“The natural environment sustains the life of all beings universally.” *Dalai Lama*

Module 3: The Designed World
Sustainable Design

In Module 1 and Module 2 of this series students investigated the world we that humans have engineered, followed by an exploration of the engineering approach seen in Nature. This final module is in a sense a capstone project that asks students to combine the ideas of Modules 1 and 2 in order to take a more sustainable approach to designing products and processes.

There are many definitions of sustainability and many frameworks for sustainable design but perhaps the simplest comes from the United Nations Brundtland Commission. *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* Sustainability is also defined in terms of a wide range of factors that are generally classified into three categories: social, environmental, and economic. Some refer to this as *people, planet,* and *profit.* Sustainable design requires *systems thinking* as it is important to consider feedback loops, connections, trade-offs, and unintended consequences if we hope to develop solutions that don’t create many more problems. As we confront the reality that resources are becoming scarcer, inequities are increasing, and the environment is degrading, taking cues from Nature as we develop new products increasingly makes sense.

This module provides links to resources for teaching all students more about sustainability and sustainable design at all grade levels. At ProjectEngin, we typically approach sustainable design from a biomimetic viewpoint. Nature does not destroy the planet as she develops solutions and she always employs circular design, valuing function-favorable structures, minimizing material consumption, and minimizing waste. Encouraging students to ask, “How would Nature do it?” usually leads to solutions that will go a long way toward protecting the earth and each other, now and in the future.

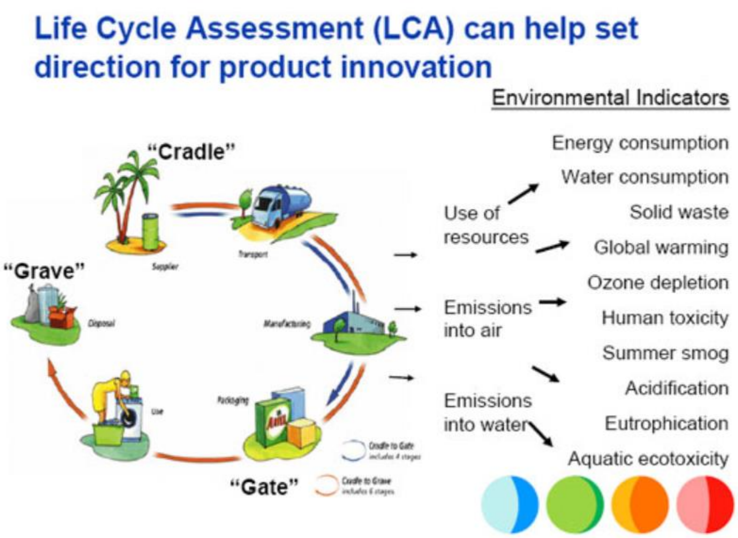
This module also contains two options for design challenges for middle and high school. The more open-ended option is to challenge teams of 2-4 students to re-design a product using circular design methods and biomimicry. If you are looking for a more specific focus, the Sustainable Packaging Project plan details an Engineering Design challenge along with resources and student worksheets. Both challenges can be done using a distance learning model and both provide a way for students to collaborate creatively. Both can be altered to fit your needs and the time that you have available.

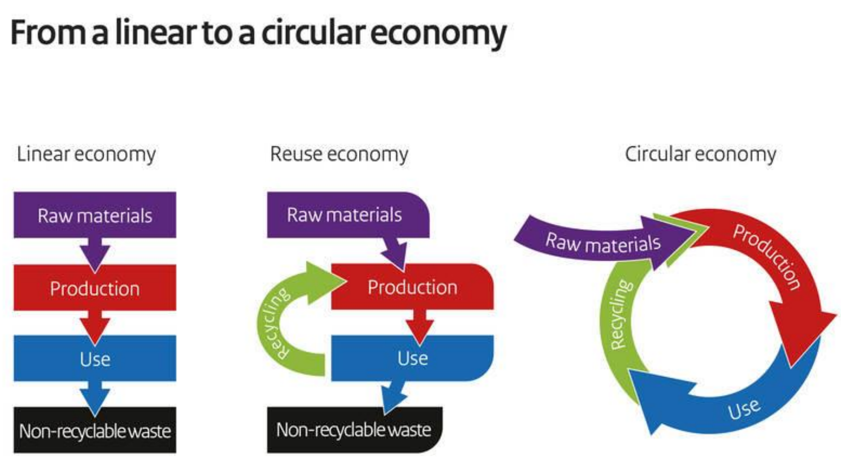
Resources for Teaching About Sustainability and Sustainable Design

Grade Level	Website/Link	Description
K-12	Teaching Sustainability: Resources for Educators	From Penn State's Center for Global Studies, a comprehensive curated list of resources for K-12 educators.
K-12	Learning for a Sustainable Future	Developed for Canadian educators and aimed at increasing environmental and sustainability education. Specific materials have been added for at-home learning.
K-12	The World's Largest Lesson	The United Nation Sustainable Development Goals cover all three aspects of sustainability (society, environment, and economy). This is a terrific website that provides resources, activities, lesson plans for educators at all grade levels.
K-12	Learning Lab Modules	Introductory sustainable design lessons (currently free for online learning) from the US Green Building Council. 45-50-minute versions for elementary, middle, and high school; focuses on over-fishing as an engagement activity
K-12	Sustainable Schools Project	Wide range of educator and student resources identified by grade level.
6-12	TED Talks Sustainability Playlist	12 TED Talks focused on Sustainable Design in a variety of applications and products.
3-8	**VIDEO:** What is Sustainable Development?	Animated video from UN-Norway and UNICEF designed to explain sustainable development to elementary and middle school students (in English).
9-12	**VIDEO:** What is Sustainability?	Whiteboard (sketch-note) animation from Sustainability Illustrated highlighting the systems aspects of sustainability
5-12	**VIDEO:** What is Sustainability? The Lexicon of Sustainability	A beautiful, simple video that highlights that sustainability means providing for the future.
3-8	**VIDEO:** What is Sustainability?	Short video that highlights plastics as well as the role of reuse and upcycling

Project Option 1: Circular Sustainable Design Challenge (Grades 8-12)

Again, think of this as a capstone project. If you have not explored or used any of the resources in Modules 1 and 2, consider using parts of them as background research for this project. Students are asked to choose to investigate a familiar product by looking into what it is made from, how it is made, how it gets to consumers, and finally, how it is disposed of. They are asked to conduct a life-cycle analysis and create a cradle-to-grave diagram (see below) for the current product and then to consider revising the process to move closer to a circular design model. Circular Design moves beyond a linear production model and even the idea of recycling to a system that encourages continuous flows in a closed loop model. Most processes in Nature follow a circular design pattern and resources related to biomimicry are shared in this document. In addition, students should be encouraged to research the use of natural materials and structures and processes inspired by nature. The final "deliverable" should be a graphic showing a more sustainable circular production process. Teachers may also want to require a brief slideshow, PowToon, or video highlighting process changes. This project can be done in teams of 2-3 or individually. The steps listed in the following table are meant as a "roadmap"; feel free to follow your own plan in using them.





"A Circular Economy for the Netherlands by 2050"

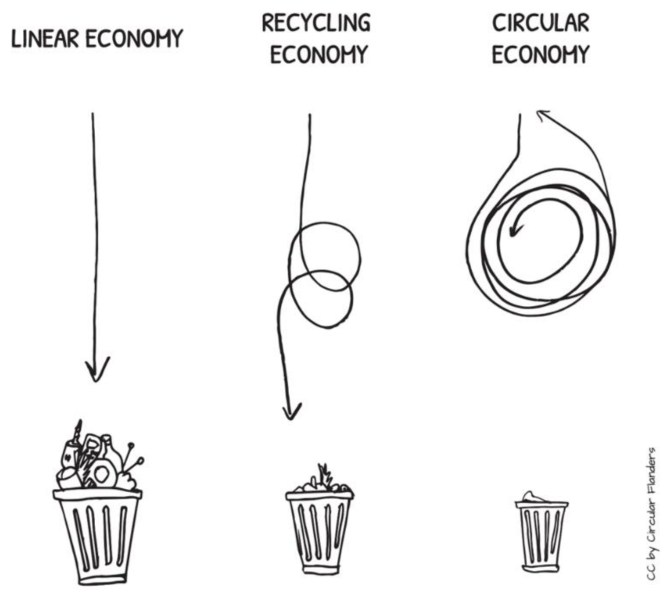
<table>
<tr><th>Project Sequence</th><th>Resources/ Worksheets</th></tr>
<tr><td>1. Choose a product to “re-engineer”</td><td>Products should be items that students are familiar with and/or use. It is helpful if there are multiple steps/ components involved in the manufacture of the item.

Students may also want to focus on something they considered in Module 1.

