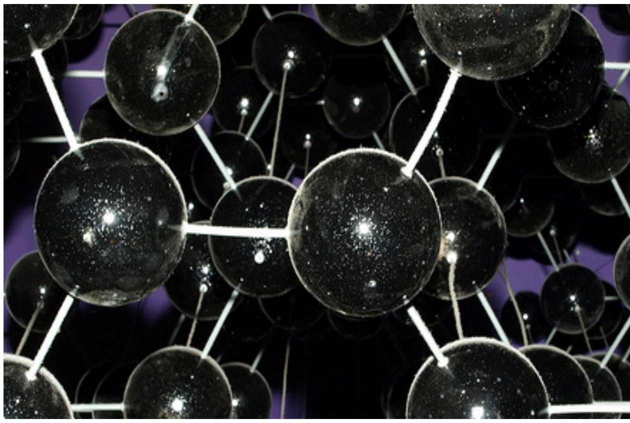


NSF Convergence Accelerator: Design for Circular Economy from Molecules to the Built Environment Workshop Report

Virtual Workshop
September 18, 24, 30, 2020

Authors:
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Additional information about the organizers can be found in Appendix A: Biography of the Organizers

We are extremely grateful to all participants for their valuable input throughout the workshop.

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We deeply grateful to the individuals who attended the workshop and contributed their time, expertise, and brilliance during the workshop.

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Executive Summary

The current linear consumption model of raw material extraction, production, use, and disposal dominates the global economy. Today, we clearly see that this linear model has led to serious unintended global consequences from resource depletion to global waste, spanning all industrial sectors, from plastics to the built environment. In contrast to linear models, circular economy (CE) aims to decouple economic growth from resource consumption by cycling products and materials back into production, either by returning materials to generate new products, or by releasing benign substances to the environment through degradation. CE principles are based on the efficient use of resources and eliminating waste from product life cycles; a truly circular economy keeps material in continuous use *by design*.

To achieve – or even begin to achieve – a circular economy, a convergent research approach needs to be employed with a multitude of disciplines -- chemistry, biology, engineering, business, economics, social sciences, and behavioral sciences all need to work in concert for circularity. By deeply integrating these diverse disciplines, we can begin to work on tackling the complex challenges that currently inhibit the growth of the circular economy today.

Our vision was to foster and catalyze circular economy design from molecules to the built environment. We held, for the first time in the US, a virtual workshop, *NSF Convergence Accelerator: Workshop on Design for a Circular Economy from Molecules to the Built Environment (NSF Award No. 2035223)*. We convened an expansive group of 95 experts to ultimately aid in creating a research agenda and the mission components in support of a new track for the NSF Convergence Accelerator program. Attendees included academia from engineering to the social sciences, industry, non-profits, government agencies, foundations, and end-users. The virtual workshop was facilitated by KnowInnovation and took place over three, three-hour sessions, over three weeks: September 18, 24, 30, 2020.

Through three highly curated agendas with a mix of keynotes, provocations, and pointed questions, we identified key Jupiter shots, anticipated 10-year and 3-year transformative and scientific impacts, focused on the societal impacts for the American people and beyond, and mapped what can be accomplished within the 1-3 year timeline given the right ecosystem in the convergence accelerator.

The upswell of ideas, plans, and enthusiasm encourages us – beyond a doubt – that design for circular economy is at the precipice of innovation, technology, and positive and equitable societal outcomes. Investing in this area is both prudent and urgent, so the U.S. can be leaders and innovators in design for circular economy. Major findings of the workshop are presented herein.

- **Design for circular economy is primed to be accelerated using a convergence research approach**. Parts of the CE ecosystem are in place in the US from people to industries and innovation, but it is fragmented and at varying degrees of sophistication. For example, the chemical industry is working towards incremental aspects of the circular economy but is lagging in terms of a transformative shift of an entire sector. The built environment is also lagging, yet truly has the potential to shift from a sector that provides *products* to a sector that provides *services*.   Additionally, the number of people, companies, decision makers, and researchers identified in the workshop further emphasizes the need for a cohort of people to coalesce around advancing design for CE in the US. Through our workshop series, we have developed **partnerships** and are continuing to foster the design for CE community in the US through on-line mechanisms, and a convergence accelerator can further foster this community.
- There is **an urgent need to educate and train not only the next generation of scientists and engineers on design for circular economy, but also anyone that does any type of design** – from the business developer who is working on designing financing strategies to policy makers who are designing circular economy interventions. We view design for circular economy as an ideal mechanism to foster and inspire the re-invention of educational approaches. We need to understand

the cognitive barriers to fostering a circular economy and then develop strategies to overcome those barriers by exploring interdependent/independent mindsets, fundamental decision processes, and systems thinking.

- **There is an urgent need for circular economy principles, standards, tools, and metrics across all levels of the supply chain.** These concepts should ensure, measure, and make transparent environmental gains; prosperous, triple bottom line circle economies at multiple scales (national, state, local, and micro); and foster meaningful and deep equity and inclusion. The overall vision is to a create transparent, multi-level shared database and tools used by product designers, brands, infrastructure planners and organizations/households to make decisions that move towards circular material choices and products/lifestyles.
- We need to **reimagine and transform how we design across all levels** -- from molecules (e.g., function-property and ecotoxicity), to materials (e.g., polymers, electronics, paper products), and to the built environment (e.g, design for value and reversible building design) and envision the end-of-life and/or re-use from the cradle to the grave using systems tools (e.g., life cycle assessment, techno-economic analysis) to guide the design.
- **We have identified deliverables** that can be achieved within the next 1-3 years, in alignment with the programmatic mission of the NSF Convergence Accelerator program and more information is in the body of the report. Some deliverables include:
    - Develop the framework for a circular economy declaration, akin to and consider in alignment with an Environmental Product Declaration (EPD), include metrics and targets for equity, justice, and inclusion;
    - Develop and complete a matrix examining functional use/products to be able to prioritize what comes next, scale, etc. for design for circular economy, with the U.S. EPA's Sustainable Materials Management Prioritization Tool is an example matrix;
    - Create a 'menu' of circular funding mechanisms and policies, including category benchmarks;
    - For the chemical industry, develop the tools to explore the following: centralized and decentralized production strategies to foster modularization of formulations; design for function and service to minimize excessive consumption and production; and key products and develop end-of-life plans;
    - Demonstrate one system in the built environment as a circular economy exemplar that functions as a service, not a product/commodity, and build the ecosystem to support this demonstration; develop a prototype material bank in one region, utilize baseline mapping for construction materials;
    - Foster design of new materials (e.g., polymers, electronics, paper products) and the materials infrastructure - with a focus on end-of-life and re-use – by bringing the key decision maker to the table.

From our brainstorming and elicitation techniques, the workshop highlighted eight broad areas that need to be accelerated and integrated to foster and converge CE: (1)Transparency, Tools and Data; (2) Innovations in the Built Environment to Foster Design for Circular Economy; (3) Disruptive Materials; (4) Circular Funding; (5) Inverting the Chemical Research and Development Process; (6) Policies; (7) Just and Equitable Circular Economy; and (8) Consumer Behavior. We delve into each of these areas in the report and the convergence of these ideas and further identify partnerships and deliverables. Lastly, we offer thoughts on applying complexity principles to facilitate the convergence process.

Most importantly, the societal impacts associated with design for the circular economy are profound. CE presents a significant economic opportunity, and it has the potential to enable long-term resilience, helping to protect against economic and trade disruption, and most importantly helping to prevent further environmental harm.

Background, Motivation and Vision

The current linear consumption model of raw material extraction, production, use, and disposal dominates the global economy. Today, we clearly see that this linear model has led to serious unintended global consequences from resource depletion to global waste, spanning all industrial sectors, from plastics to the built environment. In some industries, such as automobile production and commodity aluminum products, circular design principles have been successfully introduced, while in others such as plastics products or the built environment, progress towards circularity has been painfully slow. For example, the (thermo)plastic sector has grown by over 600% by volume over the past 30 years with only 9% recycled; 50% of plastic scrap meant for recycling was exported from higher income to lower income countries; and an estimated 5 to 12 MMTs reached our oceans in 2010 [1, 2]. About 40% of the plastic produced on the earth is used in packaging and single use items [3-5] -- material that will be immediately thrown away after a single use. The packaging industry employs over 5 million people worldwide with estimated sales of $1 trillion in 2018, and the opportunities to replace persistent plastic materials, often impossible to recycle because of their light weight, complex structures, and contamination, with those that are compostable and or degradable are gaining market share in a variety of industry sectors. Several recent reports indicate that the bioplastics industry is growing at an annual rate of between 10% and 20% [6, 7]. The growth in the construction sector to house our growing population leads to extraction of construction minerals exceeding 10 billion metric tons annually, and the construction industry alone could be responsible for up to 60% of the remaining carbon budget [8]. This industry currently favors the use of products such as composite wood materials that do not degrade such that 38 million tons are landfilled annually in the US alone [9, 10].

In contrast to linear models, circular economy (CE) aims to decouple economic growth from resource consumption by cycling products and materials back into production, either by returning materials to generate new products, or by releasing benign substances to the environment through degradation. CE principles are based on the efficient use of resources and eliminating waste from product life cycles; a truly circular economy keeps material in continuous use *by design*. The overall adoption of CE principles has been incremental at best – especially in the US – because the *market fails to account for externalities* (i.e., full environmental costs) and owing to a lack of truly circular designs to replace conventional analogs.[11]

To achieve – or even begin to achieve – a circular economy, a convergent research approach needs to be employed as a multitude of disciplines -- chemistry, biology, engineering, business, economics, social sciences, and behavioral sciences need to work in concert for circularity. By deeply integrating these diverse disciplines, we can begin to work on tackling the complex challenges that currently inhibit the growth of the circular economy today.

Our vision was to foster and catalyze circular economy design from molecules to the built environment. We held, for the first time in the US, a virtual workshop, *NSF Convergence Accelerator: Workshop on Design for a Circular Economy from Molecules to the Built Environment (NSF Award No. 2035223)*. We convened an expansive group of 95 experts to ultimately aid in creating a research agenda and the mission components in support of a new track for the NSF Convergence Accelerator program.

As we conducted the workshop design, we drew on the work of Bocken [12] and Hollander[13]. Bocken, for example, makes distinctions between circular <u>product design</u> strategies and <u>business model</u> strategies, and then shows the framework for convergence between the two. Bocken also states that CE product design is underpinned by *closing* and *slowing* resource loops. Closing resource loops involves either creating products and components that can be easily and safely absorbed by the biosphere or creating items that while they cannot be released to the ecosystem, can be easily recycled to high value uses. As such, closing loops involves: (a) Design for a biological cycle, (b) Design for a technological cycle, (c) Design for disassembly and reassembly. Design for slowing resource loops includes design for longer-life and product life extension. In design for longer life, one aims to create more robust products with longer viable service lives, while also creating designs to which consumers become emotionally attached. Product life extension can be achieved through several strategies: (a) Design for ease of maintenance and repair, (b) Design for upgradability and adaptability, (c) Design for standardization and compatibility, and (d) Design for dis- and re-assembly. During the workshop we explored the question -- what science, engineering, technology and policy are needed to realize these CE principles?

Workshop Organization Methods and Approaches

Overview

We convened an expansive group of 95 experts to ultimately aid in creating a research agenda and the mission components in support of a new track for the NSF Convergence Accelerator program. Attendees included academia from engineering to the social sciences, industry, non-profits, government agencies, foundations, and our end-users. All attendees, not including the organizers, are recognized in the Acknowledgements. The virtual workshop was facilitated by KnowInnovation and took place over three, three-hour sessions, over three weeks: September 18, 24, 30, 2020.

Through three highly curated agendas with a mix of keynotes, provocations, and pointed questions, we identified key Jupiter shots, anticipated the 10-year and 3-year transformative and scientific impacts, focused on the societal impacts for the American people and beyond, and mapped what can be accomplished with the 1-3 year timeline given the right ecosystem in the convergence accelerator.

We partnered with KnowInnovation (KI) to support all workshop logistics. KI aims to advance science by convening multi-disciplinary teams to solve complex problems, and they have been facilitating diverse team building events since 2004. KI has specifically worked with the National Science Foundation on a range of projects, and we selected KI based on their experience with NSF, substantial history, and strong team. Most importantly, virtual workshops require nimble skillsets ranging from technical set-up to facilitation; KI has these skills.

