factors such as food and waste, there may be other significant sources of greenhouse gas emissions (such as from consumption of goods and services [9]). Indeed, calculators currently are restricted in the factors they can consider *because* of the form of interaction they adopt. Answering questions requires time and effort on the part of the user—especially with detailed questions about specific behaviors. Filling out more detailed or more inclusive information about a person's lifestyle—the exact kinds of food they eat, the kinds of clothes they wear, or exactly where they drive their car—is beyond the scope of online calculators and requires more effort than many users are willing to commit. Although some projects seek to automatically record details about certain behaviors as users live their lives (e.g., [20,21]), this work is not yet linked to broader carbon calculators, and indeed specifies a different mode of interaction. Thus the effort required by the question and answer format of the interaction with these systems limits the range of factors that typical carbon calculators can include.

Furthermore, the interaction mode of answering questions and receiving a personal carbon footprint estimate gives these calculators a strong individualistic focus. Footprints are only calculated for individual households, not for entire communities. Users' footprints are also compared to broad standards, such as national or world averages, rather than to the local community. Such broad averages may be less informative than local comparisons in part because of the regional basis of some factors—for example, emissions from home heating may be generally higher in cold climates than more temperate areas, leading to an unbalanced comparison in which some users feel unjustifiably green and others are irremediably condemned. Comparisons to national averages may also be less socially relevant than more local contexts, as people tend to know their neighbors better than other residents of their country. Indeed, carbon footprint calculation is not generally a social activity, as the systems' design does not encourage estimates to be shared with others, but rather to be personally redeemed by purchasing carbon offsets [22]. Offsetting their footprint—an action supported by popular calculators—reduces a person's individual emissions, without necessarily reducing the impact on the people around them. In this way, using current calculators to estimate a person's carbon footprint affects only that individual user, even though their actions affect the environment of their entire community.

## IV. The Better Carbon Calculator

In order to address these limitations of current calculators, we have developed a novel online carbon footprint calculator called the Better Carbon calculator (Fig. 1; available online at www.bettercarbon.com). Better Carbon increases the social focus of carbon footprints and lets calculations gain a persistent significance by having a single user's results also affect the estimates of the system as a whole. In Better Carbon, the information one user provides affects the emissions estimates of future users and of the local community. Users are also able to share suggestions about how to live more sustainably, helping to support collective action. Moreover, this system can be easily extended without increasing the burden placed on the user, and may be able to achieve more accurate estimates with less user effort.

### *A. Collaborative Filtering of Carbon Footprints*

Better Carbon achieves these goals by combining collaborative filtering [6,7] with carbon footprint calculation. Collaborative filtering involves making predictions—filtering information—about an unknown user based on information about a known group of users. This method forms the basis for many recommender systems (see [5] for a review).

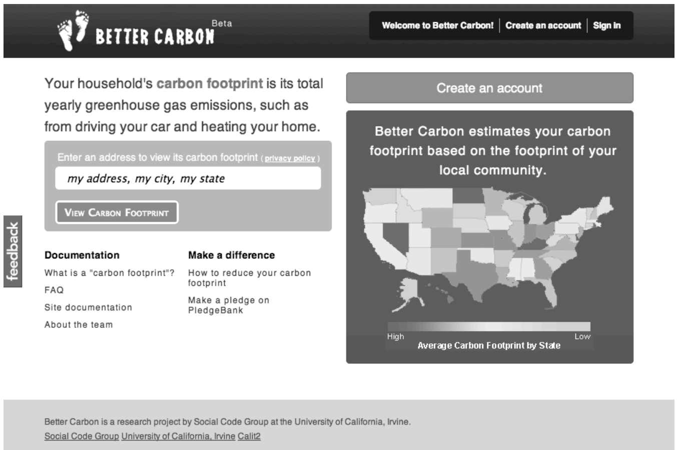

Fig. 1. Better Carbon uses collaborative filtering to quickly and easily provide a carbon footprint estimate based on a user's local community.