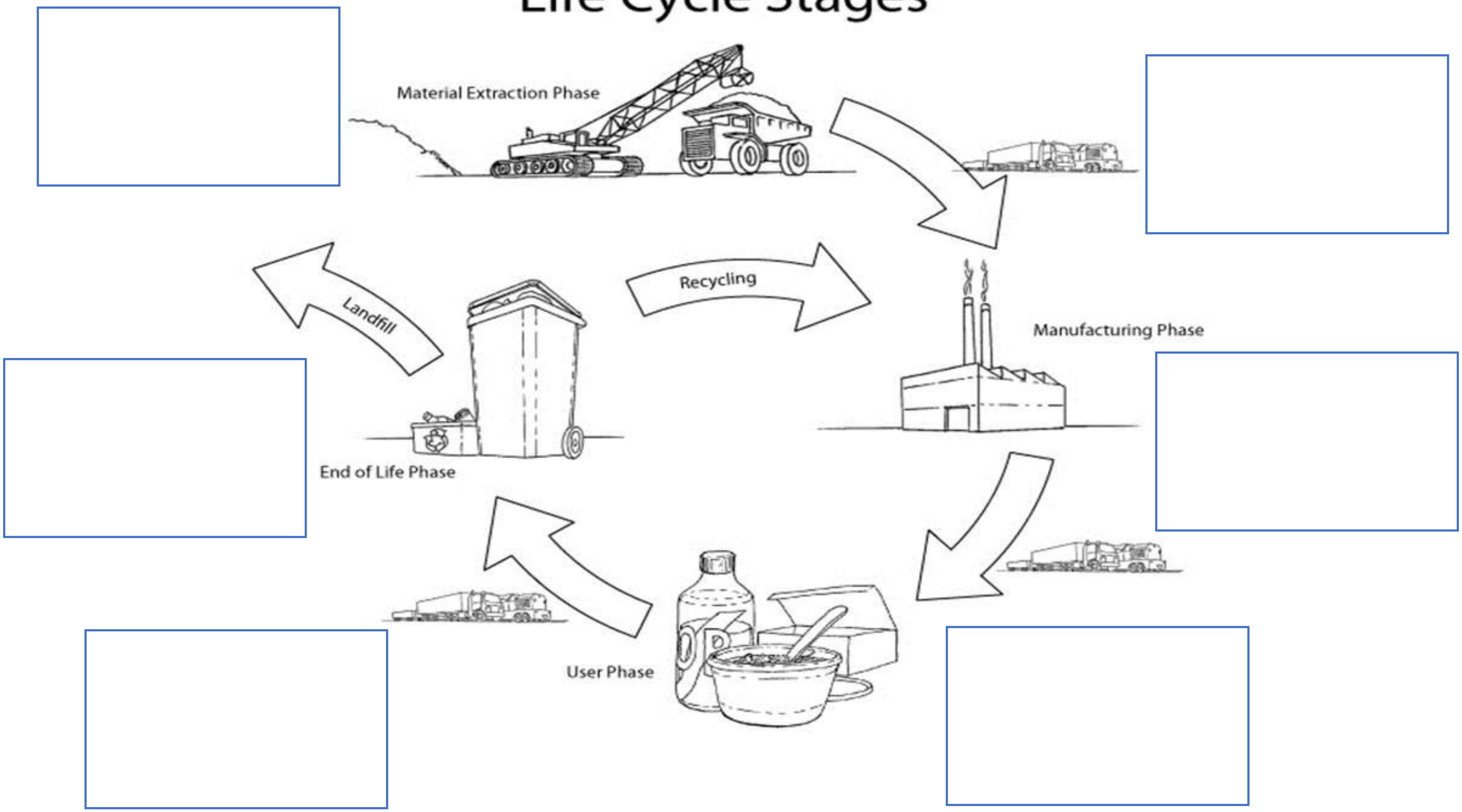
The following videos/websites can provide some background/inspiration
The Life Cycle of a T-Shirt (TED Ed)
The Story of Stuff – collection of videos focused on plastic and all the other “stuff” we depend on
What Happens to Plastic You Throw Away? (TED Ed)
Shooey Shoes – a modular approach to shoe design
Our Brains Love New Stuff… – great article about “disposable” mentality from the Harvard Business Review
What is in a Cell Phone? – fact sheet from Minerals Education Coalition
How Much Does the Fashion Industry Produce?
Fast Fashion Facts: What you need to know Great overview from 7 Billion for 7 Seas
Fighting Food Waste – making new products from waste</td></tr>
<tr><td>2. Research the overall production process of the product.

Remember to start with the raw materials and try to include all manufacturing, transportation, and distribution processes.</td><td>How It’s Made – a series of video covering lots of products. This is a good starting place.
Life Cycle of a Pencil – good example of a graphic representing the life cycle of a wooden pencil
Life Cycle Analysis of a Coffee Cup
The Life Cycle Analysis Worksheet (attached) can be used to record a summary of the process.</td></tr>
<tr><td>3. Learn about the principles of Circular Design</td><td>The Circular Classroom* – an excellent curriculum designed for Finnish classrooms. Educator Guide and Student Materials consist of 4 modules, each with videos, resources, clear explanations, and worksheets. *You can use this resource alone to create an excellent project – it is very well-done and has a strong message of designing for a better future.
VIDEO – Sustainability Illustrated sketch-note video about the circular economy.
Circular Economy – educator resources from the Ellen MacArthur Foundation (“home” of circular design)
Circular Design Guide – worksheets, videos, case studies</td></tr>
<tr><td>4. Learn about Circular Design and Processes in Nature</td><td>VIDEO – The Circular Economy in Nature (animated)
Learn from Nature – Circular Design
Nature-Inspired Design Handbook (free PDF)
Ask Nature – Rethinking Progress: The Circular Economy</td></tr>
</table>

	• Circular Economy Practitioners Guide: Strategies and Examples
5. Re-engineer your product by using circular design and borrowing ideas from Nature. Create a poster, infographic, PowToon, or video to describe and highlight the new process. Some resources that might help are listed on the right.	• **ScreenCastify** is a Google Chrome extension that is designed for education. It is free (up to 10-minute long videos) and there are how-to guides and resources on the website. • **Shadow Puppet Edu** is a highly rated (free) student-friendly video creation app available on iTunes. A video tutorial walks students through the fairly intuitive creation process. Lots of teacher resources are included in-app. • **Adobe Spark** is a free video creation app from Adobe that is offered free to students and teachers. Features an easy-to-use dashboard and lots of online help and resources. • **Animoto** is a highly rated video creation and editing app that offers teachers free accounts for up to 50 students. • **PowToons** offers a free, easy-to-use version that allows students to create a cross between an animated presentation and a video; highly engaging. • Canva – This well-known photo-editing tool for iOS and Chrome also has a free infographic creator. Some great templates and tips. • Easel.ly - Web-based tool with dozens of customizable templates. Library with basic shapes. Change fonts, colors, text styles and sizes. Great videos and tip about design. There is a free, limited version.



Life Cycle Stages



NOTES*: Use spaces on diagram above or provide detail on a separate piece of paper.*

Project Option 2: Sustainable Packaging Design Challenge (Grades 6-12)

The following project plan focuses on the challenges involved in packaging the goods we use in our daily lives. Students are asked to take an inventory of what types of packaging materials come into or are used in their homes over the course of two days. After some exploration of plastics (the predominant material used for packaging), they are challenged to use some of the ideas they learned about biomimicry in Module 2 in order to re-design packaging for an item that they use. The attached project plan follows the format of many of our ProjectEngin Engineering Design challenges and contains suggested videos, resources for background information, quick builds to “hook” students, and student Engineering Notebook worksheets. The project can be shortened or modified as needed. It is also designed to be used in a distance learning model as well as in-class scenario.

Sustainable Packaging Project Plan

Project Title: Re-Engineering Packaging

Topic: Biomimicry and sustainability; structure and function; material science

Grade Level: Grades 6-12	**Estimated Class Time:** Can be customized; 7 -15 class hours

Challenge:

Packaging is one of the most extensive uses of non-biodegradable materials, primarily plastics. In this project, students explore the reasons for and designs of various types of packaging. Each design team then chooses one type of packaging (or product that requires) to redesign using a more sustainable approach by either (1) using materials found in Nature or by (2) using biomimicry to emulate structures found in the natural world.

This design challenge can be used on a "capstone" basis the third module of the Designed World Series. Module 1 introduced students to the role and impact of Engineering in their daily lives. Module 2 introduced the idea of biomimicry and Nature's approach to sustainable design and engineering.