Our virtual workshop aimed to parallel an in-person meeting. First, we worked with KI to understand and sculpt the goals for the event. In our case, our vision was to establish the research agenda for design for a circular economy; thus, we worked with KI to develop a workshop to establish the mission components to reach this vision. During the planning period, KI set up, shared, and maintained an Asana project management board. The board served to organize project activities as well as provide links to resources from KIs knowledge base. Second, based on the first step, we developed a set of activities ranging from plenary speakers to working breakout sessions. The breakout sessions were the intensive portion of the workshop helped us to achieve our goals. KI re-created the in-person workshop experience through building a website and using KIStorm, setting up zoom and breakout rooms, working with the workshop attendees, and presenter preparation. During the workshop, KI provided an emcee, lead facilitator, co-lead facilitator, and technical support person. The workshop was recorded, and file sharing platforms were established. We established a website (www.circular-designs.org) and are using basecamp to continue to grow our community.

Note on report links. Some of the links are to the KIstorm platform. You will need to create a log in and then use the event code: circular2020

Pre-Session Planning

Our team met weekly from the date of the award to the Session 1. We recorded a session on, What is design for the circular economy? We developed a pre-workshop website. We also developed a list of recommended resources and reading prior to the start of the workshop.

We also held a virtual happy hour, which was led by Dr. Gemma Jiang (UPitt/Organizer). The goal of the happy hour was to build community, start a discussion on CE, introduce the organizers, and introduce participants to KIStorm by developing Jupiter Shots.

Session One

The aims of session 1 were to understand the challenges around design for circular economy, build community, and identify the problems we need to solve via Jupiter shots, see Appendix B: Agenda – Session 1. To achieve our aims, we first had three speakers (Linda Molnar, NSF; Melissa Bilec, UPitt/Organizer; Jason Locklin, UGa/Organizer). Dr. Molnar started the workshop with an introduction from NSF on the Convergence Accelerator Program, and Drs. Bilec and Locklin provided overview while setting forth goals and ideal outcomes for the workshop. Aforementioned hyperlinks are included to presentation slides, with the recorded video introductions found here.

Next, participants were put into two series of random breakout rooms via Zoom with goal of building community and the instructions of:
Round 1: If we had to work on a Jupiter shot together what would it be?
Round 2: What is the Jupiter shot we wish someone else would do?
Round 3: What would be the biggest game changer in the next 15 years?

During the breakout rooms, the participants were asked to also post the Jupiter shots in KIStorm. Over the entire session, 150 Jupiter shots were identified – an indicator of the amount of energy and complexity in this potential track (see Figure 1).

Figure 1. Jupiter Shots - Design for Circular Economy

After the breakout rooms, the participants were brought back into the plenary, and our provocation speaker, Michelle Tulac from the Ellen MacArthur Foundation, presented to the group. Michelle Tulac's presentation first provided background on circular economy and then moved to examples of CE projects and businesses in the US and internationally

The next portion of the agenda was that each participant was given two votes to identify the most important Jupiter shot. The voting was done in KIStorm on the Jupiter shot; the top Jupiter shots were then identified, and participants were then ushered into breakout rooms where they worked in small groups to further the ideas with the prompts, as indicated in Appendix E: Complete Template of Breakout Sessions. The session concluded with between session work of reviewing the Jupiter shots and continuing to work on the prompts.

After session 1, the organizers worked to develop the themes for the Jupiter shots via reviewing all of the post-its in KIStorm, consolidating ideas and reviewing the participant voting. Eight broad areas emerged, which were used in sessions two and three: Transparency, Tools and Data; Innovations in the Built Environment to Foster Design for Circular Economy; Disruptive Materials; Circular Funding; Inverting the Chemical Research and Development Process; Policies; Just and Equitable Circular Economy; and Consumer Behavior

Session Two

The aims of session 2 were to gather feedback on eight aforementioned areas/Jupiter shots and further develop the ideas gain a deeper understanding of the scientific and societal impacts of stewarding sessions, and start to identify immediate steps that will propel the Jupiter shot, see Appendix C: Agenda – Session 2. To achieve these aims the activities included: reporting out on small group stewarding, back casting ideas, and Pluses, Concerns, Overcomes, and Of Course you wouldn't (PPCo) exercise. The outputs were to identify next steps for developing the idea in a 1-3 year timeframe and discover emerging cross cutting themes. The general appearance of the KIStorm session is shown in Figure 2.

Prior to beginning the activities, Drs. Linda Molnar and Melissa Bilec, started the session with message to the participants to be bold in their thinking and ideas by providing examples. Next, Dr. Jemma Jambeck (UGa/Organizer), is an expert in on solid waste management, especially global waste issues and plastic contamination of our environment and ocean, including co-development of the open data citizen science platform marine debris tracker; the link to presentations are found here.

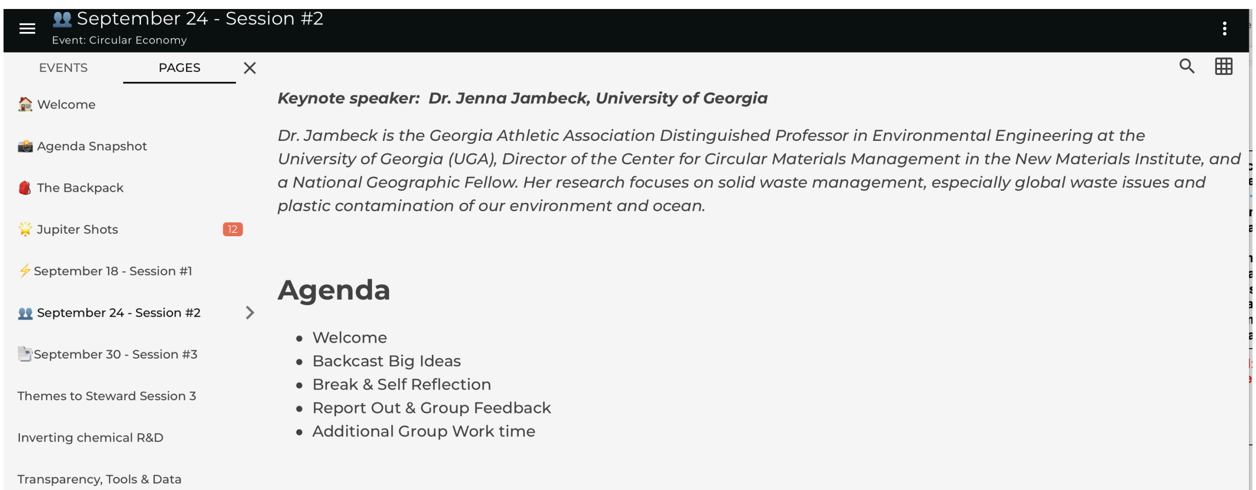

Figure 2. Session Two Example in KIStorm

Two breakout sessions were held, each lasting about 40 minutes, with the participants working in dynamic google documents with prompts, see Appendix E: Complete Template of Breakout Sessions, in one of the eight areas. The instructions for breakout 1 were a deeper dive into the context of the CE area, while thinking expansively (~40 mins) followed by a 3-4 mins present back in the plenary. Breakout 2 was then a deep dive into the milestones, paying particular attention to years 1-3, followed by a discussion on stakeholder engagement (~40 mins).

Session Three

The session three aim was to complete the prompts in Appendix E: Complete Template of Breakout Sessions. For the agenda for Session Three, see Appendix D: Agenda – Session 3. Additionally, after Drs. Bilec and Fernanda Cruz Rios Ford (UPitt/Organizer) provided opening remarks, Dr. Eric Beckman (UPitt/Organizer) provided the keynote for the session with a focus on two areas: thinking about how we teach and learn about design for circular economy and how our cognitive barriers can inhibit circular economy. Presentations for session three are found here.

Prior to the breakout sessions, Dr. Gemma Jiang (UPitt/Organizer) encouraged the participants to consider moving to a different area outside of their comfort zone in an effort to foster interdisciplinary insights. For each area, an organizer or an organizer designee lead the discussion and acted as the scribe. After the breakout sessions, every area reported back to the entire group with the organizers focused on key messages to include herein.

Design for Circular Economy – Areas of Focus

From our brainstorming and elicitation techniques, the workshop highlighted eight broad areas that need to be accelerated and integrated to foster and converge CE:

1. Transparency, Tools and Data
2. Innovations in the Built Environment to Foster Design for Circular Economy
3. Disruptive Materials
4. Circular Funding
5. Inverting the Chemical Research and Development Process
6. Policies
7. Just and Equitable Circular Economy
8. Consumer Behavior

We delve into each of these areas in the report and the convergence of these ideas and further identify partnerships and deliverables. It should be noted that these ideas are from a mix of disciplines and in some cases are not the opinions of experts. The process to capture these ideas and thoughts are discussed in Workshop Organization Methods and Approaches.

Transparency, Tools and Data

Session Participant Names:

- **Jenna Jambeck (moderator)**

  Session 3
  - Brandon Bray
  - Michael Deru
  - Bruce Hamilton
  - Carlie Herring
  - Ben R. Jordan
  - NicholsES@state.gov
  - Julie Zimmerman

  Session 2
  - Fazleena Badurdeen
  - Brajesh Dubey
  - Bruce Hamilton
  - Vikas Khanna
  - Shweta Singh

  Session 1
  - Weslynne Ashton
  - Callie Babbitt
  - Kate Beers
  - Ryan Bradley
  - Birdie Carpenter
  - Alexander Dale
  - Vikas Khanna
  - Shweta Singh

What's the big idea (2 to 3 sentence summary)?
Create a transparent, multi-level shared database and tool that is actually used by product designers, brands, infrastructure planners and organizations/households to make decisions that move towards circular material choices and products/lifestyles. This will provide visibility into a larger set of life-cycle stages on material management, recyclability in specific places, and consumer uptake/change. With quality transparent data at each stage of material and product development to understand how it fits into the larger system, decision-makers/people will be better able to make choices/decisions that lead to a more just, equitable and circular economy.

What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.

There will be greater transparency and accountability across all product and material supply chains and life cycles. Data will be collected on potential environmental justice impacts from communities/infrastructure through the supply chains and lifecycle of products. There will be a lower usage of high-toxicity or low-circularity materials or processes. Participatory methods will engage the broader community. Consumers/decision-makers will be empowered by having data about the environmental and social impacts of their choices/decisions. Transparency (from the database/tool) will engender a more just and equitable decision-making process.

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?

In 10 years:

With the driving force of supply chain resiliency, in 10 years the transformative impacts are:

- Most major brands will have shifted towards designing and manufacturing with circularity in mind; more circular material choices are based upon integrated tools and data.
- An open source, open data collaborative platform that people can use to collect circular economy metrics will be 100% complete and utilized by public, private, government and other sectors.
- The citizens that are participating in the data collection are empowered.
- The data in the platform is used for monitoring and tracking the status of the circular economy and used in decision-making (by decision-makers).
- Technology (e.g., molecular tag, bio-bar codes) has enabled traceability.
- Block-chain technology has enabled traceability.
- Biomimicry has been used to transform “waste” as an output to a needed input into other systems (and anything that creates “waste” that can’t become an input is removed from the system).

In 3 years:

- Early adopters are identified for testing.
- Create a pilot scale project in the space of one material, one industry sector (and even subset of this sector), or one geography.
- An open source, open data collaborative platform that people can use to collect circular economy metrics (25-50% complete in 3 years)
- Data is consistent, harmonized.
- Creating opportunities for stakeholders to engage.
- Regional to Global connections for material flows such as plastic - can we have a mapping to connect multiple scale?
- Incorporate citizen science and participatory sensing to help collect global decentralized data.
- Integrated AI/IoT in supply chain if needed.
- Quality impact of recycled material?
- Manufacturers track recycled materials better.

What are the barriers or gaps in achieving your idea right now?

- Availability of the data - either not existing or not accessible. Data has not been collected consistently or typically in this space and if it is, it is often kept internal to companies and not made public or open.
- Ability to connect the data, harmonization of data across different fields. Data and methods have historically been disparate and uniform methods and analyses are needed for a larger consistent data-based tool.

What might be early thinking on major milestones? Is there a prototype, method, or tool that is needed?

If going the matrix route, figuring out the first product/functional use it to try to fill out the matrix for is a major milestone. Then finishing the categories for this functional use is another big milestone. Then other functional uses can be addressed.

NSF Accelerator: What will we accomplish and why now?

What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created?