In recommender systems, users are matched based on similar preferences, with the belief that users with the same opinions on a set of items are likely to share opinions on other items. For example, a movie recommender system (such as that used by Netflix) may match you with other users who like similar movies, and then recommend movies for you that those users like but you haven't seen yet. In a similar manner, Better Carbon uses collaborative filtering to "recommend" values for carbon footprint estimates.

Better Carbon matches users based on the similarity of user-entered variables—the values that people would enter into a current carbon calculator, such as the fuel efficiency of their car or the cost of their home electricity bill each month. Users that have similar habits and carbon lifestyles are thus able to provide estimates about other aspects of each other's environmental impact. Specifically, Better Carbon matches users based on shared variables, considering variables for which both users have provided data. This is the equivalent of determining what movies both users like or dislike in a recommender system. Shared user variables are compared using cosine similarity: the system normalizes each variable, uniformly orders them and treats them as a high-dimensional vector, then calculates similarity as the cosine of the angle between these vectors. Better Carbon is then able to predict other, non-shared variables (the variables not specified by the user) by taking the average of similar users' values of those variables, weighted by the users' similarity. So rather than estimating the movie most liked by similar users (that hasn't yet been seen by the calculating user), our system estimates the average value entered by similar users (for variables that haven't yet been provided by the person using the system).

### B. *Using the Better Carbon Calculator*

In order to focus on the effects of greenhouse gas emissions on local communities, Better Carbon is a location-based calculator—users' carbon footprints are tied to their home addresses. Visitors to the site are able to enter their address and immediately get a rough estimate of their household's footprint, without being required to answer any other questions. This estimate is generated based on the information previously entered by other, nearby users, through the use of collaborative filtering with geographic closeness as a measure of similarity (rather than matching based on shared variables). While with our current data, location-based similarity is no more accurate than a static average of all users, geographic nearness is slightly correlated with similarity ($r = .029$), and thus such accuracy may appear with increased usage. The collaborative basis of their estimated footprint is explained to users, as well as the source breakdown of their emissions, and how their footprint compares to local community, national, and world averages.

After receiving this rough estimate, users can improve the accuracy of the calculation by correcting and refining the estimated details of their carbon lifestyles (see Fig. 2). Users are presented with the collaboratively estimated values of the variables used to calculate their footprint, and are able to change these values to make them more accurate. For example, the system may estimate that a user drives a mid-sized car that gets 21 miles per gallon (mpg) approximately 10,000 miles per year, but the user can clarify that their mid-sized car actually gets 24 mpg and they travel closer to 12,000 miles per year. This process uses the same question-answer interaction that is used by other calculators, thereby following accepted practice. Additionally, the system's collaboratively-generated estimates help to augment this interaction—if a user only answers some of the questions (perhaps because they don't know the answers off-hand), the estimates for the other variables also become more accurate as the collaborative filtering system is better able to match to similar users with this new information. In this way, users are only required to answer a subset of questions in order to get an accurate carbon footprint estimate. Furthermore, as users add more information and improve the accuracy of their estimate, they also improve the collaborative estimates for all future users.

| Car & Public Travel (7.29 tons) | | | |
|---|---|---|---|
| | Your Household | | Irvine (Avg) |
| Number of miles driven per year | 7771.86 | (estimated) | 6666.67 |
| Miles per gallon | 18.00 | (exact) | 30.00 |
| Vehicle fuel type | Gasoline | (exact) | 1.00 |
| Vehicle size | Mid-sized car | (exact) | 1.50 |
| Miles traveled via public transportation per month | 107.39 | (estimated) | 83.33 |
| **Home Energy (6.18 tons)** | | | |
| | Your Household | | Irvine (Avg) |
| $ spent on electricity per month | 45.00 | (exact) | 23.00 |
| $ spent on natural gas per month | 35.46 | (estimated) | 8.00 |
| $ spent on other fuel per month | 3.59 | (estimated) | 0.00 |
| $ spent on water and sewage per month | 39.80 | (estimated) | 20.00 |
| Square feet of household | 900.00 | (exact) | 808.00 |

Fig. 2. This excerpt from the Better Carbon webpage (reformatted slightly to fit this paper) shows how users can specify exact details of their carbon lifestyle, or may use the values estimated through the system's collaborative filtering.