Curricular Connections	Skills Focus
Science Impact resistance; forces; material structure and properties; food safety	Critical Thinking Determine what is critical in a package design; trade-offs in packaging choices versus environmental impacts
Mathematics Area to volume calculations; 2-dimensional to 3-dimensional visualization; cost/benefit analysis	Collaboration Involves a team with different roles - material choice, overall design, visual impact
Art Aesthetic appeal of packaging; design of logo or branding	Creativity Constraints of minimal environmental impact while meeting packaging goals enhances creative choices
Social Studies Impact of plastic packaging on culture and environment	Communication Different roles of team members create need for communication; packaging design is key to "branding"
ELA Labeling; technical writing on packaging	Empathy Understand end user/consumer needs and appeal
Other:	Global View Wide ranging impacts of packaging material consumption and disposal of waste
	Systems Thinking Feedback loops based on materials use and disposal; carbon, water, and energy footprints of materials
	Other: Issue is current as we we rely more on shipping and delivery of goods; need for disposal materials to limit exposure to infection

Overall Plan	
Hook	Choose any of the following videos focused on new Packaging Materials – including mushrooms! 1. Ecovative Design turns agricultural waste and mushroom fibers into packaging https://youtu.be/ACoA6vUD-h8 2. Nova episode about mushroom materials https://youtu.be/OpDXD0WBZuQ 3. Fungus: Plastics of the Future. Discusses the development of fungi plus 3D printing as a viable replacement for plastic https://youtu.be/jnMXH5TqqG8 4. National Geographic video: Engineers and designers are utilizing the natural abilities of various fungi for antibiotics, building materials, water filtration. https://youtu.be/BlcKBKJ8uro
Engagement Activity or Quick Build	Options for both in class and distance learning: In Class: See attached Can-Holder Quick Build - students are challenged to re-design a common plastic object using simple materials Distance Learning: See attached World of Waste Investigation. Students are asked to track and analyze the type and amount of packaging waste that enters their home over two days.
Background Instruction	Practical Action Plastics Challenge has a wide range of background information, resources, and activities to support learning about issues related to plastic use and packaging challenges. Highly recommended. https://practicalaction.org/schools/plastics-challenge/ The video "From Oil to Plastic" (https://www.youtube.com/watch?v=IwdUwffecsM) provides a concise overview of plastics manufacturing. TedEd has a great video lesson tracing what happens to different types of plastics that we throw away - https://ed.ted.com/lessons/what-really-happens-to-the-plastic-you-throw-away-emma-bryce
Background Research	Plastics 101 from the American Chemistry Council - background on all things plastics https://plastics.americanchemistry.com/Plastics-101/ Summary of different types of plastics from Nat Geo https://www.nationalgeographic.com/news/2018/05/plastics-explained/ Attached articles: "Production, use, and fate of all plastics ever made" "Food packaging and its environmental impact" Research into biomimicry from Designed World Module 2: Engineering Naturally (can be found at https://myedexpert.com/item/engineering-naturally-designed-world-module-2/)

Engineering Design Process	
Know Your Problem • Know your end user • Identify constraints • Define criteria	1. Student should choose (or be assigned) a specific product or purpose to design new, sustainable packaging for 2. Students should identify end-user and possible constraints and complete the "Identifying Constraints" form as a team (attached) 3. Students should develop and rank criteria in order of importance. The "Criteria Ranking" form can be used for this (attached)
Know Your Options • Research • Brainstorm	1. Students should conduct any needed additional research before brainstorming solutions (see Background Research and Instruction sections above for possible resources). Topics for research include plastics chemistry and manufacturing, packaging design, and materials and structures that Nature uses for protection and transport. 2. Students brainstorm possible solutions. The Brainstorm Summary form (attached) can be used to record and categorize ideas. Miro, Popplet, and MindMeister are some good options for online brainstorming apps. At the end of this stage, the team should complete the Initial Design Plan (attached) as they move on to developing a solution and building a prototype.
Develop a Solution • Choose a design • Identify needed materials • Create a plan; make a sketch • Build the prototype • Present the prototype • Get feedback • Plan modifications to make it better	As they complete the previous steps, student groups will settle on a possible solution and begin the prototyping stage. They should follow the Initial Design Plan and keep constraints and criteria in mind as they create their prototype. Distance Learning: It may be easier for teams to create something other than a physical product prototype. Options that work well include PowToons or video marketing campaigns that can be shared with the class. Teams should be reminded to highlight connections to constraints and criteria in any graphics that they create. Submit Final Design Summary (attached) and any required final documentation

Eco-Can Carrier! – Teacher Guide

QUICK BUILD CHALLENGE: Design an eco-friendly soda carrier that won’t hurt the environment, wildlife, or pollute.

MATERIALS:

6 full cans of soda
1 piece of Cardboard (10” x 10”) 2
sheets of Copy Paper
12” Duct Tape

1 Wax paper
12” String
6 Popsicle Sticks
4 Rubber bands

Instructions:

1. Introduce design challenge and demonstrate the problem with plastic rings used to hold the cans you bought for class.
2. Give each student a rubber band and ask them to put it around their wrist. Challenge students to get it off using only the hand the rubber band is on. This is what animals caught in plastic can-carriers experience.
3. Divide students into teams of 3 to 4.
4. Discuss design constraints (limitations) with class.
5. Discuss design criteria with class. Guide students through identifying design criteria by discussing what some of the goals of the holder are. *Teacher Note: Encourage each team to work together to identify a list of key criteria, then work independently as they rank them.*
6. Brainstorm possible solutions
7. Choose the design that best meets the criteria and constraints.
8. Make a prototype out of the materials provided. Consider different kinds of handles, ways to arrange the cans, how to remove the cans, and impact on environment.
9. Design teams test their prototype and record observations.
10. Using their testing results, have the class identify modifications to their design to better meet the needs of their design space and the end user.

World of Waste Investigation

How much waste do we get rid of in one day and what happens to this waste?

Objective: Collect, analyze, and graph data about the types and quantity of waste you generate in one day and estimate the amount of waste generated a in a week, month, and year. Explain how this waste effects the environment and better alternatives to use instead of plastic.

Introduction: **At home, identify the packaging waste you and your family use in the next two days.** Fill out the chart below. Record your lists based on what *you **ACTUALLY** do* rather than what you can possibly do.

Items you throw away	Items you recycle	Items you re-use

1) Which types (i.e. plastics, glass, metal, paper) of items do you typically throw away?

   Recycle?

   Re-use?

2) What do you think happens to waste that you throw away?

3) After monitoring and recording your waste for two days, share your results with the class.

Analysis:

1) Where did most of your class' waste come from? Why do you think this was the most common type of waste?

2) How much of this type of waste was recycled? Did this surprise you? Brainstorm possible reasons for why this type of waste did or did not get recycled.

3) Did your behavior change because you were monitoring the items you use, throw away and recycle in a day? If so, in what way? If not, do you think you would be more aware now after completing this activity?

Optional Extension: What happens to our trash?

Reading and images from: How Landfills Work
Ph.D. Freudenrich - http://science.howstuffworks.com/environmental/green-science/landfill9.htm

You have just finished your meal at a fast food restaurant and you throw your uneaten food, food wrappers, drink cup, utensils and napkins into the trash can. You don't think about that waste again. On trash pickup day in your neighborhood, you push your can out to the curb, and workers dump the contents into a big truck and haul it away. You don't have to think about that waste again, either. But maybe you have wondered, as you watch the trash truck pull away, just where that garbage ends up.

Americans generate trash at an astonishing rate of 4.6 pounds (2.1 kilograms) per day per person, which translates to 251 million tons (228 million metric tons) per year [source: EPA]. This is almost twice as much trash per person as most other major countries. What happens to this trash? Some gets recycled or recovered and some is burned, but the majority is buried in landfills.

The trash production in the United States has almost tripled since 1960. This trash is handled in various ways. About 32.5 percent of the trash is recycled or composted, 12.5 percent is burned and 55 percent is buried in landfills [source: EPA]. The amount of trash buried in landfills has doubled since 1960. The United States ranks about in the middle of the major countries (United Kingdom, Canada, Germany, France and Japan) in landfill disposal. The United Kingdom ranks highest, burying about 90 percent of its solid waste in landfills.

There are two ways to bury trash:

- **Dump** - an open hole in the ground where trash is buried and that has various animals (rats, mice, birds) swarming around. (This is most people's idea of a landfill!)
- **Landfill** - carefully designed structure built into or on top of the ground in which trash is isolated from the surrounding environment (groundwater, air, rain). This isolation is accomplished with a bottom liner and daily covering of soil. A **sanitary landfill** uses a clay liner to isolate the trash from the environment. A **municipal solid waste (MSW) landfill** uses a synthetic (plastic) liner to isolate the trash from the environment

Trash put in a landfill will stay there for a very long time. Inside a landfill, there is little oxygen and little moisture. Under these conditions, trash does not break down very rapidly. In fact, when old landfills have been excavated or sampled, 40-year-old newspapers have been found with easily readable print. Landfills are not designed to break down trash, merely to bury it. When a landfill closes, the site, especially the groundwater, must be monitored and maintained for up to 30 years!