In 1-3 Years
We can complete the Matrix examining functional use/products to be able to prioritize what comes next, scale, etc. The U.S. EPA's Sustainable Materials Management Prioritization Tool is an example of a matrix covering a broad array of human health and environmental impacts, as well as products and materials, that could be informative for this kind of development: https://www.epa.gov/smm/sustainable-materials-management-prioritization-tools

This will be done by the following:
Create a database of industrial functional uses and current materials (formulations/mixtures/pure) to provide that functional use. Correlate use to structure-activity or physiochemical properties (Don't forget to cross with toxicity and environmental impact). Create design space for each functional use to inform design and innovation of new or improved materials to meet need with reduced environmental impact and potential for circularity, if/when it makes sense. Define important characteristics of CE.

At the same time, conduct an analogous audit of natural systems to exploit biomimicry in identifying functional uses in natural systems that map onto human/industrial functional uses and collect data on the materials that nature uses to provide those functions and the synthetic routes used to create those materials.

Pick a functional use to start and expand/scale, for example, could be candy wrappers to buildings, but not everything should be designed for a circular economy, so we need to be thoughtful about which functional use we apply CE to.

Create a matrix! Functional use on the vertical access (or/also products) and characteristics of CE along the top to figure out 1) what should be "circularized"? 2) for those that should, we can prioritize them based upon where they are along the scale of "circularity" (use existing data from NIST, the European Union, and OECD, but also identify data gaps in defining circularity). Fill out the matrix for one functional use.

This matrix can also serves different geographies in the sense that both the product and contact matter for circularity. In some geographies/context some products will be more circular than others. This matrix can inform the decision: If we want to push circularity, do we change the intrinsic elements properties of a product or do we change the context? (and policy and trade can be drivers of these changes as well). One simple example: EPS food containers

Why is this idea ready for rapid acceleration?
This idea uses available technology and data to start, but then quickly pushed the "system" (all stakeholders/the community) to fill data gaps and expand thinking. The matrix can motivate systems change, but in a stepwise way so that progress is made consistently over time to reach an entire paradigm shift. There is desire at the industry, government, NGO and public for this type of tool – and it can utilize existing data since it is a matrix-framework, not a new database that must be created, which would be "reinventing the wheel".

NSF Convergence: What would your convergence accelerator ecosystem look like?
- Computing power
- Server space
- Data visualization
- Portals for data entry and download access
- Mobile technology facilitation (apps, etc.)

Eventually the ecosystem could match physical applications and CE characteristics with functional use on its own; and use machine learning to formulate materials and these matches.

What groups might be involved and why to realize your big ideas?
Private sector/Industry needs to be involved. We need industry engagement/inviting them to participate. Make the information valuable to them to incentivize participation. The need potential economic impacts illustrated to them, and there needs to be a business case for their participation/providing data. Government decision-makers, policy-makers, including those working in trade policy could be important since trade and globalization are such important driving factors in materials use/consuming of materials and goods (e.g., amendments to the Basel Convention for trade in global plastic scrap). This issue may be a part of UNEA 2022, so international leaders may become involved, as well as civil society. And finally, the community, through participatory sensing, citizen science and open data, will be important contributors, but they also need to be empowered, as well as benefit from the program in tangible ways.

How do we teach circular design in higher-education? K-12? Communities? Our designers? (Owners?)

- Rapid prototyping, what is the best way to provide the function and service? Make challenges open-ended so that there is not one right answer.
- Project-based learning in local communities (engaging the community in a project as well as students and both groups get to learn)
    - Solar decathlon example - this is an opportunity to include CE. This is a great use once the data and tools are available. (circles back to the need for data and tools!). Including CE concepts in design tools. NREL design tools could incorporate CE.
    - EC3 tool is being expanded with NREL as well
- Incorporate CE data into tools that are used by students to design products, buildings, etc. so that they are making decisions based upon bring in those qualities as well and they learn the importance of them. These tools are also used by designers.
- Communities can learn by contributing data through participatory sensing (e.g., about products, waste, litter, as examples).

Innovations in the Built Environment to Foster Design for Circular Economy

Session Participant Names

- **Melissa Bilec (moderator)**

  - Ahmed K. Ali
  - Michael Deru
  - Matthew Eckelman
  - Billie Faircloth
  - David Grau
  - Simi Hoque
  - I.S. Jawahir
  - Kristen Parrish
  - Joy Pauschke
  - Brandon Ross
  - Jorge Vanegas
  - Hamed Yassaghi

What's the big idea (2 to 3 sentence summary)?
We posed a series of compelling questions that we believe are key ideas that need to be explored.

How can we incorporate CE practices into buildings from the pre-design phase to operations, and how can we monitor and quantifying the performance of those CE practices? During the design phase, recommend considering the end-of-life of not only the whole but also components and systems.

Building on the work at the Berkeley Lab, can CE decisions occur during key points in the real estate/building/infrastructure development life cycle? Physical design, lending, building codes, utilities, zoning, and city design all allow buildings to change in response to social conditions and needs.

What are the material flows for the construction sector, as we need this information to develop baseline measures?

How can we create buildings as material banks in the US? Recommend drawing from Europe.

What can we learn from the manufacturing sector to improve CE in the built environment to foster closed loop practices? Can we look to industrial symbiosis for inspiration?

What are the material and system innovations - or new applications - that need to occur so our building stock can remain in place, while being energy efficient?

What is a new definition for service life? What ownership models need to change?

How do we foster innovation and incentivize small businesses? Since the building construction industry has not changed for 100 years, how can we change the whole industry and incorporate CE?

How do we create the practices and multiple scales to facilitate circular ownership models?

How do we change the industry from order-takers to value-makers to foster the values of CE? Recommend bringing in all stakeholders, including the owner. Must bring in the community and work with the community, not in the community.

What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.

- Minimize construction waste streams, thereby mitigating environmental impacts
- Minimize operational energy of buildings
- Create small-scale business opportunities for building customization, material recycling, and material reuse.
- Design for flexibility, design for adaptability and change for durability of cultural use.
- Lower the threshold for entry to building ownership and wealth generation because it can allow small players to get involved.
- Bridging the gap between governmental actors, policy makers, designers and users towards a sustainable growth.

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?

In 10 years:

- Systems (lending, legal, …) that disrupt the current situation of development driven by first costs.
- Interlinked systematic approach towards mitigating ecological, economical and equitable disruptions.
- Manufacturers have closed loop material sourcing for the majority of material inputs and end-of-life recovery is part of the design and operation of the products.
- Seamless tracking of all materials

In 3 years:

- Model codes, zoning, lending documents, physical designs that can be adopted at scale by businesses, cities, developers, and other stakeholders.
- Increase awareness about the importance in developing and implementing CE.
- Create CE Action Plan for clients
- Manufacturers develop plans for closed loop material sourcing and end-of-life
- Modularization

NSF Accelerator: What will we accomplish and why now?

What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created?

- Demonstrate one product or system in the built environment as an exemplar (lighting, fixtures, insulation and/or thermal comfort and healthy environment) as a service.
- Develop the framework for a circular economy akin to an Environmental Product Declaration (EPD). This EPD should include sustainable value and metrics. Demonstrate for one product category. For example, the steel sector might be a good first start. This CE EPD could be transferrable to other products across sectors.
- Develop global flow material accounting for construction commodities; develop a complete mapping of resources.
- Develop a prototype a material bank in one region, utilize baseline mapping for construction materials
- Prototype the "e" in CE; value added with triple bottom line accounting and life cycle assessment, combine this with idea with innovation and creative business models.
- A body of case studies and data

- Basic economic modeling
- Preliminary framework that maps and defines the roles of stakeholders in a CE (i.e. owners, lenders, designers, users, contractors, government, O&M personnel). The framework could also feature business opportunities that don't yet exist in the building sector.

Why is this idea ready for rapid acceleration?
Parts of the CE ecosystem are in place in the US from people to industries and innovation, but it is fragmented and at varying degrees of sophistication. The built environment is also lagging, yet truly has the potential to shift from a sector that provides *products* to a sector that provides *services*.

NSF Convergence: What would your convergence accelerator ecosystem look like?
(e.g., Do you need an incubator space? Is it a wet lab or dry lab? Do you need a sustainability expert?) Focus on a region or two across the US. Develop the tools and date to implement CE for the built environment for a project. Bring together all the stakeholders (building occupants, municipalities, NGOs/entrepreneurs, banks and investors, building owners, code developers, contractors, material designers, manufacturers, landowners, building information modelers, sensor developers, non-profits, architects, engineers, sustainability experts, urban planners) and collaborative design and implement the CE protype.

What groups might be involved and why to realize your big ideas?
Building occupants, municipalities, NGOs/entrepreneurs, banks and investors, building owners, code developers, contractors, material designers, manufacturers, landowners, building information modelers, sensor developers, non-profits, architects, engineers, sustainability experts, urban planners. All of these groups are a part of the building life cycle.

What strategies, tools, and methods are needed to INTEGRATE and SCALE from the molecular level to the built environment? (e.g., what analytical and computational tools can we utilize and further develop? How can convergence research foster this scaling and interdisciplinarity?)
- Determine the barriers to reuse, develop the strategies to mitigate these barriers.
- Focus on providing services not products/consumptive models.
- Utilize isotope tracing for tracking materials

How do we teach circular design in higher-education? K-12? Communities? Our designers? (Owners?)
- What are the cognitive barriers to CE? How do we overcome the barriers? How do we explore the interdependent/independent mindsets with respect to CE. What is the fundamental decision process that needs to be explored?
- Incorporate CE into the DNA of all elements
- Recommend infusing curricular approaches into intro to engineering courses? Engage first year students (and transfer students) to consider systems thinking approaches/CE/supply chain/etc.
- Education curriculum needs to include convergence, consumerism, learn from other cultures, systems-thinking
- Look to the IDEO model to foster circular thinking, as IDEO fosters curiosity and imagination
- Consider professional development, higher education, and K-12
    - Train the trainer approaches (RET, community college training, training owners/engineers/contractors/architects)
    - Creative, innovative, design (base as a triangle), entrepreneurial thinking (pulls up the other three/top of pyramid) within the digital thinking environment
- Recruitment opportunity- does this help us to recruit a different type of student?

Disruptive Materials

Sessions Participant Names

- **Jason Locklin (moderator)**
  - Kate Beers
  - Birdie Carpenter
  - Grace Chen
  - Marian Chertow
  - Jay Fitzgerald
  - Richard Gross
  - Zhibin Guan
  - George W Huber
  - Eric Klingenberg
  - Brent Shanks
  - Meg Sobkowicz
  - Julie Zimmerman

What's the big idea?
Redesign materials (polymers, electronics, paper products) and the materials infrastructure where material producers will be responsible for the end of life of their material from the cradle to the grave using systems tools (life cycle assessment, techno-economic analysis) to guide the materials design.

Segregation by application (do not sort by polymer type). For example: Food packing - design for compostable - regenerate the soil; textiles - make more textiles, 3D printing, building materials.

The idea is to redesign materials based on different mechanisms of breakdown. For example, if you have multilayer/multicomponent materials can we have one set of materials that we break down (to monomers) by oxidation, one set by biochemical processes, etc. This allows us to deal with mixed materials that are all designed in a way to provide uniform monomers.

Create a materials map around a community or around an application. Software where one can go in and say, these properties are needed, and it provides us with materials available to use. We can use AI to help solve these challenges. Takes into account the tradeoffs (environmental, other tradeoffs).

What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.

- Have technologies that not only solve materials problems but also regenerate the earth
- Develop truly systems approach toward materials design and the whole life cycle

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?
In 10 years:

- Converge simplicity and diversity for materials design through modularity (a biomimetic approach). This involves making plastic from monomers like CO_2, greenhouse gases, or food waste for single use and food packaging that can ultimately be returned to the carbon cycle through organic recycling.

- An infrastructure and policies based on materials map(s) and systems thinking for materials design that allow for diversity of materials tailored to responsible, efficient use.
- A materials science community that can easily adapt, apply and scale concepts in design from nature into new, tailored materials.

In 3 years:

- Have a materials map created with artificial intelligence to provide thoughtful selection of materials for specific applications. This likely will involve applying digital design and manufacturing.
- Identify the largest volume culprits where we cannot get things back and use thoughtful selection.
- Make bioplastics (e.g., PHA's) cost and performance effective and competitive to petrochemical based plastics, particularly in the area of single use items and packaging.
- Develop technology for recycling mixed plastics without the need of physical separation.
- Using reactive or more imaginative processing technologies to cut down on multi-materials.
- Develop a materials map of natural systems and natural materials to ask "how does nature provide this function in a material?" and "how can we mimic it?"