Finally, along with the breakdown of their greenhouse gas emissions, Better Carbon presents users with suggestions for reducing their carbon footprint provided by nearby and similar users. These suggestions are collected when users register with the site in order to refine their footprint estimate—users are asked to describe one action they take to reduce their carbon footprint. In answering this question, users are encouraged to think about their actions and how they currently reduce their environmental impact, and then share those suggestions with others (e.g., "I buy most food at the farmers' market"). Users who view these suggestions can get ideas for reducing their carbon footprint, which may be more applicable to them because the suggestions come from similar users. Furthermore, groups of similar and nearby users may view and adopt the same suggested behaviors, thus supporting collective environmental action. In this way, matching similar users through collaborative filtering allows Better Carbon to both provide more accurate carbon footprint estimates (that affect the entire community) and assist with collective action by sharing suggestions among its users.

## V. EVALUATION

We have validated our method for collaboratively estimating carbon footprints using real data from 397 users. Users were recruited through Amazon Mechanical Turk—a micro-task marketplace that can allow researchers to engage users quickly and at low cost [23] (for details about the user population of this system, see [24]). Recruited users include people from 48 U.S. states, as well as Washington D.C. Users were asked for information about their carbon lifestyles (the same questions they would answer when filling out a typical carbon calculator), which we then used to seed and test our algorithm.

We evaluate our results by determining the *mean absolute error* (MAE) of the estimated variable values as compared to the actual given values. Thus MAE measures the average error produced by our estimates. For example, using the mean variable values of the 397 test users as an estimated carbon footprint produces an average MAE of 0.083 (out of 1.0 for the normalized variables) per variable—so when using the mean of the values provide by all 397 users, an estimated variable is wrong by an average of 8.3%. (Note that these errors may either offset or compound with each other in estimating total carbon footprint).

However, by using collaborative filtering and weighting the estimate by the cosine similarity between users, we can estimate the values of user variables with an average MAE of 0.078 per variable—an improvement of 5.8% over a straight average of all users. Thus this method is able to produce a (slightly) better estimate than the baseline average even with only a small number of users in the system. In addition, as more users calculate their footprint and input information about their carbon lifestyle, the accuracy of estimates is likely to improve even more. In this way, collaborative filtering with only a small amount of data is able to provide more accurate estimates than predefined, statistically measured average values—an accuracy that can continue to improve as the system grows.

In addition to the validation of our collaborative filtering algorithm, we evaluated a prototype of the Better Carbon calculator by conducting a user study through Mechanical Turk, comparing our system with other popular carbon footprint calculators ([15-19]). For each of these five calculators, we asked 20 people for comparisons to Better Carbon, gathering a total of 100 user evaluations. Users were asked to calculate their footprint using each of the two systems, and then answer a number of questions about their experience and opinions of the different calculators. In order to reduce the likelihood of invalid responses from Mechanical Turk, we made sure to also ask verifiable questions (following [23]), such as the impact factors included in each calculator. Note however that using Mechanical Turk as a platform does encourage respondents to test the sites as quickly as possible, potentially influencing their evaluations.

Respondents reported that calculating a footprint using Better Carbon takes slightly less time than other carbon calculators: an average of 4.1 minutes vs. 4.7 minutes. Furthermore, the time needed to calculate a footprint using our system had a higher standard deviation: 4.7 minutes vs. 3.5 minutes. This points to how respondents in our study demonstrated two different ways of using Better Carbon: users can either get a quick, rough estimate based purely on their address, or can get a more detailed estimate by refining their information. This distinction can also be seen in respondents' evaluations of Better Carbon's ease of use. Overall, 62% of users perceived Better Carbon to be as easy or easier to use than other popular calculators, in a large part because respondents could estimate their carbon footprint using only their address. As one user reported: "Better Carbon is definitely easier to use because I only had to enter my home address. With the EPA calculator I had to enter many different types of information." This perceived ease of use was tied to how users interacted with the system and how much information they had to enter—for example, one user claimed TerraPass [18] was easier to use because it had "Less information involved" while another said Better Carbon was easier "because I had to provide much less information." In this way, the system's ability to provide a carbon footprint estimate quickly based only on address seems to make it both faster and easier to use than other popular carbon calculators.