1) Explain what happens to our trash that is thrown away.

2) List 2 facts about waste from the article that you did not know before or surprised you.

3) What is one question you still have or are wondering about?

PLASTICS

Production, use, and fate of all plastics ever made

Roland Geyer,[1]* Jenna R. Jambeck,[2] Kara Lavender Law[3]

Plastics have outgrown most man-made materials and have long been under environmental scrutiny. However, robust global information, particularly about their end-of-life fate, is lacking. By identifying and synthesizing dispersed data on production, use, and end-of-life management of polymer resins, synthetic fibers, and additives, we present the first global analysis of all mass-produced plastics ever manufactured. We estimate that 8300 million metric tons (Mt) as of virgin plastics have been produced to date. As of 2015, approximately 6300 Mt of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. If current production and waste management trends continue, roughly 12,000 Mt of plastic waste will be in landfills or in the natural environment by 2050.

INTRODUCTION

A world without plastics, or synthetic organic polymers, seems unimaginable today, yet their large-scale production and use only dates back to ~1950. Although the first synthetic plastics, such as Bakelite, appeared in the early 20th century, widespread use of plastics outside of the military did not occur until after World War II. The ensuing rapid growth in plastics production is extraordinary, surpassing most other man-made materials. Notable exceptions are materials that are used extensively in the construction sector, such as steel and cement (*1*, *2*).

Instead, plastics' largest market is packaging, an application whose growth was accelerated by a global shift from reusable to single-use containers. As a result, the share of plastics in municipal solid waste (by mass) increased from less than 1% in 1960 to more than 10% by 2005 in middle- and high-income countries (*3*). At the same time, global solid waste generation, which is strongly correlated with gross national income per capita, has grown steadily over the past five decades (*4*, *5*).

The vast majority of monomers used to make plastics, such as ethylene and propylene, are derived from fossil hydrocarbons. None of the commonly used plastics are biodegradable. As a result, they accumulate, rather than decompose, in landfills or the natural environment (*6*). The only way to permanently eliminate plastic waste is by destructive thermal treatment, such as combustion or pyrolysis. Thus, near-permanent contamination of the natural environment with plastic waste is a growing concern. Plastic debris has been found in all major ocean basins (*6*), with an estimated 4 to 12 million metric tons (Mt) of plastic waste generated on land entering the marine environment in 2010 alone (*3*). Contamination of freshwater systems and terrestrial habitats is also increasingly reported (*7*–*9*), as is environmental contamination with synthetic fibers (*9*, *10*). Plastic waste is now so ubiquitous in the environment that it has been suggested as a geological indicator of the proposed Anthropocene era (*11*).

We present the first global analysis of all mass-produced plastics ever made by developing and combining global data on production, use, and end-of-life fate of polymer resins, synthetic fibers, and additives into a comprehensive material flow model. The analysis includes thermoplastics, thermosets, polyurethanes (PURs), elastomers, coatings, and sealants but focuses on the most prevalent resins and fibers: high-density polyethylene (PE), low-density and linear low-density PE, polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethylene terephthalate (PET), and PUR resins; and polyester, polyamide, and acrylic (PP&A) fibers. The pure polymer is mixed with additives to enhance the properties of the material.

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RESULTS AND DISCUSSION

Global production of resins and fibers increased from 2 Mt in 1950 to 380 Mt in 2015, a compound annual growth rate (CAGR) of 8.4% (table S1), roughly 2.5 times the CAGR of the global gross domestic product during that period (*12*, *13*). The total amount of resins and fibers manufactured from 1950 through 2015 is 7800 Mt. Half of this—3900 Mt—was produced in just the past 13 years. Today, China alone accounts for 28% of global resin and 68% of global PP&A fiber production (*13*–*15*). Bio-based or biodegradable plastics currently have a global production capacity of only 4 Mt and are excluded from this analysis (*16*).

We compiled production statistics for resins, fibers, and additives from a variety of industry sources and synthesized them according to type and consuming sector (table S2 and figs. S1 and S2) (*12*–*24*). Data on fiber and additives production are not readily available and have typically been omitted until now. On average, we find that nonfiber plastics contain 93% polymer resin and 7% additives by mass. When including additives in the calculation, the amount of nonfiber plastics (henceforth defined as resins plus additives) manufactured since 1950 increases to 7300 Mt. PP&A fibers add another 1000 Mt. Plasticizers, fillers, and flame retardants account for about three quarters of all additives (table S3). The largest groups in total nonfiber plastics production are PE (36%), PP (21%), and PVC (12%), followed by PET, PUR, and PS (<10% each). Polyester, most of which is PET, accounts for 70% of all PP&A fiber production. Together, these seven groups account for 92% of all plastics ever made. Approximately 42% of all nonfiber plastics have been used for packaging, which is predominantly composed of PE, PP, and PET. The building and construction sector, which has used 69% of all PVC, is the next largest consuming sector, using 19% of all nonfiber plastics (table S2).

We combined plastic production data with product lifetime distributions for eight different industrial use sectors, or product categories, to model how long plastics are in use before they reach the end of their useful lifetimes and are discarded (*22*, *25*–*29*). We assumed log-normal distributions with means ranging from less than 1 year, for packaging, to decades, for building and construction (Fig. 1). This is a commonly used modeling approach to estimating waste generation

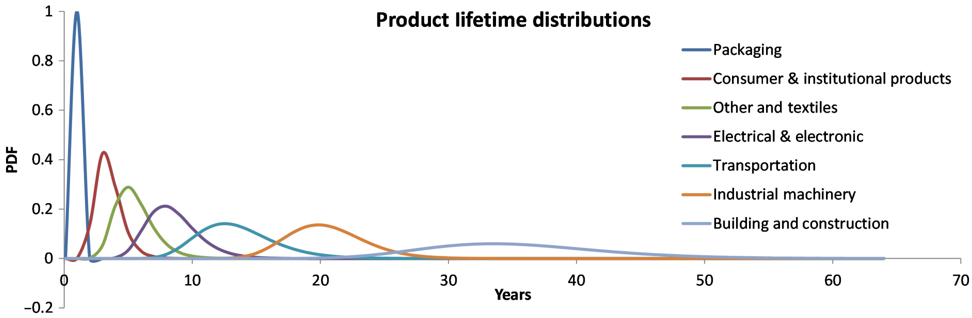

Fig. 1. Product lifetime distributions for the eight industrial use sectors plotted as log-normal probability distribution functions (PDF). Note that sectors other and textiles have the same PDF.

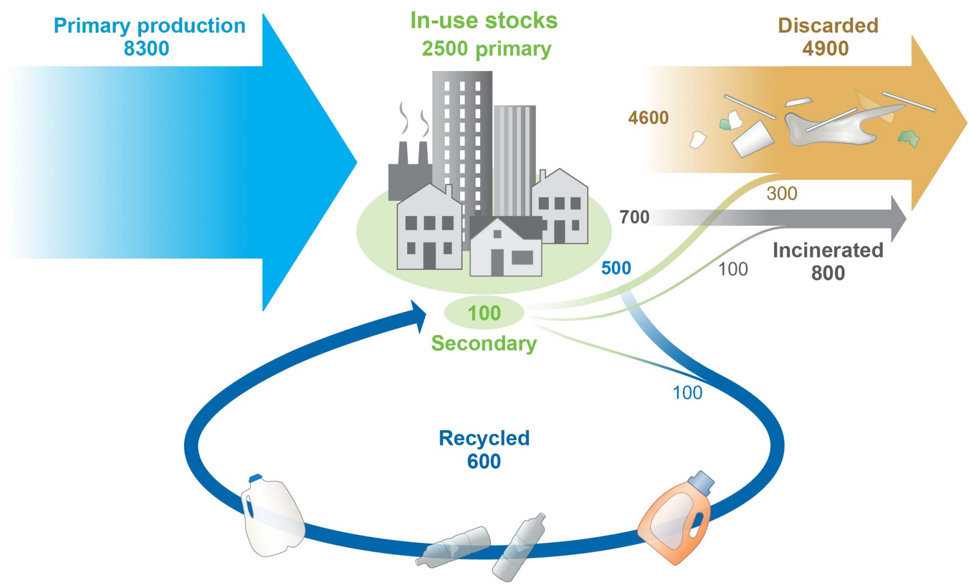

Fig. 2. Global production, use, and fate of polymer resins, synthetic fibers, and additives (1950 to 2015; in million metric tons).

for specific materials (*22*, *25*, *26*). A more direct way to measure plastic waste generation is to combine solid waste generation data with waste characterization information, as in the study of Jambeck *et al.* (*3*). However, for many countries, these data are not available in the detail and quality required for the present analysis.