What are the barriers or gaps in achieving your idea right now?
There are economic and policy barriers to materials disruption (for example, requiring recycled content is a barrier to first-generation innovative greener new materials since they will definitionally not have recycled content until the 2nd generation).

What might be early thinking on major milestones? Is there a prototype, method, or tool that is needed?
Can we learn from lessons for other large scale federally-funded innovation disruption programs such as DARPA and ARPA-E? Use those lessons learned to drive innovation in the materials space.

NSF Accelerator: What will we accomplish and why now?
What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created?

In order to decide what endpoint that we actually focus on to create disruptive materials, we need to decide and change the design criteria that incentivize these innovations. This is why we need a convergent approach. Some examples of this are:

1. Bring end-use waste handlers to the table and provide input that guides materials design
2. You have to know the technologies to even begin to understand the right fiscal incentives/appropriation/actions (to decide whether to tax, incentivize, set up credit model, etc.)

Bringing everyone to the table can be incentivized by providing funding from the NSF accelerator and other national agencies (DOE).

Why is this idea ready for rapid acceleration?
Everyone agrees the time is now and disruptive materials design in the circular economy is the perfect topic for rapid acceleration before it becomes too late.

NSF Convergence: What would your convergence accelerator <u>ecosystem</u> look like?
(e.g., Do you need an incubator space? Is it a wet lab or dry lab? Do you need a sustainability expert?)
Innovations will likely need wet lab and pilot scale production facilities. Working closely with industry partners that allow for technology evaluation at scale is key.

What strategies, tools, and methods are needed to INTEGRATE and SCALE from the molecular level to the built environment? (e.g., what analytical and computational tools can we utilize and further develop? How can convergence research foster this scaling and interdisciplinarity?)

There are a range of tools and methods currently available (LCA, TEA, systems dynamics, agent based modeling, operations research, EEIO, etc) that can be used to help understand opportunities and create solutions spaces. We have been working on this question - how can we combine different methods to try and answer different research questions around the circular economy - and it has been presented at the ACLCA conference.

So that said - the methods are feasible there, but we need the data and the expertise with these different methods to work out how to develop tools to answer our research questions - happy to share the presentation material to contribute to the conversation

How do we teach circular design in higher-education? K-12? Communities? Our designers? (Owners?)

Two things to teach students who work in any type of circular design class are a focus on life cycle assessment and techno-economic analysis. In addition, the limitations and assumptions that go into building these models need to be taught as well as how these models should be interpreted.

Teach current infrastructure for material production and recycling. We do not fully understand the complex supply-chain networks for most materials.

Circular Funding

Session Participant Names
- **Michelle Tulac (moderator)**
- **Peter Fadoul (co-moderator)**

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  - Ryan Bradley
  - Keith Chanon
  - David Constable
  - April Crow
  - Brajesh Dubey
  - I.S. Jawahir
  - Jacki Laiz
  - Liz Nichols
  - Seth Olson
  - Kathryn Peretti
  - Susan Thomas
  - Jorge Venegas

What's the big idea (2 to 3 sentence summary)?
Finance can enable the transition to a circular economy and help measure progress and outcomes, ultimately driving better economic growth and positive impacts. There are many ways to better deploy capital around the circular economy, create value, and manage risks, however further analysis of the specific financial mechanisms, as well as alignment around reporting and regulations is necessary for understanding the range of opportunities. An analysis of all types of finance should be undertaken to help design finance systems that can help build economic and natural capital and deliver society-wide benefits.

Circular economy related investment is happening across sectors and asset classes throughout the world. Some current financing mechanisms include: corporate bonds, private market funds, including venture capital, private equity and private debt, bank lending, project finance, and insurance. Governments, central banks, and financial regulators can complement and enable the shift in the private sector. They can help create the conditions for financing the circular economy at scale through risk-sharing, incentives, public finance, blended finance, and relevant policies and regulations.

What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.
Financial systems can support a circular economy that is regenerative and restorative by design. For example, with investment in R&D, innovation, and infrastructure, we can move away from the linear model that's extractive, wasteful, and polluting. We can develop alternative materials and practices that are safe, renewable, reusable, recyclable, and that keep value in the economy. Environmental, Social, and Governance (ESG) criteria as well as new metrics and frameworks can inform target setting and decision-making that help address global challenges. Data and technology, along with true cost accounting and pricing natural capital and externalities, can provide greater insight and accountability. Finance plays a critical role in the transition to the circular economy across actors, sectors, and regions.

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?

In 10 years:

- Disruptive amount of capital deployed towards high impact areas (e.g. large infrastructure, materials innovation, regenerative agriculture, manufacturing, healthcare, auto/aero, pharma industries) aligned with global commitments (e.g. science-based targets, UN SDGs, Paris Agreement, etc.).
- Universal adoption by national and international finance community of an investment framework for identifying highest-return (from an environmental and economic perspective) circular technologies and processes to invest in across different sectors, with feasibility assessment embedded to identify opportunities for risk-sharing.
- Changed culture within finance sector to increase awareness of the limitations of materials and resources and circular technologies/practices as solutions.

In 3 years:

- Working with key stakeholders in finance and asset management ecosystem, create investment framework for identifying highest-return (from an environmental and economic perspective) circular technologies and processes to invest in across different sectors, with feasibility assessment embedded to identify opportunities for risk-sharing; begin to mobilize capital toward solutions with the greatest potential for positive impacts (e.g. climate targets, increasing biodiversity, etc.).
- Embed explicit metrics and considerations for circularity across all major investor strategies and evaluations; establish standards (e.g. incorporation of externalities, standardized reporting requirements, etc.) for wide adoption across finance/investment sector to drive accountability.
- Increased emphasis on pricing of natural capital and pricing externalities.
- Better understand the flows through the economy and feedstocks used in material/product production.
- Create comprehensive circular marketplace to facilitate exchange and trade of circular materials such as recovered steel, disassembled capital equipment, etc.

What are the barriers or gaps in achieving your idea right now?

- Category benchmarks, indicating how the circular economy can deliver returns and measure performance.
- Co-benefits tend to be both opaque and dispersed, making accounting for the impact difficult.
- Cost competitiveness of alternative and/or recycled vs. virgin materials.
- Varying recommendations and standards surrounding ESG reporting frameworks.
- Relatively low penetration of understanding of circular economy priorities in finance sector.

What might be early thinking on major milestones? Is there a prototype, method, or tool that is needed?

Several groups can work in parallel (and partnership) in pursuit of these objectives. This would involve establishing a coalition of actors focused on setting standards and measurements (e.g. taxonomy, KPIs), launching an adjacent research and deliverable focused consortium (e.g. similar to Project Drawdown), and mobilizing multi stakeholders to produce demonstration projects that turn concepts and models into practice and pilots.

NSF Accelerator: What will we accomplish and why now?

What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created?

- Create a ‘menu’ of circular funding mechanisms that investors can reference, including category benchmarks indicating how the circular economy can deliver returns and measure performance
- Develop greater awareness in both consumers and companies of supply chain limitations

- Standards development for circularity and waste quantification

Why is this idea ready for rapid acceleration?
The circular economy presents a multi-trillion-dollar economic opportunity. It enables long-term resilience, helping to protect against economic and trade disruption, as well as helping to prevent further environmental harm. There are significant value creation and capture opportunities. Technology advancements in traceability, transparency, AI, and big data provide greater insight in the flow of products, materials, and information. There's an increased adoption of risk-sharing practices and new collaboration models. ESG investment is primed for acceleration, some recent reports indicate that ESG approaches are more resilient and offer better returns amid crisis. The circular economy can reduce costs, increase revenues, manage risks, and keep value in the economy.

NSF Convergence: What would your convergence accelerator ecosystem look like?
(e.g., Do you need an incubator space? Is it a wet lab or dry lab? Do you need a sustainability expert?)

The convergence accelerator ecosystem would include representatives from reporting and target-setting organizations (e.g. Task Force on Climate-related Financial Disclosures, Sustainable Accounting Standards Board), advanced manufacturing institutes (e.g. Nimble, REMADE, IACMI), members from organizations like Science Based Targets initiative, Net-Zero Asset Owner Alliance, Climate Action 100+, and investors from a range of financial institutions, including circularity and sustainability-dedicated investment firms and US banks. Members would also include corporate and industry representatives, leading circularity businesses, as well as "hard to abate" or "make circular" industries (e.g. built environment, plastics manufacturer, etc.)

The ecosystem would include opportunities to test, pilot, scale and develop capacity. This would require demonstration sites for prototyping and pilots (e.g. cities, campuses, neighborhoods), commercial or private sector locations (e.g. retailers), and digital environments (e.g. online marketplaces), and connecting with accelerators and incubators across the US.

What groups might be involved and why to realize your big ideas?
This convergence accelerator would create peer-to-peer knowledge sharing opportunities and engage people with a range of experience and expertise, including (in addition to the groups mentioned in the preceeding question): international trade, data science, material science (e.g. Citrine), as well as trade organizations (APR, RRS, SWANA, ISRI, ACC), political leaders, and economists.

How do we teach circular design in higher-education? K-12? Communities? Our designers? (Owners?)
- Include a circular economy course as a core module in business and management programs.
- Transform the way chemistry is taught. Currently there's a notion that "everything is free", that Hydrogen "just appears", and heat sources can simply be "turned on".
- Include circular economy and systems thinking and practice in Next Generation Science Standards.
- Introduce "Materials Flows 101" for K-12 schools (e.g. transforming leftover lunch into compost in school gardens to understand the bioeconomy)
- Educate students on the larger impacts of consumer choices and behavior
- Create more cross-disciplinary design programs, particularly at the undergraduate level (e.g. material science and computer science; business degrees and engineering), this can help teach students each major to think in each other's space. Cross-disciplinary exposure can help overcome biases and prepare for multi stakeholder engagement in the real world.
- Create more applied learning opportunities, internships and fellowships, that are tackling real

world problems in the circular economy whether it be in circular finance, product design, business model innovation, etc

- Create a Complementary Masters program in Circular Economy or Manufacturing alongside a PhD program.

Inverting the Chemical Research and Development Process

Session Participant Names

- **Eric Beckman (moderator)**

  - Melissa Bilec
  - Keith Chanon
  - Jay Fitzgerald
  - Eric Klingenberg
  - Jason Locklin
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  - Brent Shanks
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  - Meg Sobkowicz
  - Susan Thoman
  - Goetz Veser
  - Kelly Williams
  - Wei You
  - Julie Zimmerman

What's the big idea (2 to 3 sentence summary)?
For nearly 150 years, the chemical enterprise has commercialized products based upon an adaptation strategy, where new molecules are discovered serendipitously and then adapted to as many applications as possible. The "big idea" here is to determine how to "flip" this paradigm such that molecules are designed for intended purposes, which would provide an opening for circular design to be applied to creation of new chemical products versus relying upon ad hoc recycling of existing solutions.

What are the positive societal outcomes? Designing chemical products from first principles should allow for enhanced circularity (rather than trying to create ad hoc recycling processes for existing products). Design from first principles should also reduce long-term liability owing to widespread use of adapted yet environmentally flawed products. Design from first principles should lead to cleaner and greener chemical processes, which would then be better neighbors to communities (enhancing environmental justice). Designing from first principles will enhance the diversity of the chemical industry workforce, as new perspectives will be needed and welcomed versus the current incrementally-improvement paradigm.

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?
In 10 years:

- That chemical companies are required to accept returns of their products upon end of useful life
- The chemical industry moves to a leasing model rather than a sales model, where service is provided instead of simply pounds of product.
- For the first time, chemical products can be de novo designed

- Chemical waste to landfill drops by an order of magnitude or more

In 3 years:
- Agreement on the missing tools for circular design is achieved.

What are the barriers or gaps in achieving your idea right now?
The science around designing chemical products from first principles (from molecular attributes to formulation details to process synthesis) is not sufficient to allow its practice. Further, while the desired outcomes of circular design are generally agreed upon, there is less agreement on what the strategies to achieve those outcomes should be. Finally, because the needed strategies are still somewhat vague, both the tools and basic science required are still sparse – this framework of outcomes leading to strategies leading to tools resting upon fundamental science will have to be fully fleshed out.