However, this ease of use comes at a price: only 18% of users reported perceiving Better Carbon to be more accurate than other calculators (12% reported them equal), usually because of its simplified use and lack of questions. Indeed, in comparison to Better Carbon, a calculator's ease of use and perceived accuracy[1] were inversely correlated ($r = -.272$, $p < .01$). There is a definite trade-off between perceived accuracy and ease of use, in part due to how accuracy is based on the number and detail of questions asked, or as one respondent claimed: "The EPA asked more questions, so I assume this one is more accurate." In this way, asking more questions makes a carbon calculator more difficult to use, but seem more accurate. Nevertheless, Better Carbon attempts to use collaborative filtering to be both easy to use *and* accurate—it can provide accurate estimates with fewer questions, thus making it simpler to use. Though this evaluation suggests that the system has not yet achieved this goal (as it is not seen to

[1] Calculator accuracy is almost impossible to determine, as users have no absolute measurement of their footprint other than that given by the calculator. Thus we discuss *perceived* accuracy—how much users trust the result given.

be accurate), keeping Better Carbon easy to use while also making its accuracy more apparent is an important step for increasing the system's adoption.

Finally, Better Carbon also appears to have a stronger basis in the user's community than other carbon calculators. Of 50 subjects who were asked which calculator "creates a stronger link between users and their communities," 28 respondents (56%) chose Better Carbon, 19 (38%) choose the other calculator, and 3 (6%) had no preference. This perceived sociality came about through the system's focus on the local community: according to one user, with Better Carbon "you become aware of what the community averages are and you can work to change that for the better." Many respondents felt that the comparisons to local averages gave the system a stronger sense of community: "it pulls up the averages from your area. That way you can get a feel for the carbon footprint of other people in our area." Indeed, these comparisons enabled by the location-based nature of the system seem to give it a more social basis than the collaborative filtering that enables the system (though also acknowledged by a few respondents). Finally, the suggestions for reducing impact from nearby and similar users was also appreciated—as one user said: "I liked the statements from my locality at the end of the Better Carbon - that brought it home."

Interestingly, many users who believed other calculators created stronger communal links than Better Carbon pointed to the perceived higher accuracy of those calculators. For example, one user chose the Nature Conservancy [15] as more social "because it shows you a good footprint based on your actual personal habits," a common indictment of Better Carbon's perceived lack of accuracy. Another respondent suggested a possibly reason for the link between accuracy and sociality by claiming that the An Inconvenient Truth calculator [17] was more social because "users would consider it the more valid of the two." Perceived validity may affect how users discuss their footprint with others outside of the interaction with the calculator, and so may be able to increase the social basis of carbon footprint calculation in and of itself. This idea further emphasizes the need for carbon calculators' estimates to be seen as accurate, in order to allow such calculations to enable collective action across a community. Thus overall, while Better Carbon is seen as more social than other calculators, an improved understanding of its accuracy may increase this social focus even further.

## VI. Discussion

Better Carbon seeks to increase the social focus of carbon footprint calculation by letting people's estimates affect not only themselves, but also the community as a whole. The system's use of collaborative filtering means that individual calculations are generated by the entire community of other users, as values provided by similar users shape the presented estimate. Thus when people estimate their greenhouse gas emissions using Better Carbon, the estimate provided is both a function of the community's estimates and a contribution to the community's estimates. Collaborative filtering means that carbon footprint calculation is no longer a purely individual action. Furthermore, the location-based nature of Better Carbon causes this collective carbon footprint to be tied more tightly to the local community—where a person lives and the people they live near affect their carbon footprint estimates as well as their actual carbon footprint. This linkage is a mirror of how individual environmental impacts affect the community and the world around a person, while also being influenced by the society people live in. Thus Better Carbon creates a closer mapping between collective environmental impacts and the computed estimates of those impacts.