We estimate that in 2015, 407 Mt of primary plastics (plastics manufactured from virgin materials) entered the use phase, whereas 302 Mt left it. Thus, in 2015, 105 Mt were added to the in-use stock. For comparison, we estimate that plastic waste generation in 2010 was 274 Mt, which is equal to the independently derived estimate of 275 Mt by Jambeck *et al.* (*3*). The different product lifetimes lead to a substantial shift in industrial use sector and polymer type between plastics entering and leaving use in any given year (tables S4 and S5 and figs. S1 to S4). Most of the packaging plastics leave use the same year they are produced, whereas construction plastics leaving use were produced decades earlier, when production quantities were much lower. For example, in 2015, 42% of primary nonfiber plastics produced (146 Mt) entered use as packaging and 19% (65 Mt) as construction, whereas nonfiber plastic waste leaving use was 54% packaging (141 Mt) and only 5% construction (12 Mt). Similarly, in 2015, PVC accounted for 11% of nonfiber plastics production (38 Mt) and only 6% of nonfiber plastic waste generation (16 Mt).

By the end of 2015, all plastic waste ever generated from primary plastics had reached 5800 Mt, 700 Mt of which were PP&A fibers. There are essentially three different fates for plastic waste. First, it can be recycled or reprocessed into a secondary material (*22*, *26*). Recycling delays, rather than avoids, final disposal. It reduces future plastic waste generation only if it displaces primary plastic production (*30*); however, because of its counterfactual nature, this displacement is extremely difficult to establish (*31*). Furthermore, contamination and the mixing of polymer types generate secondary plastics of limited or low technical and economic value. Second, plastics can be destroyed thermally. Although there are emerging technologies, such as pyrolysis, which extracts fuel from plastic waste, to date, virtually all thermal destruction has been by incineration, with or without energy recovery. The environmental and health impacts of waste incinerators strongly depend on emission control technology, as well as incinerator design and operation. Finally, plastics can be discarded and either contained in a managed system, such as sanitary landfills, or left uncontained in open dumps or in the natural environment.

We estimate that 2500 Mt of plastics—or 30% of all plastics ever produced—are currently in use. Between 1950 and 2015, cumulative waste generation of primary and secondary (recycled) plastic waste amounted to 6300 Mt. Of this, approximately 800 Mt (12%) of plastics

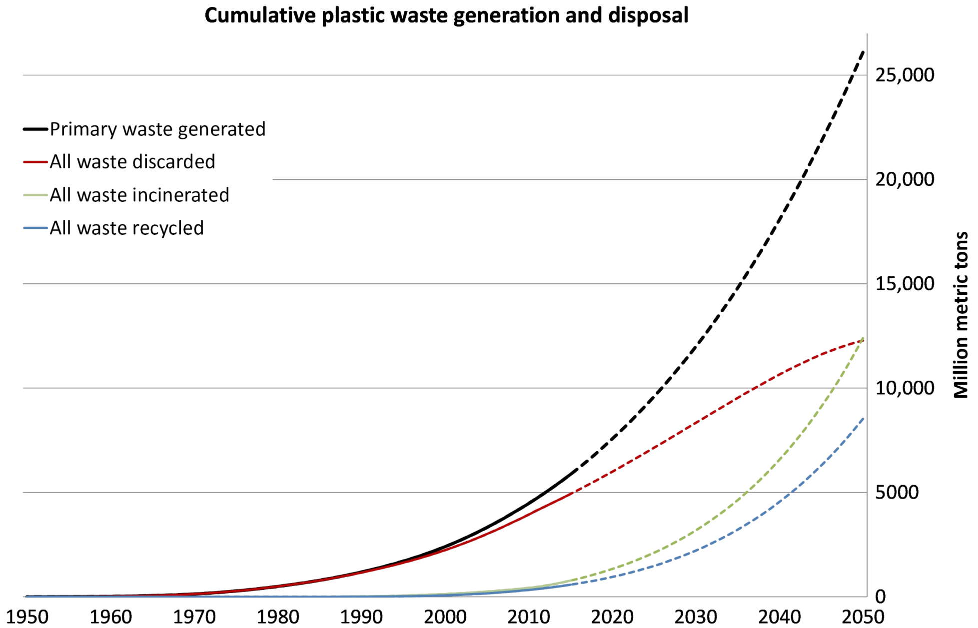

Fig. 3. Cumulative plastic waste generation and disposal (in million metric tons). Solid lines show historical data from 1950 to 2015; dashed lines show projections of historical trends to 2050.

have been incinerated and 600 Mt (9%) have been recycled, only 10% of which have been recycled more than once. Around 4900 Mt—60% of all plastics ever produced—were discarded and are accumulating in landfills or in the natural environment (Fig. 2). Of this, 600 Mt were PP&A fibers. None of the mass-produced plastics biodegrade in any meaningful way; however, sunlight weakens the materials, causing fragmentation into particles known to reach millimeters or micrometers in size (*32*). Research into the environmental impacts of these "microplastics" in marine and freshwater environments has accelerated in recent years (*33*), but little is known about the impacts of plastic waste in land-based ecosystems.

Before 1980, plastic recycling and incineration were negligible. Since then, only nonfiber plastics have been subject to significant recycling efforts. The following results apply to nonfiber plastic only: Global recycling and incineration rates have slowly increased to account for 18 and 24%, respectively, of nonfiber plastic waste generated in 2014 (figs. S5 and S6). On the basis of limited available data, the highest recycling rates in 2014 were in Europe (30%) and China (25%), whereas in the United States, plastic recycling has remained steady at 9% since 2012 (*12*, *13*, *34*–*36*). In Europe and China, incineration rates have increased over time to reach 40 and 30%, respectively, in 2014 (*13*, *35*). However, in the United States, nonfiber plastics incineration peaked at 21% in 1995 before decreasing to 16% in 2014 as recycling rates increased, with discard rates remaining constant at 75% during that time period (*34*). Waste management information for 52 other countries suggests that in 2014, the rest of the world had recycling and incineration rates similar to those of the United States (*37*). To date, end-of-life textiles (fiber products) do not experience significant recycling rates and are thus incinerated or discarded together with other solid waste.

Primary plastics production data describe a robust time trend throughout its entire history. If production were to continue on this curve, humankind will have produced 26,000 Mt of resins, 6000 Mt of PP&A fibers, and 2000 Mt of additives by the end of 2050. Assuming consistent use patterns and projecting current global waste management trends to 2050 (fig. S7), 9000 Mt of plastic waste will have been recycled, 12,000 Mt incinerated, and 12,000 Mt discarded in landfills or the natural environment (Fig. 3).

Any material flow analysis of this kind requires multiple assumptions or simplifications, which are listed in Materials and Methods, and is subject to considerable uncertainty; as such, all cumulative results are rounded to the nearest 100 Mt. The largest sources of uncertainty are the lifetime distributions of the product categories and the plastic incineration and recycling rates outside of Europe and the United States. Increasing/decreasing the mean lifetimes of all product categories by 1 SD changes the cumulative primary plastic waste generation (for 1950 to 2015) from 5900 to 4600/6200 Mt or by −4/+5%. Increasing/decreasing current global incineration and recycling rates by 5%, and adjusting the time trends accordingly, changes the cumulative discarded plastic waste from 4900 (for 1950 to 2015) to 4500/5200 Mt or by −8/+6%.

The growth of plastics production in the past 65 years has substantially outpaced any other manufactured material. The same properties that make plastics so versatile in innumerable applications—durability and resistance to degradation—make these materials difficult or impossible for nature to assimilate. Thus, without a well-designed and tailor-made management strategy for end-of-life plastics, humans are conducting a singular uncontrolled experiment on a global scale, in which billions of metric tons of material will accumulate across all major terrestrial and aquatic ecosystems on the planet. The relative advantages and disadvantages of dematerialization, substitution, reuse, material recycling, waste-to-energy, and conversion technologies must be carefully considered to design the best solutions to the environmental challenges posed by the enormous and sustained global growth in plastics production and use.

MATERIALS AND METHODS

Plastic production

The starting point of the plastic production model is global annual pure polymer (resin) production data from 1950 to 2015, published by the Plastics Europe Market Research Group, and global annual fiber production data from 1970 to 2015 published by The Fiber Year and Tecnon OrbiChem (table S1). The resin data closely follow a second-order polynomial time trend, which generated a fit of $R^2 = 0.9968$. The fiber data closely follow a third-order polynomial time trend, which generated a fit of $R^2 = 0.9934$. Global breakdowns of total production by polymer type and industrial use sector were derived from annual market and polymer data for North America, Europe, China, and India (table S2) (*12*, *13*, *19–24*). U.S. and European data are available for 2002 to 2014. Polymer type and industrial use sector breakdowns of polymer production are similar across countries and regions.