What might be early thinking on major milestones? Is there a prototype, method, or tool that is needed?
If outcomes and strategies can be agreed upon, then groups in academia and industry can work to create the tools and basic science necessary for design of circular products.

NSF Accelerator: What will we accomplish and why now?
A key issue remains how to design tools (across length scales) that address various strategies for circular design, namely: Strategies:
- Design for emotional attachment
- Design for multiple lives (applications) without alteration
- Design for in-service upgrading and repair
- Design for recovery/collection
- Design for disassembly, separation of components, and reuse or reassembly
- Design that reduces complexity OR design for temporary/reversible complexity
- Design that reduces dissipation; promotes supported function
- Design that reduces material & energy intensity

Tools needed will differ by industrial segment and by length scale; all tools will require an underpinning of basic science.

Why is this idea ready for rapid acceleration?
Work by the Ellen MacArthur Foundation has moved circular design to the forefront of public consciousness; at the same time many of the most valuable products of the chemical industry are seen as particularly damaging or polluting – the waste issue remains an existential threat to the industry as a whole. Changing a 150-year old design paradigm, however, will be very difficult – an NSF program that accelerates change through convergent research work will be of great benefit. Given the conservative nature of the chemical enterprise, it is difficult to see how dramatic change will be accomplished without an outside influence like an NSF accelerator.

NSF Convergence: What would your convergence accelerator <u>ecosystem</u> look like?
The ecosystem will require a means by which new concepts can be rapidly prototype, regardless of length scale, as well as a means by which the general public and other stakeholders can help co-create new designs. Given the reluctance of large established companies to disrupt their own product lines, the convergence accelerator will need mechanisms by which small enterprises involved in new circular designs can be created and/or supported. Because both tool and basic science development will underpin the new designs, there needs to be facilities to accomplish this development and to integrate it into the prototyping and business activities of the ecosystem (testbeds).

What groups might be involved and why to realize your big ideas?
The general public is highly aware (owing to multiple press reports) of the burden placed upon natural aquatic systems by synthetic polymer waste; the public would be very interested to see new designs that alleviate this burden on natural systems. As per Stahel's original writings on circularity, new circular designs should lead to creation of higher quality jobs from design through repair and refurbishment to end-of-life deconstruction and reuse. Large legacy chemical companies will be very interested in any developments in the direction of circular chemical product design but may be reticent about disrupting their own legacy product lines; this should provide openings for startup companies in this space where legacy firms can act as investors. Because legacy firms are generally unwilling to practice self-disruption, they may fail to engage with a convergence accelerator because it is too future looking (rather than addressing ad hoc recycling processes that would not require changes to design or design paradigm).

How do we teach circular design in higher education? K-12? Communities? Our designers? (Owners?)
We can only teach circular design if we can address all of the issues: desired outcomes, strategies, tools, and fundamental science – whenever we can agree upon or create these four features, we have been able to teach the overall paradigm effectively to both undergraduate and graduate students. While there may be some agreement on the desired outcomes, it's not clear which strategies are most relevant to which disciplines (or economic segments). Further, tool development has lagged and much of the underlying basic science may be missing.

Policies

Session Participant Names

- **Alexander Dale (moderator)**

- Callie Babbitt
- Brie Berry
- Brandon Bray
- Keith Chanon
- Liz Nichols
- Brandon Ross
- Susan Ruffo
- Meg Sobkowicz Kline
- Richard Skorpenske
- Susan Thoman

What's the big idea (2 to 3 sentence summary)?
How can we create a policy environment that is conducive to a circular economy?

We want an accelerator that develops and adapts policy analysis methods with social science, technical skills like LCA and MFA, and local stakeholders to identify flexible policy approaches and tools to evaluate policies for different scales and sectors.

Focused on three different primary levers:

- Policies that discourage a linear economy (pricing in externalities like landfills, bans on complex single-use items, etc.)
- Policies that encourage a circular economy (support for commercialization, incentives or requirements, better systems for consumer-level collection and sorting, extended producer responsibility schemes, etc.)
- Policies that enable trial & implementation of new ideas (building codes, financing/insurance requirements, certification requirements, etc.)

Recommend emphasis on local and state-scale policy, less focused on federal and international policy - those scopes are more broadly covered, have institutions with more resources already, and have fewer clear pathways to policy implementation. In addition, many federal policies emerge from successful examples at smaller scales.

- Policy complexities:
    - Local Jurisdictions - most materials management happens locally and understanding what model policies are is important.
    - Leakage risks - how do we emphasize policies that avoid people just moving to other locations?
    - Understanding better contracting options - e.g. solid waste systems at municipal levels are contracted for long time periods, and have competition on rates but poor understanding of how co-mingling of products
    - Interactions - across policy domains, targets, and compartments, sometimes created adverse outcomes
    - Models - some examples of groups/communities functioning already as circular to some extent; lessons from EU and key differences (e.g., EPR at state level fought vs. EU top down); capabilities in different countries and how that influences approaches (e.g., Amazon, single use plastics)

- Linkages - how do you link upstream (e.g., design, labeling) to downstream (waste management, collection, recycling/recovery infrastructure), and establish lines of communication and information flow between stakeholders along this path) - independent pieces all working on this, but not connected.
- Varied tools - EPR, recycled content standard, bans, etc.; how to harmonize across scales and jurisdictions
- Scale - local to international (e.g., what can cities be doing vs. what can international trade policy accomplish?)
- Foci - CE - recognizing varied approaches for sectors and compartments
- Paradigms - varied across countries and domains of thoughts
- Measurement - how do we measure quantities of plastic to possibly manage
- Limits - What should the "plastic budget" or cap be? Should this be a possible approach to limit (modeled after carbon emission caps)

What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.

- People live in places where governments, residents, and businesses all tend towards choices that are more circular, whether in the materials they use/produce, the way materials are collected and reused, how infrastructure is built, etc.
- Lower incidence of new landfills and excess non-degradable materials (litter).
- Broader societal appreciation for policy environment as one way of shaping the world we live in.

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?

In 10 years:

Transformative: A fulsome, analytical understanding of the universe of policy options and their interactions.

- Creation of a clearinghouse of these policies and a tool that can help organizations/governments wanting to implement these policies to understand how they've been implemented, successes, failures, etc.
- Toolkit of model policies at more local jurisdictions, with validation from a trusted source (a team in the accelerator or the accelerator itself)
- An awareness of the importance of context for implementing effective policy

Scientific: Continuous policy analysis across many materials and sectors

- Integrating awareness of jurisdictional scales, LCA data, and circular material flows into policy analysis methods.
- New methods for transdisciplinary public policy work that integrate technical aspects with business supply chains, social science approaches, and local stakeholders.

In 3 years:

Transformative: A roadmap towards an analytical understanding of the universe of policy options across sectors/materials and their interactions, and a detailed understanding of a single sector (e.g. polymers or textiles).

- Key policy/regulatory practices that a) enshrine linearity or b) promote circularity for that sector
- Looking at local/state/federal policies, within and outside the US.

Scientific: Policy analysis - what existing policies are most effective? How can their effectiveness be improved?

- How have LCA and other material analyses been used in international contexts? How can they help unlock multilateral circular economy policy?
- Social science work of how consumers understand and interact with policy and policy process

What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created?

- Demonstrating use of existing or new policy analysis tools (both quant and qual) for circular economy sectors.
  - Adjustments for complex cross-sector relationships (e.g. intersection of urban policy, utility policy, complex outcomes
  - Adjustments for circular material flows and end-of-life.
- Tools for sharing the results of analysis with policymakers, consumers, private sector
  - Publications and workshops can have limited impact - can we do better?
  - Education of local policymakers and stakeholders

Specific research questions:

- What policies have been most effective at encouraging/discouraging a circular economy, and what have been the local and social factors involved in that success?
- What are recommended single or combinations of policies to speed circularity for a specific sector or jurisdictional space?
- What are the most frequent real-world complexities that result in unintended consequences of existing policies in this space?
- What circular economy goals are communities most interested in achieving, and how can that knowledge be passed up the value chain?

Specific example: What are plausible ways to implement extended producer responsibility, considering point of obligation, which products/materials are best suited, jurisdictional scale, complexity of truly circular materials, etc.?

Why is this idea ready for rapid acceleration?

- Growing awareness of the role of policy in meeting large-scale challenges, but policy analysis for some of these new tools has maybe lagged.
- Lots of technical innovations stay in the technical world, but don't get implemented because of policy environment - building codes, insurance, finances.
- We need to avoid ignoring research analysis of effective policy in favor of just leaning on tech innovation. (Policy is incredibly important, but we don't study it enough.)
- Needs complex interdisciplinary teams blending technical expertise on materials and processing with policy analysis and social science.

NSF Convergence: What would your convergence accelerator <u>ecosystem</u> look like?

- Place-based labs/incubators to understand successful examples of different policy types, either aimed at consumer-facing or corporate systems.
- Time from staff in executive and legislative policy-makers and regulators
- Ideally this includes some international experts, subject to NSC and security limitations.
- Community leaders and semi-formal businesses such as second-hand stores that are a key part of material flow but rarely in decision process.
- Municipal materials managers (governmental and policy)

What groups might be involved and why to realize your big ideas?

- Why does it matter to them or their constituents?

- How does it impact them (economically, politically, environmentally, technologically, etc.)?
- How will they be engaged (research, partnerships, legislatively, adoption, implementation, etc)?
- What might stop them from engaging, and how might we incentivize them?
- Cross-sector thinking to understand how to link consumer demand or policy objectives to market objectives through responsive policy.
- National Association of Environmental Legislators

What strategies, tools, and methods are needed to INTEGRATE and SCALE from the molecular level to the built environment?

- Model policies that can be replicated to many jurisdictions, with awareness of how to adapt for context, different industries, and adaptability without losing core goals.
- Strategies to avoid leakage across jurisdictions with different approaches to corporate mandates, consumer-facing waste systems.
- A library of key concepts with different terms in different fields, and acknowledging/translating between those terms without losing the importance of the nuance in those fields.
- Analysis of how consumer behavior influences and is influenced by different policies.

How do we teach circular design in higher-education? K-12? Communities? Our designers?

- Place-based labs/incubators that connect local stakeholders to issues of circular policy and design.
- Because of the more local policy focus, emphasis can be with local jurisdictions, and policymakers who often don't know what's happening where they are. Just explaining what's happening is useful
- For Higher Education, trans-disciplinary education is key.
- Corporate education in communities - a module on circular economy could plug into those programs. Programs generally look like specific 1hr-full day engagement with schools, often in underprivileged communities.
- Community College or mid-career opportunities - boot camp for established and emerging leaders to understand what policies are in place or possible (part. around circularity)

Just and Equitable Circular Economy

Session Participant Names

- **Fernanda Cruz Rios (moderator)**

  - Weslynne Ashton
  - Brieanne Berry
  - Brandon Bray
  - Michael Deru
  - Eric Klingenberg
  - Leidy Klotz
  - Amy Landis
  - Ellie Moss
  - Christine Ortiz
  - Amanda Roberts Thompson
  - Victor Thompson

What's the big idea (2 to 3 sentence summary)?

Creating circular economies that are *built on* principles of justice, equity, and inclusion. That means breaking down hierarchies and decentralizing the decision-making power in research and development, co-creating solutions through inclusive design approaches, and rethinking educational systems to include diverse perspectives in meaningful ways. In truly circular economies, people are not regarded as merely consumers but "prosumers", that is, everyone is empowered to be part of the design and development of products and services.

What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.

When built on principles of **equity**, circular economies foster innovative business models that result in *affordable solutions*; thus, increasing access and quality of life in historically marginalized communities. Promoting equity in circular economies also involve creating benefits for small businesses that engage in circular economy practices (e.g., repair shops). Similarly, **inclusive** circular economies value participatory design approaches, where local communities (including historically marginalized communities) are empowered to co-create solutions that would increase their wellbeing. These approaches go beyond traditional "community engagement" methods, where the community is consulted about a pre-established problem, but left out from the final decision-making process. In "circular" research and development processes, communities actively participate in the design process from the problem definition to the final solution. Finally, circular economies built on **diversity** must leverage diverse perspectives not only through participatory approaches but as a fundamental part of the design and education process. In this context, promoting diversity from K-12 to higher education to faculty and industry positions is paramount to creating circular economies. Current diversity initiatives in education are important but not enough: we must rethink the entire process of producing and distributing knowledge, who has been part of the process, who has been left out, and how we can not only include diverse perspectives in the conversation but *leverage* their contributions and worldviews.