Nevertheless, the community-based carbon footprint provided by Better Carbon is notably distinct from the actual environmental impact of that community—reducing a user's estimated carbon footprint is not the same as reducing a user's actual carbon footprint. This distinction can get especially confused as users are asked to help contribute to Better Carbon's simulation of the world and method for estimating impact. For example, users may be tempted to report that they drive less in order to lower the footprint estimated for themselves and their community, but this is not the same as *actually* driving less. The goal is not to reduce carbon footprint estimates, but to actually reduce environmental impact. Still, by creating a tighter coupling between the collective basis of carbon footprints and carbon footprint estimates, Better Carbon may help enable a shift in how people think about environmental sustainability. Rather than necessarily providing a more accurate simulation, Better Carbon uses a new, collaborative, implicit simulation to help motivate people to take collective action [14]. Even so, being able to more tightly link estimates to real world actions (such as through advances in ubiquitous sensing systems, e.g. [25]) can help to more accurately model this complex system in which everyone's actions are intertwined.

In addition to increasing the focus on community present in carbon footprint calculation, Better Carbon also enables such calculation to be more easily extended. Current carbon calculators are limited in the number of environmental impact factors that they can consider due to the reliance on users to answer questions about every one of the considered factors—each new factor included thus requires more user input and effort. But because Better Carbon users are able to calculate their footprints without answering all available questions, this system can include more variables and factors without requiring further user effort. Users can answer only a portion of the questions, relying on answers provided by matched similar users to ensure a reasonably accurate estimate for the fields left blank. Furthermore, Better Carbon estimates are persistent: users can spread out their calculation over time, answering more questions as they gather more information. In this way, Better Carbon supports future research better than other calculators—as new sources of greenhouse gas emissions become known and quantified, Better Carbon can include them in its calculation without requiring users to do more work and thus without increasing the barrier to entry. Although modeling the emissions from a person's entire life is extremely difficult, collaborative filtering eases the estimation of individual users' carbon footprints.

However, it is possible that not requiring significant effort from users may be somewhat detrimental. There may be benefits to requiring a user to work through each step of the calculation process and answer all the questions, considering each impact factor and the kinds of behaviors that lead to high amounts of greenhouse gas emissions. By forcing users to acknowledge these myriad aspects of their lives, current calculators are able to promote change—users may never have realized the significance of the impact caused by a particular aspect of their carbon lifestyle. Nevertheless, Better Carbon can still support these kinds of revelations, as estimated measures of each component of a person's footprint may be higher or lower than expected. Users are also encouraged to inspect the estimates for errors (and correct the system's estimate when they occur), thereby letting them explore these high impact areas of their lifestyles. Thus Better Carbon seeks to enable the reduction of environmental impact on a large scale, as users can both assess and lower their carbon footprints as a community.

## VII. Conclusion and Future Work

In this paper we have introduced the Better Carbon calculator, a system that uses collaborative filtering to make an easier, more extendable carbon footprint calculator. We demonstrate that even a simple collaborative filtering algorithm can be used to provide accurate carbon footprint estimates with less user input than current methods. Further work is needed to determine how to better perform collaborative filtering of carbon footprints—such as through adding different weightings to more indicative impact factors or by exploring more complex metrics for measuring similarity. Indeed, the mode of interaction presented here could be combined with currently popular carbon calculators, taking advantage of their high numbers of users to explore and improve collaborative filtering algorithms. In the future, we will continue exploring methods for allowing communal knowledge and actions to affect individual views of sustainability, focusing on using sociality to measure and improve environmental impact.

Every day, humans use social interactions to help them solve problems in their daily lives. We cooperate on solutions untenable for individuals, providing each other with social support. Technological systems may also sometimes be improved by this kind of sociality, particularly when addressing complex problems such as environmental sustainability. The Better Carbon calculator demonstrates one particular way that a technology can both benefit from and support human sociality. By adding this kind of sociality to previously non-social human-computer interactions, designers and researchers can better help people surmount difficult problems and enact positive social change.


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