Global additives production data, which are not publicly available, were acquired from market research companies and cross-checked for consistency (table S3) (*17*, *18*). Additives data are available for 2000 to 2014. Polymer type and industrial use sector breakdowns of polymer production and the additives to polymer fraction were both stable over the time period for which data are available and thus assumed constant throughout the modeling period of 1950–2015. Any errors in the early decades were mitigated by the lower production rates in those years. Additives data were organized by additive type and industrial use sector and integrated with the polymer data. $P_i\ (t)$ denotes the amount of primary plastics (that is, polymers plus additives) produced in year t and used in sector i (fig. S1).

Plastic waste generation and fate

Plastics use was characterized by discretized log-normal distributions, $\mathrm{LTD_i}\ (j)$, which denotes the fraction of plastics in industrial use sector i used for j years (Fig. 1). Mean values and SDs were gathered from published literature (table S4) (*22*, *25–29*). Product lifetimes may vary significantly across economies and also across demographic groups, which is why distributions were used and sensitivity analysis was conducted with regard to mean product lifetimes. The total amount of primary plastic waste generated in year t was calculated as $\mathrm{PW}\ (t) = \Sigma_{i=1}^{8}\Sigma_{j=1}^{65}P_i(t-j)\cdot\mathrm{LTD}_i(j)$ (figs. S3 and S4). Secondary plastic waste generated in year t was calculated as the fraction of total plastic waste that was recycled k years ago, $\mathrm{SW}\ (t) = [\mathrm{PW}\ (t-k) + \mathrm{SW}\ (t-k)][\mathrm{RR}\ (t-k)]$, where k is the average use time of secondary plastics and $\mathrm{RR}\ (t-k)$ is the global recycling rate in year $t-k$. Amounts of plastic waste discarded and incinerated are calculated as $\mathrm{DW}(t) = [\mathrm{PW}(t) + \mathrm{SW}(t)\cdot\mathrm{DR}(t)$ and $\mathrm{IW}(t) = [\mathrm{PW}(t) + \mathrm{SW}(t)]\cdot\mathrm{IR}(t)$, with $\mathrm{DR}(t)$ and $\mathrm{IR}(t)$ being the global discard and incineration rates in year t (fig. S5). Cumulative values at time T were calculated as the sum over all $T-1950$ years of plastics mass production. Examples are cumulative primary production $\mathrm{CP}_i(T) = \Sigma_{t=1950}^{T}P_i(t)$ and cumulative primary plastic waste generation, $\mathrm{CPW}(T) = \Sigma_{t=1950}^{T}\mathrm{PW}(t)$ (Fig. 3).

Recycling, incineration, and discard rates

Time series for resin, that is, nonfiber recycling, incineration, and discard rates were collected separately for four world regions: the United States, the EU-28 plus Norway and Switzerland, China, and the rest of the world. Detailed and comprehensive solid waste management data for the United States were published by the U.S. Environmental Protection Agency dating back to 1960 (table S7) (*34*). European data were from several reports by PlasticsEurope, which collectively cover 1996 to 2014 (*12*, *13*, *38*). Chinese data were synthesized and reconciled from the English version of the China Statistical Yearbook, translations of Chinese publications and government reports, and additional waste management literature (*35*, *36*, *39–41*). Waste management for the rest of the world was based on World Bank data (*37*). Time series for global recycling, incineration, and discard rates (fig. S5) were derived by adding the rates of the four regions weighted by their relative contribution to global plastic waste generation. In many world regions, waste management data were sparse and of poor quality. For this reason, sensitivity analysis with regard to waste management rates was conducted.

The resulting global nonfiber recycling rate increased at a constant 0.7% per annum (p.a.) between 1990 and 2014. If this linear trend is assumed to continue, the global recycling rate would reach 44% in 2050. The global nonfiber incineration rate has grown more unevenly but, on average, increased 0.7% p.a. between 1980 and 2014. Assuming an annual increase of 0.7% between 2014 and 2050 yielded a global incineration rate of 50% by 2050. With those two assumptions, global discard rate would decrease from 58% in 2014 to 6% in 2050 (fig. S7). The dashed lines in Fig. 3 are based on those assumptions and therefore simply forward projections of historical global trends and should not be mistaken for a prediction or forecast. There is currently no significant recycling of synthetic fibers. It was thus assumed that end-of-life textiles are incinerated and discarded together with all other municipal solid waste.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/7/e1700782/DC1

fig. S1. Global primary plastics production (in million metric tons) according to industrial use sector from 1950 to 2015.

fig. S2. Global primary plastics production (in million metric tons) according to polymer type from 1950 to 2015.

fig. S3. Global primary plastics waste generation (in million metric tons) according to industrial use sector from 1950 to 2015.

fig. S4. Global primary plastics waste generation (in million metric tons) according to polymer type from 1950 to 2015.

fig. S5. Estimated percentage of global (nonfiber) plastic waste recycled, incinerated, and discarded from 1950 to 2014 [(*12*, *13*, *34–42*) and table S7].

fig. S6. Annual global primary and secondary plastic waste generation TW (t), recycling RW (t), incineration IW (t), and discard DW (t) (in million metric tons) from 1950 to 2014.

fig. S7. Projection of global trends in recycling, incineration, and discard of plastic waste from 1980 to 2014 (to the left of vertical black line) to 2050 (to the right of vertical black line).

table S1. Annual global polymer resin and fiber production in million metric tons (*12–15*).

table S2. Share of total polymer resin production according to polymer type and industrial use sector calculated from data for Europe, the United States, China, and India covering the period 2002–2014 (*12*, *13*, *19–24*).

table S3. Share of additive type in global plastics production from data covering the period 2000–2014 (*17*, *18*).

table S4. Baseline mean values and SDs used to generate log-normal product lifetime distributions for the eight industrial use sectors used in this study (*22*, *25–29*).

table S5. Global primary plastics production and primary waste generation (in million metric tons) in 2015 according to industrial use sector.

table S6. Global primary plastics production and primary waste generation (in million metric tons) in 2015 according to polymer type/additive.

table S7. Additional data sources for U.S. plastics recycling and incineration.

table S8. Complete list of data sources.

REFERENCES AND NOTES

1. World Steel Association (WSA), "Steel Statistical Yearbooks 1978 to 2016;" www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook-.html.
2. U.S. Geological Survey (USGS), "Cement Statistics and Information;" https://minerals.usgs.gov/minerals/pubs/commodity/cement/.
3. J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan, K. L. Law, Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015).
4. D. Hoornweg, P. Bhada-Tata, C. Kennedy, Environment: Waste production must peak this century. *Nature* **502**, 615–617 (2013).
5. D. C. Wilson, *Global Waste Management Outlook* (International Solid Waste Association and United National Environment Programme, 2015).