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?

In 10 years:

- A *science reform*: transforming the way we produce and distribute scientific knowledge by

questioning the underlying assumptions, hierarchies, and distribution of power inherent to the current scientific method. For example, questioning who is involved and who is left out of the scientific production; including marginalized communities in the problem definition and research design processes; and working towards democratizing science by creating more accessible ways to produce and communicate scientific knowledge.
- A global, transparent database of circular economy initiatives and designs in various sectors, and their societal impacts (with metrics) in local, regional, and broader contexts.
- New business models for colleges and universities to foster collaboration and partnerships instead of the current exacerbated competition for students and resources.
- A political scenario that encourages targets for justice, equity, diversity, and inclusion as sine qua non for circular economies.
- Platforms for the democratization of the design process that provides accessible tools for people to co-create "circular" solutions for their needs (e.g., products or services).
- A society in which high-quality, sustainable, transparent products and services are available, accessible, and affordable so people can make informed choices based on their values.

In 3 years:

- Creating a shared vision around a definition for circular economies that goes beyond economic and environmental gains (the current "win-win" discourse) and is centered around social equity, justice, and inclusion.
- Training engineers and design professionals in justice, equity, diversity and inclusion.
- Developing frameworks to guide designers through the incorporation of
- Developing metrics and targets for equity, justice, and inclusion (building on existing tools like Social Life Cycle Assessment and social justice labels).
- Identifying a toolkit for stakeholders to quantify impacts to equity (e.g., IMPLAN).
- Developing innovative models for participatory research design (e.g., STATION 1).
- Creating better jobs within circular economies, where more value is placed on human creativity and bottom-up solutions, organizational structures are decentralized, and the workers have better rights and work-life balance).
- Understanding the design decision-making process from a mindset perspective: the values, mindsets, and mental models of the designers and how they create hindrances and opportunities to circular economies.
- Creating (and leveraging existing) incubators in universities to solve real-world problems in local communities within the context of circular economies; engaging and training students from multiple disciplines; and partnering with local government, industries, and NGOs.
- Support place-based teams to understand barriers and enablers for circular economies in different geographical contexts (e.g., Elinor Ostrom and the governance of common pool resources).
- Experimenting with changes in the university curricula for several disciplines (especially STEM disciplines) to include qualitative data analysis methods, and participatory research design methods.
- Supporting initiatives to dramatically increase diversity in higher education in all disciplines and leveraging networks for knowledge exchange between universities.
- Raising public awareness about (equitable, just, and inclusive) circular economies.
- Scaling up local initiatives for equitable and just circular economies and integrating value chains to create benefits for all stakeholders.

What are the barriers or gaps in achieving your idea right now?
The team did not explicitly discuss barriers or gaps. However, some barriers may be implicit in the group discussion. For example:

- the lack of a shared vision around circular economies,
- the lack of a social justice, equity, and inclusion focus within the current circular economy narrative,
- and, perhaps the most important, the lack of metrics and smart targets to assess, monitor, and improve societal aspects in circular economies.

What might be early thinking on major milestones? Is there a prototype, method, or tool that is needed?
The team did not explicitly discuss early milestones. However, based on the team discussion on other topics, the most *urgent* needs are:
1) tools and metrics to quantify and assess societal impacts within the context of circular economies;
2) and 2) transformative participatory methods in design, research, and development.

Why is this idea ready for rapid acceleration?
It's not a matter of whether the idea is ready or not for rapid acceleration; instead, it should be accelerated in every way possible due to its urgency.

NSF Convergence: What would your convergence accelerator ecosystem look like?
(e.g., Do you need an incubator space? Is it a wet lab or dry lab? Do you need a sustainability expert?)
A convergence accelerator for just and equitable circular economies would require interdisciplinary spaces for faculty and students to gather and co-create circular economy research agendas that are rooted in local communities and prioritize marginalized groups. Ideally, teams would involve students and faculty from diverse disciplines, in addition to designers, circular economy experts, and experts in participatory approaches to design and innovation. Universities would likely be able to tap existing resources (e.g., physical spaces, transdisciplinary initiatives, community liaisons) to create sustaining networks and foster connections, partnerships across disciplines, sectors, and scales.

What groups might be involved and why to realize your big ideas?
All society members must be involved in the creation of just and equitable circular economies. That includes, but is not limited to, policymakers, NGOs, companies, community members, professional designers, faculty, students, researchers, funding organizations, incubators and start-ups, universities, K-12, governments, and business owners. Mindset and cultural barriers were the most discussed obstacles within the Just and Equitable Circular Economies team. Engaging behavioral specialists is key to create the right conditions and supporting environment within all societal institutions mentioned above. The role of society leaders, as discussed by the team, is to engage the stakeholders, provide learning opportunities, and offer opt-in contributions. Emphasis was given to letting stakeholders come up with bottom-up solutions and design their contribution to just and equitable circular economies. However, incentives may be needed to ensure that targets for justice, equity, and inclusion are met.

Another important aspect to fostering inclusive stakeholder engagement opportunities is providing society members with *multiple* ways to engage (e.g., in person, through mail, phone, internet, etc.). Providing equitable access to community engagement methods is vital to inclusive processes, especially after the COVID pandemic.

How do we teach circular design in higher-education? K-12? Communities? Our designers? (Owners?)
Creating just and equitable circular designs may start with normalizing discussions around equity, social justice, inclusion, and diversity issues by including these topics into the curriculum of all disciplines from K-12 to higher education. An effective way to do so would be identifying issues that are pertinent to each course and environment. For that purpose, ABET criteria can be changed to incorporate a description of how each course commits to integrate equity, justice, diversity, and inclusion issues. In parallel to directly

addressing these topics in class, educators must receive training to acknowledge how currently taught principles have been built on structural racism. Educators must learn to question the origins of the knowledge that is shared and identify alternative tools to learning and measuring student progress that are meaningful to historically marginalized groups.

Consumer Behavior

Session Participant Names

- **Gemma Jiang (moderator)**

  - Weslynne Ashton
  - Callie Babbitt
  - Fazleena Badurdeen
  - Clay Bunyard

What's the big idea (2 to 3 sentence summary)?
The consumer connects the dots between products (upstream; resources) and waste (downstream). We would like to apply systems thinking to affect mindset shifts, which will in turn lead consumers to change their behaviors.

What are the positive societal outcomes?
Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.

- Less waste to be "managed"
- Standardization of waste management (at least at consumer level in U.S.)
- High consumer compliance with desired behaviors as the social norm/default behavior
- Economic incentives align with and promote circular economy behaviors
- Create products/services aligned with CE that are *better* for consumers (economically, in function, aesthetics, availability, convenience, etc.) and will therefore be preferentially selected
- Robust consumer take-back models across industries with high consumer participation rates (i.e. replicate Patagonia's success with product take-back/Worn Wear program)

What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive?
In 10 years:

- More availability of stores that offer bulk bins and refill stations
- Community organizing that can help to encourage support for different members--reciprocity for helping each other--maybe this becomes community gardens, canning foods, etc.
- Financial implications: pay for throw
- Eliminate 50% of consumer packaging
- Shifted consumer mindset
- Shifting economic model
- Shifting business mindset

In 3 years:

- Develop education strategies for different age groups that are appropriate for those ages and relevant to their value systems
- Stronger adoption of reused consumer packaging
- Repairs for home appliances (consumer acceptance, and company offer)
- Make it a competition about how long you have had this item (not how new) --cultural shift
- Waste tours: help consumers have direct experience of the waste problem, esp. How they impact underprivileged communities

What are the barriers or gaps in achieving your idea right now?

The barriers are the disconnect between consumers and companies and consumers and waste management.

NSF Accelerator: What will we accomplish and why now?
What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created?

- Consumer-compay partnership
- Build communities of peers, apply peer pressure
- Find the right people to seed the ideas
- Leverage marketing strategies to educate consumers
- Consumer research to understand the disparate markets and consumer attitudes and the drivers for different populations
- Identify strategies for education for different populations
- Behavioral science to understand consumer motivation
- Campaigns to help people have direct experience of the impact of their waste—for example, start a campaign to have everybody carry around their trash for a day
- Co-op; reciprocity; intergenerational collaboration
- Have an emphasis on business recycling, which is different than residential recycling
- Take community approach

Why is this idea ready for rapid acceleration?
This idea needs to be accelerated in collaboration with upstream stakeholders (eg. companies) and downstream stakeholders (eg. waste management)

NSF Convergence: What would your convergence accelerator ecosystem look like?
(e.g., Do you need an incubator space? Is it a wet lab or dry lab? Do you need a sustainability expert?)

- Materials and design: eg. color implication for recycling for different products; choose materials for products that can create emotional attachment
- Behavioral science, ethics, nudging (incentives); individual & organizational behaviors
- Data scientists/AI: how to capture information that describes the issues? Matching data with issues, continuously getting a pulse on how consumers are feeling about the issues. Data threads all of these.
- Businesses: manufacturing, supply chain; business continuity is the equivalence of sustainability
- Government and NGO: advocacy group creating photography and journalisms
- Investors: they drive the direction of industries
- Consumers
- Educators

How do we teach circular design in higher education? K-12? Communities? Our designers? (Owners?)
Create bite size materials with an invitation for deep dive
Leverage AI and data science to understand consumers need dynamically and customize messages for what customers specifically value

Thoughts on Facilitating Convergence

Overview
A convergence accelerator team, consisting of diverse disciplines and stakeholders, works to converge upon breakthrough solutions for society's complex challenges. Convergence can be challenging to achieve, given the current cultural and institutional roadblocks that have created disciplinary and stakeholder-based siloed structures. The volatile, uncertain, complex, and ambiguous (VUCA) nature of the challenges convergence accelerator teams seek to address calls for innovative facilitation efforts. Principles from complexity science, such as ecosystem consciousness, multidimensionality and emergence, could be applied to enhance the convergence process. We recommend three types of 'containers of transformation' developed and tested in the current NSF-Growing Convergence Research project[1] several co-authors of this report are working on.

Complexity and Convergence: The Big Picture
In 1948, Warren Weaver called for the scientific community to pay attention to "problems of organized complexity", the essence of which was "dealing simultaneously with sizable number of factors which are interrelated into an organic whole" [14]. Problems of organized complexity are presented today as complex adaptive systems, or systems that exhibit certain nonlinear characteristics, such as far-from-equilibrium, bifurcation, emergence, and phase transitions [15, 16].

Over the past 70 years, the scientific community has made significant advances in studying problems of organized complexity, from ant colonies to urban cities, from human brains to computer software [17]. Like the clockmaker metaphor of the Newtonian paradigm prevalent in the industrial age, the emergent worldview in complexity belongs to this moment in time. The conceptual tools developed to study these problems of organized complexity can aid in accelerating convergence upon solutions for complex challenges of societal importance.

[18] defined convergence as the process of merging different technologies, handling disciplines, and devices into an amalgamated whole to create new paths and opportunities. Convergence stands in sharp contrast to the current silo-based, fragmented structures separating disciplines and stakeholder groups.

Convergence teams will substantially benefit from facilitation efforts to successfully navigate the convergence process. The analogy of flying an airplane helps to illustrate the point. The existing fragmented structures, the underlying mental models and consciousness are like gravity; convergence research is like flying. Just like planes need fuel to break the gravitational pull, convergence research needs a consistent infusion of energy to sustain the transformational process in structures, mental models, and consciousness [19, 20], until this new paradigm takes root and becomes the prevailing model. Complexity principles and practices can be leveraged to facilitate the convergence process.

Complexity Principles Applicable for Convergence
Below are three principles from the complexity paradigm that are highly relevant to convergence research. They all call for significant shifts in mindset and consciousness from the existing silo-based structures.

1. **Ecosystem consciousness: An inversion of perspectives**

Useful convergence research requires nothing short of a transformation of the human consciousness from centering on the needs and wants of the ego, i.e. individual parts of the system, to centering on the ecosystem, i.e., the whole [19, 20]. Ecosystem consciousness is possible and necessary because in complex systems the whole (ecosystem) is bigger than the sum of its parts (ego); the wellbeing of the

[1] Award ID:1934824, NSF-GCR: Collaborative Research: Convergence Around the Circular Economy

whole and the parts are interdependent and mutually reinforcing. Therefore, leadership challenge is to make a feasible whole out of infeasible parts.

Compared to traditional discipline-based research, convergence research calls for an inverse perspective. For convergence research, the point for all involved is the same societal challenge; each stakeholder examines their unique view from the same ecosystem consciousness. Instead of asking only questions that a single discipline has answers to, a convergence team asks real question of societal importance and works synergistically to find solutions. A good illustration is a smoothie as mentioned in the workshop: each fruit and vegetable lose their own identity and form an organic whole.

Such a shift in consciousness and perspective is a prerequisite for a genuinely convergent journey.

2. Positive-sum game: The principle of multidimensionality
Complex systems are governed by multidimensionality, which maintains that opposing tendencies coexist and interact to form **complementary relationships**. This is a non-zero-sum formulation: A loss for one side is not necessarily a gain for the other; on the contrary, both opposing tendencies can increase or decrease simultaneously. The mutual interdependence of opposing tendencies is characterized by an "and" instead of an "or" relationship. There is potential to create positive-sum solutions [21].

The popular culture creates the fallacy of binary thinking as epitomized by the "pendulum swing" analogy. In this scenario, the opposite responses form adversarial relationships, an "either…or…" relationship. **They are cast so that a win for one is invariably associated with a loss for the other**. It is a zero-sum game. While this is true of mechanical systems governed by point attractors such as the pendulum, it is not true of complex systems governed by strange attractors. Swinging like a pendulum is not the only way of solving problems. Unlimited potential is available to create solutions that serve the wellbeing of all.

3. Emergence: global outcome arising from local interactions
Complex systems operate in far-from-equilibrium conditions with latent potential for transformation. Change does not need to be imposed from external environments or top-down hierarchical power, as is traditionally understood. Instead, change happens due to interaction between agents in the system and the nonlinear feedback process characteristic of far-from-equilibrium conditions. Autonomous agents change in response to interaction, based only on the local information available to them. But greater coordination, coherence and creativity emerge at the global level as a result. This process is also referred to as 'self-organization', the process of system change in complex, nonlinear systems [15, 17, 22].

Emergence stands in contrast to prediction. Emergence means that it is impossible to foresee the global outcome of interaction between individuals or reduce the global pattern to individual agents [22]. Hence, our approach to leading systemic change must change. Rather than introducing policies, rules or technologies to improve a system, we focus on creating the "enabling conditions for emergence". Characteristics of such conditions include [23]: interaction, interdependency, coherent social network, shared vision, diversity of ideas and expertise, individual agency, and creative constraints.

Containers of Transformation
In convergence research practice, creating enabling conditions is often operationalized as holding space for convergence-related activities. Such spaces serve the dual purpose of creating educational experience for team members and facilitate the convergence process. The concept of a "space" or "container" is useful here because it emphasizes boundary to a system. A bounded system stops energy from dissipating, which makes transformation possible (Goldstein, 1994).

Below are three types of transformative containers we have developed and tested in the NSF-GCR circular economy project. We talk about the containers in terms of their purpose and rationale, which are widely applicable to different contexts. However, it is worth bearing in mind that complexity is highly context specific [24], so how each container is going to look is explicitly dependent on the context from which the containers operate. We give examples of the containers in the GCR circular economy project.

1. Container for small, intensive transdisciplinary research team
Purpose: To hold intentional space for structures and processes for cross-disciplinary interaction

Rationale: Just as we need different labs for different types of scientific experiments, we need a container where researchers from different disciplines can explore the unknown, feel psychologically safe to fail, and interact with the frequency and an intensity that will lead to the emergence of innovative outcomes. Despite the best intentions, large project teams with diverse stakeholders often fall back into their silos—the power of "gravity" at work. Small, close-knit transdisciplinary teams form "cliques" where new ideas can be tried, and breakthrough innovations are likely to happen (Uhl-Bien, Marion, & McKelvey, 2007).

Examples: In the NSF-GCR circular economy project, we pioneered convergence circles (C-Circles) [25] and three-minute pitches [26]. Each C-Circle or pitch team comprises 4–5 researchers from at least three disciplines who represent the best approximation of a transdisciplinary circular economy research team. The initial team goes through a facilitated process of generating research questions, coming up with research designs, and conducting quick cycle prototypes to pressure test the ideas. Once the idea has gained support in the larger team, a formal research project will be formed to further develop and execute the idea. These small transdisciplinary teams not only directly facilitate interdisciplinary relationships by following up on innovative research ideas, but also create decentralized leadership structure by strengthening student leadership.

2. Container for affective relationships
Purpose: To provide opportunities for team members to experience each other beyond their research expertise.

Rationale: 1) The power of convergence research comes from leveraging diverse perspectives. However, integrating diverse perspectives will inevitably generate friction, which will, in turn, lead to interpersonal discomfort (Hassan, 2014). Friction, or task-related conflicts, build up pressure, and breakthrough innovation may happen due to that pressure (Uhl-Bien, Marion, & McKelvey, 2007). But too much pressure could break the team. We need lubricants to ease the stress from frictions and keep the group together. 2) The interactive, nonlinear feedback process in complex social systems dictates that the search for greater productivity should not stop at only task-related relationships. The principle of multidimensionality maintains that different types of relationships could become complementary and create a synergy that leads to better outcomes. Results from network analysis research demonstrate that both task-related networks (such as information sharing and advice seeking), and affective networks (such as friendship, social, and trust) exert significant influence on outcomes (such as performance, innovation, change) [27]. 3) Other theoretical frameworks point to similar directions. According to Theory U (Scharmer, 2018; Senge et al., 2005), deep learning needs to involve the head, the heart, and the hand. Research expertise opens the mind, and the affective relationship opens the heart.

Examples: In the NSF-GCR-circular economy project, we pioneered one such container called "Conversation Café" [28]. In this intentional conversational space, team members have dialogues on their everyday challenges, such as difficulty working with uncertainty. This project team consists of 21 team members from four different institutes, with six different disciplines (from engineering to anthropology) represented and a wide range of research expertise from undergraduate students to full professors. The

Conversation Café series provided this diverse group of people a level playing field to relate personally. Team members reported “feeling closer, more intimate” as a result of participating in the Café.

Many schools of thoughts offer practical and effective ways of hosting such spaces, such as Theory U (Scharmer, 2018), nonviolent communication [29], Bohm Dialogue [30], authentic relating [31], and liberating structures [32]. Researchers and practitioners should explore ways to incorporate these methods to design spaces for enhancing affective relationships among team members.

3. Container for whole-person immersion
Purpose: To create experiences of interdependence that go beyond the mind.

Rationale: The latest research on neuroscience and consciousness [20, 33] points to the importance of whole-person immersion in learning. One of the most effective paths to develop ecosystem awareness is for team members to experience the team as an organic whole. In the process of forming an organic whole that did not exist before, the boundaries between individuals are penetrated and gradually disappear. In order to achieve that, the boundary between the mind and body needs to disappear first. An experience, different from knowledge, involves the whole body.

Examples: At the beginning of the NSF-GCR-Circular economy project, we had a team building activity in the “Escape Room.” Over the course of one hour, all team members were involved in finding the clues to escape from the room. It was a great example of whole person immersion. Retreats, boot camps, nature adventures, and learning journeys are examples of such containers, but the activities need to be designed with a solid understanding of the theory.

As Albert Einstein so famously said, “We cannot solve our problems with the same thinking we used when we created them.” The thinking that created the problems are epitomized by Newtonian determinism, where the whole can be studied by dissecting the parts--hence the fragmentation which remains. Solving complex problems requires applying complexity principles at all levels of systemic change: structure, mindset, and consciousness (Scharmer, 2018; Senge et al., 2005). The NSF Convergence Accelerator program provided unprecedented opportunities for diverse disciplines and stakeholders to come together and make structural changes. Such monumental efforts need to be powered by significant efforts in shifting mental models and consciousness.

Summary, Conclusions, and Next Steps

Our vision was to foster and catalyze circular economy design from molecules to the built environment. We held, for the first time in the US, a virtual workshop, *NSF Convergence Accelerator: Workshop on Design for a Circular Economy from Molecules to the Built Environment.* We convened an expansive group of 95 experts to ultimately aid in creating a research agenda and the mission components in support of a new track for the NSF Convergence Accelerator program. Attendees included academia from engineering to the social sciences, industry, non-profits, government agencies, foundations, and end-users. Through three highly curated agendas with a mix of keynotes, provocations, and pointed questions, we identified key Jupiter shots, anticipated the 10-year and 3-year transformative and scientific impacts, focused on the societal impacts for the American people and beyond, and mapped what can be accomplished with the 1-3 year timeline given the right ecosystem in the convergence accelerator.

The upswell of ideas, plans, and enthusiasm encourages us – beyond a doubt – that design for circular economy is at the precipice of innovation, technology, and positive and equitable societal outcomes. Investing in this area is both prudent and urgent, so the U.S. can be leaders and innovators in design for circular economy. **Design for circular economy is primed to be accelerated using a convergence research approach**. Parts of the CE ecosystem are in place in the US from people to industries and innovation, but it is fragmented and at varying degrees of sophistication. Additionally, the number of people, companies, decision makers, and researchers identified in the workshop further emphasize the need for a cohort of people to coalesce around advancing design for CE in the US.

There is **an urgent need to educate and train not only the next generation of scientists and engineers on design for circular economy, but also anyone that does any type of design** – from the business developer who is working on designing financing strategies to policy makers who are designing circular economy interventions. We need to **reimagine and transform how we design across all levels** -- from molecules to materials and to the built environment and envision the end-of-life and/or re-use from the cradle to the grave using systems tools to guide the design. **There is also an urgent need for circular economy principles, standards, tools, and metrics across all levels of the supply chain.** These concepts should ensure, measure, and make transparent environmental gains; prosperous, triple bottom line circle economies at multiple scales (national, state, local, and micro); and foster meaningful and deep equity and inclusion.

Most importantly, the societal impacts associated with design for the circular economy are profound. CE presents a significant economic opportunity, and it has the potential to enable long-term resilience, helping to protect against economic and trade disruption, and most importantly helping to prevent further environmental harm.

Through our workshop series, we have developed **partnerships** and are continuing to foster these partnerships. We view this workshop as the start of our Design for Circular Economy community in the US. We have established a website (www.circular-designs.org) and are using basecamp to continue to grow our community.

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Appendix A: Biography of the Organizers

	**Melissa Bilec (PI),** University of Pittsburgh. Dr. Melissa Bilec is an associate professor in the Swanson School of Engineering's Department of Civil and Environmental Engineering; she is the Deputy Director of the Mascaro Center for Sustainable Innovation. She is also the Roberta A. Luxbacher Faculty Fellow, and she serves as the Pitt STRIVE Director of Faculty Community Building and Engagement for Diversity, Equity, and Inclusion. Dr. Bilec's research is motivated by her strong commitment to develop positive, quantitative, and sustainable solutions for the built environment. Most recently, she is working to solve the global plastic waste challenge through the advancement and development of design for circular economy. **mbilec@pitt.edu**
	**Eric Beckman (Co-PI),** University of Pittsburgh. Eric Beckman received his BS in chemical engineering from MIT in 1980, and a PhD in polymer science from the University of Massachusetts in 1988. Dr. Beckman assumed his faculty position at the University of Pittsburgh in 1989, was promoted to associate professor in 1994, and full professor in 1997. He received a Young Investigator Award from the National Science Foundation in 1992, and the Presidential Green Chemistry Award in 2002. He previously served as Associate Dean for Research for the School of Engineering and Chairman of Chemical Engineering. In 2003, Dr. Beckman co-founded the Mascaro Center for Sustainable Innovation, a school of engineering institute that examines the design of more sustainable infrastructure. In 2005, he co-founded Cohera Medical Inc. to commercialize surgical adhesive technology developed at the University. Dr. Beckman took an entrepreneurial leave of absence from the University in 2007-2009 to help move the products to market. Dr. Beckman's research group examines the use of molecular design to solve problems in green product formulation and in the design of materials for use in tissue engineering. He has published over 175 papers and has received more than 40 US patents. **beckman@pitt.edu**
	**Jenna Jambeck (Co-PI),** University of Georgia. Dr. Jambeck is the Georgia Athletic Association Distinguished Professor in Environmental Engineering in the College of Engineering at the University of Georgia (UGA), Director of the Center for Circular Materials Management in the New Materials Institute, and a National Geographic Fellow. Her research focuses on solid waste management, especially global waste issues and plastic contamination of our environment and ocean, including co-