6. D. K. A. Barnes, F. Galgani, R. C. Thompson, M. Barlaz, Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. B* **364**, 1985–1998 (2009).
7. M. Wagner, C. Scherer, D. Alvarez-Muñoz, N. Brennholt, X. Bourrain, S. Buchinger, E. Fries, C. Grosbois, J. Klasmeier, T. Marti, S. Rodriguez-Mozaz, R. Urbatzka, A. D. Vethaak, M. Winther-Nielsen, G. Geifferscheid, Microplastics in freshwater ecosystems: What we know and what we need to know. *Environ. Sci. Eur.* **26**, 12 (2014).
8. M. C. Rillig, Microplastic in terrestrial ecosystems and the soil? *Environ. Sci. Technol.* **46**, 6453–6454 (2012).
9. K. A. V. Zubris, B. K. Richards, Synthetic fibers as an indicator of land application of sludge. *Environ. Pollut.* **138**, 201–211 (2005).
10. R Dris, J Gasperi, C Mirande, C Mandin, M Guerrouache, V Langlois, B. Tassin, A first overview of textile fibers, including microplastics, in indoor and outdoor environments. *Environ. Pollut.* **221**, 453–458 (2016).
11. J. Zalasiewicz, Colin N. Waters, Juliana Ivar do Sul, Patricia L. Corcoran, Anthony D. Barnosky, Alejandro Cearreta, Matt Edgeworth, Agnieszka Gałuszka, Catherine Jeandel, Reinhold Leinfelder, J.R. McNeill, Will Steffen, Colin Summerhayes, Michael Wagreich, Mark Williams, Alexander P. Wolfe, Yasmin Yonan, The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. *Anthropocene* **13**, 4–17 (2016).
12. PlasticsEurope, *The Compelling Facts About Plastics: An Analysis of Plastic Production, Demand and Recovery for 2006 in Europe* (PlasticsEurope, 2006).
13. PlasticsEurope, *Plastics—The Facts 2016: An Analysis of European Plastics Production, Demand and Waste Data* (PlasticsEurope, 2016).
14. The Fiber Year, *The Fiber Year 2017: World Survey on Textiles & Nonwovens* (The Fiber Year GmbH, 2017).
15. J. Mills, "Polyester & Cotton: Unequal Competitors," Tecnon OrbiChem presentation at Association Française Cotonnière (AFCOT), Deauville, France, 6 October 2011.
16. European Bioplastics, *Bioplastics—Facts and Figures* (European Bioplastics, 2017).
17. Global Industry Analysis (GIA), "Plastic Additives: A Global Strategic Business Report" (MCP-2122, GIA, 2008).
18. S. Rajaram, "Plastic Additives: The Global Market" (PLS022B, BCC Research, 2009).
19. American Chemistry Council (ACC), *Resin Review: The Annual Statistical Report of the North American Plastics Industry* (ACC, 2009).
20. Plastemart, "China leads in growth of polymers & plastic products;" www.plastemart.com/upload/Literature/chineseplasticandpolymergrowth.asp).
21. *Indian Petrochemical Industry: Country Paper from India*, Asia Petrochemical Industry Conference, Seoul, South Korea, 7 to 8 May 2015 (Chemical and Petrochemicals Manufacturers' Association India, 2016).
22. N. H. Mutha, M. Patel, V. Premnath, Plastics material flow analysis for India. *Resour. Conserv. Recycl.* **47**, 222–244 (2006).
23. American Chemistry Council (ACC), *Resin Review: The Annual Statistical Report of the North American Plastics Industry* (ACC, 2012).
24. American Chemistry Council (ACC), *Resin Review: The Annual Statistical Report of the North American Plastics Industry* (ACC, 2013).
25. J. Davis, R. Geyer, J. Ley, J. He, T. Jackson, R. Clift, A. Kwan, M. Sansom, Time-dependent material flow analysis of iron and steel in the UK: Part 2. Scrap generation and recycling. *Resour. Conserv. Recycl.* **51**, 118–140 (2007).
26. B. Kuczenski, R. Geyer, Material flow analysis of polyethylene terephthalate in the US, 1996–2007. *Resour. Conserv. Recycl.* **54**, 1161–1169 (2010).
27. S. Murakami, M. Oguchi, T. Tasaki, I. Daigo, S. Hashimoto, Lifespan of commodities, part I: The creation of a database and its review. *J. Ind. Ecol.* **14**, 598–612 (2010).
28. D. R. Cooper, A. C. H. Skelton, M. C. Moynihan, J. M. Allwood, Component level strategies for exploiting the lifespan of steel in products. *Resour. Conserv. Recycl.* **84**, 24–34 (2014).
29. Drycleaning Institute of Australia, *International Fair Claims Guide for Consumer Textiles Products* (Drycleaning Institute of Australia, 2015).
30. R. Geyer, B. Kuczenski, T. Zink, A. Henderson, Common misconceptions about recycling. *J. Ind. Ecol.* **20**, 1010–1017 (2015).
31. T. Zink, R. Geyer, D. Startz, Toward estimating displaced production from recycling: A case study of U.S. aluminum. *J. Ind. Ecol.* 10.1111/jiec.12557 (2017).
32. A. L. Andrady, *Plastics and Environmental Sustainability* (John Wiley & Sons, 2015).
33. C. M. Rochman, M. A. Browne, A. J. Underwood, J. A. van Franeker, R. C. Thompson, L. A. Amaral-Zettler, The ecological impacts of marine debris: Unraveling the demonstrated evidence from what is perceived. *Ecology* **97**, 302–312 (2016).
34. U.S. Environmental Protection Agency (EPA), *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2012* (EPA, 2014).
35. National Bureau of Statics of China, "Annual Data, China Statistical Yearbook, 1996-2016;" (www.stats.gov.cn/ENGLISH/Statisticaldata/AnnualData/).
36. M. Zhan-feng, Z. Bing, China plastics recycling industry in 2008. *China Plastics* **23**, 7 (2009).
37. D. Hoornweg, P. Bhada-Tata, *What a Waste: A Global Review of Solid Waste Management* (Urban Development Series Knowledge Papers, World Bank, 2012).
38. Consultic, *Post-Consumer Plastics Waste Management in European Countries 2014 – EU28 + 2 Countries*, Final report, PlasticsEurope, October 2015.
39. R. Linzner, S. Salhofer, Municipal solid waste recycling and the significance of the informal sector in urban China. *Waste Manage. Res.* **32**, 896–907 (2014).
40. National Development and Reform Commission of China, "Annual Report on Comprehensive Utilization of Resources in China 2014;" http://hzs.ndrc.gov.cn/zhly/201410/W020141015504221663989.pdf.
41. China Ministry of Commerce, "China Renewable Resources Recycling Industry Development Report 2016;" http://f.boolv.com/News/Image/20160811/201608110819469264.pdf.
42. U.S. Environmental Protection Agency (EPA), *Municipal Solid Waste in the Unites States: 2011 Facts and Figures* (EPA530-R-13-001, U.S. EPA, 2013).

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Food packaging and its environmental impact

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FOOD PACKAGING AND ITS ENVIRONMENTAL IMPACT

The Institute of Food Technologists has issued a Scientific Status Summary on food packaging and its impact on the environment. Here is a synopsis.

Advances in food processing and packaging play a primary role in keeping the United States food supply one of the safest in the world. Packaging protects food between processing and usage by the consumer. Following usage, food packaging must be removed in an environmentally responsible manner. Packaging technology must therefore balance food protection with other issues, including energy and material costs, heightened social and environmental consciousness, and strict regulations on pollutants and disposal of municipal solid waste (MSW).

MSW consists of items commonly thrown away, including packages, food scraps, yard trimmings, and durable items such as refrigerators and computers. Legislative and regulatory efforts to control packaging are based on the mistaken perception that packaging is the largest component of MSW. Instead, the Environmental Protection Agency (EPA, 2006) found that only approximately 31% of the MSW generated in 2005 was from packaging-related materials; this percentage has remained relatively constant since the 1990s despite an increase in the total amount of MSW. Non-packaging sources such as newsprint, telephone books, and office communications generate more than twice as much MSW.

Nevertheless, food packaging is a noteworthy contributor to MSW because food is the only product class typically consumed three times per day by virtually every person. Accordingly, food packaging accounts for almost two-thirds of total packaging waste by volume (Hunt et al., 1990). Moreover, food packaging is approximately 50% (by weight) of total packaging sales.

Although the specific knowledge available has changed since publication of "Effective Management of Food Packaging: From Production to Disposal," the Institute of Food Technologists' first Scientific Status Summary on the relationship between food packaging and MSW (IFT, 1991), the issue remains poorly understood, complicating efforts to address the environmental impact of discarded packaging materials.

Consequently, IFT has issued a new Scientific Status Summary that describes the role of food packaging in the food supply chain, the types of materials used in food packaging, and the impact of food packaging on the environment. Appearing in the April 2007 issue of *Journal of Food Science*, the new Summary, "Food Packaging—Roles, Materials, and Environmental Issues," provides an overview of EPA's solid waste management guidelines and other waste management options, addresses disposal methods of and legislation on packaging disposal, and describes the current sustainable cradle-to-cradle concept, which replaces the cradle-to-grave emphasis. The sustainability goal of the cradle-to-cradle concept is to recover sufficient materials and energy in a way that imposes zero impact on future generations. This article is a synopsis of the Scientific Status Summary.

Food Packaging Roles and Materials

The principal roles of food packaging are to protect food products from outside influences and distribution damage, to contain the food, and to provide consumers with ingredient and nutrition information. Traceability, convenience, and tamper indication are secondary functions of increasing importance. The goal of food packaging is to contain food in a cost-effective way that satisfies industry requirements and consumer desires, maintains food safety, and minimizes environmental impact.

Package design and construction play significant roles in determining the shelf life of a food product. The right selection of packaging materials and technologies maintains product quality and freshness during distribution and storage. Materials that have traditionally been used in food packaging include glass, metals (aluminum, foils and laminates, tinplate, and tin-free steel), paper and paperboards, and plastics. Today's food packages often combine several materials to exploit each material's functional or aesthetic properties.

As research to improve food packaging continues, advances in the field may affect the environmental impact of packaging. The table on p. 49 summarizes the advantages and disadvantages of various packaging materials in terms of product protection, product distribution, and environmental impact.

Waste Management Approach

Proper waste management is important to protect human health and the environment and to preserve natural resources. EPA's guidelines for solid waste management (EPA, 1989) emphasize the use of a hierarchical, integrated management approach involving source reduction, recycling, composting, combustion, and landfilling.

• **Source Reduction** (i.e., waste prevention) is reducing the amount and/or toxicity of the waste ultimately generated by changing the design, manufacture, purchase, or use of the original materials and products. EPA considers source reduction the best way to reduce the impact of solid waste on the environment because it avoids waste generation altogether.