	development of the open data citizen science platform marine debris tracker. **jjambeck@uga.edu**
	**Jason Locklin (Co-PI),** University of Georgia. Jason Locklin obtained his BS from Millsaps College in 1999. He graduated with his MS from UAB in Chemistry in 2002 and PhD from the University of Houston in 2004. Jason then went on as a Director of Central Intelligence Postdoctoral Scholar at Stanford University in 2005 in the Department of Chemical Engineering. In 2007, Locklin joined the University of Georgia in the Department of Chemistry and the College of Engineering and was promoted to Professor in 2018. He founded the New Materials Institute in 2016 that focuses on green engineering principles and circular materials management. Locklin has been awarded the Central Intelligence Agency Young Investigator Award, NSF CAREER Award, the Northeast Georgia ACS Chemist of the Year for Research, and Atlanta Magazine Groundbreaker Award. He is a Distinguished Faculty Scholar in the College of Engineering and the Site Director for the National Science Foundation Industry University Collaborative Research Center -- Center for Bioplastics and Biocomposites at UGA. **jlocklin@uga.edu**
	**Gemma Jiang (SP)**, University of Pittsburgh. Dr. Gemma Jiang is the founding director of the Organizational Innovation Lab at Swanson School of Engineering, and the founding host of Pitt u.lab hub. She holds a PhD degree in Educational Leadership from Clemson University. As an action researcher, she believes in integrating research with practice. Her primary focus is to apply the latest thinking in research into practice, and to gather data from the frontier of practice to improve theory. The theoretical frameworks she subscribes to include complexity leadership theory, Theory U, systems thinking. She is involved in a wide range of projects from National Science Foundation funded projects with a focus on circular economy, to local foundation funded projects with a focus on the Pittsburgh ecosystem for children thriving. **gej20@pitt.edu**
	**Fernanda Cruz Rios,** University of Pittsburgh. Dr. Cruz Rios is a postdoctoral associate in the Swanson School of Engineering's Department of Civil and Environmental Engineering. She is currently working with Dr. Bilec on the Convergence Around of Circular Economy project. Dr. Cruz Rios's research focuses on the circular economy in the built environment (specifically circular building design, materials reuse, and life cycle assessment). **fernandacruzrios@pitt.edu**

Appendix B: Agenda – Session 1

Session 1: Circular Economy
Friday, September 18

Title	**September 18: Generate Lots of Ideas**
KI Team	Donnalyn, Jocelyn, Effie
Time	180 minutes (Times are in EDT)
Audience	All (Organizers, Participants, and NSF Observers)
Presenters	See Below
Google form	Stewarding Jupiter Shot
Flow	Aims: ● Understand the Challenge ● Build community ● Identify problems we need to solve ● Idea Generation and gather interest around "Jupiter shots" Content/Activities: ● Speed Networking (Random/Interdisciplinary) ● Identifying the most novel ideas Output: ● Idea Exploration ● Groups identify how these BIG ideas will have a future impact and how stakeholders involved

Time (EDT)	Duration	Descr.	Purpose	Who?
11:00 AM	60	Tech set up	60 minutes prior to get everything set up (12:00 pm ET is go Time) 30 mins prior we will meet the CE team	KI
12:00 PM	13	KI Welcome & Instructions	KI will go over basic tech and the agenda for the day Capturing questions for NSF	DL

12:13	2	Introduce Linda		ORGANIZERS*Melissa*
12:15	10	NSF Convergence Accelerator	Introduction from NSF on the Convergence Accelerator	Linda (NSF)
12:25	10	Context setting	Presentation of the series, goals, ideal outcomes	ORGANIZERS *Melissa and Jason*
12:35	31	2 mins set up Speed Networking / Small Group Networking	Organizers please check out the prompts. Run through rounds and instructions for the activity Breakout Groups will be randomized Bring participants back after each round. 2 min broadcast warning	
1:06 pm	3 min	Provocation Setup	Capturing questions and Jupiter shots from the speaker's presentation Instruct the participants where to capture these	KI
1:09 pm	12 min. actual 20	Provocation	Speaker inspiration. KI reminds participants to add to the wall throughout provocation and the day 15 min talk / 5 min Q&A	Michelle Tulac, EMF

1:21 pm	3 mins	Instructions for Break - Incubation and Break	Give instructions for incubation and ask participants to add to the wall. This is a break with a purpose. Please go for a walk. Incubation is important. Gaps, are you excited about what's on the wall? If not, put it there? Are you colleagues represented? Concrete? Other materials?	KI
1:33 PM	15 mins	Solo reflection & they can take break	Participants on break and Incubating	
1:38 pm 1:48 PM	5 mins	Welcome Back and Activity Setup	Purpose of what's next	KI Team
1:43 PM	5 min	Voting	Everyone gets 2 votes	KI Team
1:48 PM To	5 min	Team for Stewarding	**Sign up for the 1** you would like to chat about today. KI will create new pages for each one.	KI
1:53 PM	40 min	Stewarding Jupiter shots	Small groups (4-6 ppl) are formed around a novel idea they would like to explore further *PESTLE factors (political, economic, scientific, technological, legal, environmental)* Jupiter shot Template	KI team. Organizers please check out the prompts

2:37 PM	15	Close Homework - use one as an example - Convergence & divergence	Next Steps and Homework	KI / ORGANIZERS: Homework - for organizers, what is missing?

Appendix C: Agenda – Session 2

Thursday, September 24th
Session 2: Circular Economy

KiStorm Link - https://kistorm.com/go/circular2020
KiStorm Event Code - circular2020
Tech - jocelyn.tejeda@knowinnovation.com

Title	**September 24: Disruptive Thinking AND Backcasting**
KI Team	Donnalyn, Jocelyn, Effie
Time	180 minutes (Times are in EDT)
Audience	All (Organizers, Participants, and NSF Observers)
Presenters	See Below
Flow	Aims: ● Gather feedback on BIG idea and develop further ● Gain a deeper understanding of the scientific and societal impacts of stewarding sessions ● Start to identify immediate steps (2-3 years) that will propel the Jupiter shot Content/Activities: ● Report out on small group stewarding ● Backcasting idea ● PPCo to gather feedback Output: ● Identify next steps for developing the idea in a 2-3 year timeframe ● Discover emerging cross cutting themes

Time (EDT)	Actual Start time	Duration	Descr.	Purpose	Who?
11:00 AM		60	Tech set up	60 minutes prior to get everything set up (12:00 pm ET is go Time) 30 mins prior we will meet the CE team	KI

12:00 PM	12:00	5	KI Welcome Back	Review goals/aim for the day	DL
12:05 PM	12:03	12	Organizer Welcome and Refresh		*Melissa & Linda*
12:17 PM	12:19 pm 12:20 pm	1 min 15 mins	Melissa to introduce Jenna Jenna Keynote		 Jenna
12:33 PM	12:40 pm	7	Breakout instructions	KI - Intro to next activity Melissa - discuss new themes added and the big goal/ideal outcome	Melissa and Donnalyn
12:40 PM	12:50	35	Small group discussions	Rotate, think big, AND take a deeper dive.	
1:15 PM	1:25 pm 1:30 pm	5 40	PPCo Report out	Instructions 9 groups get 3 mins for report out, 1 min for transition	
2:00 PM	2:07	5	Break		KI

2:05 PM	2:11pm 2:18 pm	 40	Instructions Backcast	Introduction of Activity on Mural	KI
2:50 PM	2:52 pm	10 mins	Closing & Next Steps	Give instructions for participant homework	KI Eric

Appendix D: Agenda – Session 3

Session 3: Circular Economy

KiStorm Link - https://kistorm.com/go/circular2020
KiStorm Event Code - circular2020
Tech - jocelyn.tejeda@knowinnovation.com

Title	**Session 3**
KI Team	Donnalyn, Jocelyn, Effie
Time	180 minutes (Times are in EDT)
Audience	All (Organizers, Participants, and NSF Observers)
Presenters	See Below

Time (EDT)	**Actual Start time**	Duration	Descr.	Purpose	Who?
11:00 AM		60	Tech set up	60 minutes prior to get everything set up (12:00 pm ET is go Time) 30 mins prior we will meet the CE team	KI
12:00 PM	12:00 pm	5	KI Welcome Back	Review goals/aim for the day	DL
12:05 pm	12:02 pm	10	Organizer Welcome and Refresh	Summary of Session 1 and 2 and Goals for Session 3	*Melissa and Nanda*
12:15 pm	12:11 pm - 12:13 pm 12:13 pm	1 min 20 mins	Melissa to introduce Eric Eric's Keynote		 Eric

12:35 pm	12:33 pm	5	Breakout instructions	KI - Intro to next activity	Gemma and Donnalyn
12:40 pm	12:40	5	Sign-Up for Theme	KI - directions	All
12:45 pm	12:40 pm	60	Small group discussions	People can rotate if they like	
1:45 pm		10	break		
2:00 pm		 40	PPCo Report out	Instructions 8 groups get 3 mins for report out, 1 min for feedback & transition	
2:40 pm			10 mins	Closing & Thank yous Next Steps/opt out	

Appendix E: Complete Template of Breakout Sessions

Please have your camera on and quickly introduce yourself, (name, department, superpower in convergence and/or circular economy) (10 minutes).
Please **identify a colleague to act as scribe.** To keep things moving and for equity reasons, we suggest the person whose **first name** starts with the letter closest to the **beginning** of the alphabet. (1 min)

Jupiter Shot (e.g., Innovations in the Built Environment to foster CE)
Session Name and email • …. • ….
What's the big idea (2 to 3 sentence summary)? ….
We encourage you to think of the outcomes first. **What are the positive societal outcomes? Please consider diversity, equity, and inclusion when answering this question. Other outcomes include, but are not limited to, environmental benefits, positive economic gains, and increase in quality of life.** ….
What are the anticipated transformative and scientific impacts? THINK BIG. What will be disruptive? **In 10 years:** • …. • …. • … • **In 3 years:** • …. • ….
What might be early thinking on major milestones? Is there a prototype, method, or tool that is needed? **We invite you to draw out the milestones based on your previous conversations.** Link to mural (~40 mins to complete)- https://app.mural.co/t/knowinnovation3615/m/knowinnovation3615/1600907198670/4cd6d8cca95aa1ea2f36f245b5bc2316071b4c95 Once complete, please answer the questions below regarding stakeholders
NSF Accelerator: What will we accomplish and why now?

What can be accomplished in the next 1-3 years? (from mural). What are the prototypes, methods, or tools that might be created? … **Why is this idea ready for rapid acceleration?** …. ….
NSF Convergence: What would your convergence accelerator <u>ecosystem</u> look like? (e.g., Do you need an incubator space? Is it a wet lab or dry lab? Do you need a sustainability expert?) • ….. **What groups might be involved and why to realize your big ideas?** • Why does it matter to them or their constituents? • How does it impact them (economically, politically, environmentally, technologically, etc.)? • How will they be engaged (research, partnerships, legislatively, adoption, implementation, etc)? • What might stop them from engaging, and how might we incentivize them?
What strategies, tools, and methods are needed to INTEGRATE and SCALE from the molecular level to the built environment? (e.g., what analytical and computational tools can we utilize and further develop? How can convergence research foster this scaling and interdisciplinarity?) • … • …
How do we teach circular design in higher-education? K-12? Communities? Our designers? (Owners?) •
What are the barriers or gaps in achieving your idea right now?
What expertise is needed?

Appendix E: Recommended Reading and Resources

Below you will find some foundational information which may be useful in working towards building the circular economy of the future.

- NSF Convergence Accelerator Program Link: https://www.nsf.gov/od/oia/convergence-accelerator/
- Link: Production, use, and fate of all plastics ever made. Science Advances, AAAS, July 2017
- Website: What is the Circular Economy. Ellen Macarthur Foundation
- Link: Circular economy- A new relationship with our goods and materials would save resources and energy and create local jobs, explains Walter R. Stahel. Nature, Comment, March 2016
- Link: Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering
- Link: Plastics for a Circular Economy Workshop: Summary Report. US Department of Energy
- Link: Complexity Leadership Theory: Shifting leadership from the industrial age to the knowledge era . The Leadership Quarterly, August 2007
- Link: Making the circular economy work for human development . Resources, Conservation and Recycling. May 2020
- Link: Myths of the Circular Economy . Discard Studies. November 2019
- Link: Policies for Green Design . Journal of Environmental Economics and Management. September 1998