Source reduction encompasses using less packaging, designing products to last longer, and reusing products and materials (EPA, 2002). Specific ways to achieve source reduction include using thinner gauges of packaging materials (i.e., lightweighting), purchasing durable goods, purchasing larger sizes (which use less packaging per unit volume) or refillable containers, and selecting nontoxic products.

• **Recycling** diverts materials from the waste stream to material recovery. Unlike reuse, which involves using a returned product in its original form, recycling involves reprocessing material into new products.

A typical recycling program entails collection, sorting and processing, manufacturing, and sale of recycled materials and products. Almost all packaging materials (glass, metal, thermoplastic, paper, and paperboard) are technically recyclable, but economics favor easily identified materials such as glass, metal, high-density polyethylene, and polyethylene terephthalate.

• **Composting**, considered by EPA as a form of recycling, is the controlled aerobic or biological degradation of organic materials, such as food and yard wastes. Accordingly, it involves arranging organic materials into piles and providing sufficient moisture for aerobic decomposition by microorganisms. Because organic materials make up a large component of total MSW (about 25% for food scraps and yard trimmings), composting is a valuable alternative to waste disposal.

• **Combustion,** the controlled burning of waste in a designated facility, is an increasingly attractive alternative for waste that cannot be recycled or composted. Reducing MSW volume by 70–90%, combustion incinerators can be equipped to produce steam that can either provide heat or generate electricity (waste-to-energy combustors). In 2004, the U.S. had 94 combustion

Scientific Status Summary Online

The IFT Scientific Status Summary, "Food Packaging—Roles, Materials, and Environmental Issues," appears in the April 2007 issue of *Journal of Food Science* and is also available online at www.ift.org. It was written by Kenneth Marsh, Ph.D. (ken@drkenmarsh.com), a Professional Member and Fellow of IFT, President of Kenneth S. Marsh & Associates, Ltd., and Executive Director of the Woodstock Institute for Science in Service to Humanity, 102B Ole Towne Sq., Central, SC 29630, and Betty Bugusu, Ph.D. (bbugusu@ift.org), Research Scientist, Dept. of Science and Technology Projects, Institute of Food Technologists, 1025 Connecticut Ave. N.W., Washington, DC 20036.

facilities, 89 of which were waste-to-energy facilities, with a process capacity of approximately 95,000 tons/day or about 13% of MSW (Kiser and Zannes, 2004).

• **Landfilling** provides environmentally sound disposal of any remaining MSW and the residues of recycling and combustion operations. As waste disposal methods, both landfilling and combustion are governed by regulations issued under subtitle D of the Resource Conservation and Recovery Act (40 CFR Parts 239–259). Thus, today's landfills are carefully designed structures in which waste is isolated from the surrounding environment and groundwater.

EPA also strives to motivate behavioral change in solid waste management through nonregulatory approaches such as pay-as-you-throw and *WasteWise*. In pay-as-you-throw systems, residents are charged for MSW services on the basis of the amount of trash they discard. This creates an incentive to generate less trash and increase material recovery through recycling and composting. *WasteWise* is a voluntary partnership between EPA and U.S. businesses, institutions, nonprofit organizations, and government agencies to prevent waste, promote recycling, and purchase products made from recycled contents.

Moreover, EPA's *Environmentally Preferable Purchasing* program helps federal agencies and other organizations purchase products with less effect on human health and the environment than other products that serve the same purpose. Pollution prevention is the primary focus, with a broader environmental scope than just waste reduction.

Disposal Statistics

The most recently compiled waste-generation statistics indicate that 245.7 million tons of MSW were generated in 2005, a decrease of 1.6 million tons since 2004 (EPA, 2006). The decrease in waste generation is partly attributable to the decreased rate of individual waste generation.

EPA analyzes MSW in two ways:

1. By materials: paper and paperboards, glass, metals, plastics, rubber and leather, textiles, wood, food scraps, and yard trimmings.

2. By major product categories: *containers and packaging* (mainly waste from food packaging, such as soft drink cans, milk cartons, and cardboard boxes); *nondurable goods* (newspapers, magazines, books, office paper, tissues, and paper plates and cups); *durable goods* (household appliances, furniture and furnishings, carpets and rugs, rubber tires, batteries, and electronics); and *other wastes*.

The containers and packaging category remained relatively constant at about 31% of the total waste generated between 2003 and 2005. EPA analysis of individual MSW generation rate shows a relatively constant rate of 4.5 lb/person/day since the 1990s, excluding the years 2000 and 2004 when it reached an all time high of 4.6 lb/person/day.

Even though waste generation has steadily grown since 1960, recovery through recycling has also increased. In 2005, 79 million tons (32.1%) of MSW was recovered through recycling and composting—slightly more than 58.4 million tons by recycling and 20.6 million tons by composting. The net per capita recovery reached an all-time high of 1.5 lb/person/day.

Recovery was the highest for the containers and packaging category (39.9% of amount generated), followed by nondurable goods (31%).

Despite the trend of increased recovery rates, the quantity of MSW requiring disposal has historically risen as a result of the increase in amounts generated. In 2005, approximately 168 million tons (68%) of MSW was discarded into the municipal waste stream—33.4 million tons (20%) combusted prior to disposal and 133.3 million tons directly discarded in landfills. The total amount of MSW generated has actually declined slightly since 2004; however, it is too early to determine if this is a change in the overall trend or merely a small variation that will not be maintained.

Limitations of Solid Waste Management Practices

Proper waste management requires careful planning, financing, collection, and transportation. Solid waste generation increases with population expansion and economic development and poses several challenges. For example, source reduction and convenience are often opposing goals in food packaging. Convenience features such as unit packages, dispensability, and microwavability usually require additional packaging. Similarly, tamper-indication features also add to the amount of waste generated.

Moreover, recycling and reuse are influenced by the costs of transporting, sorting, and cleaning collected materials. Many recycled materials, primarily plastics and paperboard, are restricted from food-contact applications. And both combustion and landfilling can have negative impacts on the environment through release of greenhouse gases or contamination of air and groundwater.

These aspects of packaging design and disposal must be weighed against environmental concerns in packaging. Because consumers dictate what is produced by what they choose to buy, at some point they need to evaluate whether the convenience and added safety are worth the increase in materials.

Choosing Packaging Materials

The key to successful packaging is to select the package material and design that best satisfy competing needs with regard to product char-

Packaging material properties, consumer and environmental issues, and cost

	Product characteristics/food compatibility		Consumer/marketing issues		Environmental issues		
Material	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**	**Cost**
Glass	• Impermeable to moisture and gases • Nonreactive (inert) • Withstands heat processing	•Brittle and breakable • Needs a separate closure	• Transparent: allows consumer to see product • Can be colored for light-sensitive products	• Poor portability: heavy and breakable • Relatively difficult to decorate	• Reusable • Recyclable • Often contains recycled content	• Heavy and bulky to transport	• Low-cost material, but somewhat costly to transport
Aluminum	• Impermeable to moisture and gases • Resistant to corrosion • Withstands heat processing	• Cannot be welded • Limited structural strength	• Easy to decorate • Lightweight • Good portability • Not breakable	• Limited shapes	• Recyclable • Lightweight • Economic incentive to recycle	• No disadvantages in rigid form • Separation difficulties in laminated form	• Relatively expensive, but value encourages recycling
Tinplate	• Impermeable • Strong and formable • Resistant to corrosion • Withstands heat processing	• Can react with foods; coating required	• Easy to decorate	• Typically requires a can opener to access product	• Recyclable • Magnetic, thus easily separated	• Heavier than aluminum	• Cheaper than aluminum
Tin-free steel	• Strong • Good resistance to corrosion • Withstands heat processing	• Difficult to weld, requires removal of coating • Less resistant to corrosion	• Easy to decorate	• Typically requires a can opener to access product	• Recyclable • Magnetic, thus easily separated	• Heavier than aluminum	• Cheaper than tinplate
Polyolefins	• Good moisture barrier • Strong • Resistant to chemicals	• Poor gas barrier	• Lightweight	• Slight haze or translucency	• Recyclable[a] • High-energy source for incineration	Easily recycled in semi-rigid form, but identification and separation more difficult for films	• Low cost
Polyester	• Strong • Withstands hot filling • Good barrier properties		• High clarity • Shatter resistant		• Recyclable[a,b]	• Easily recycled in rigid form, but identification and separation more difficult for films	• Inexpensive, but higher cost among plastics
Polyvinyl chloride	• Moldable • Resistant to chemicals		• High clarity		• Recyclable[a]	• Contains chlorine • Requires separating from other waste	• Inexpensive
Polyvinylidene chloride	• High barrier to moisture and gases • Heat sealable • Withstands hot filling		• Maintains product quality		• Recyclable[a]	• Contains chlorine • Requires separating from other waste	• Inexpensive, but higher cost among plastics
Polystyrene	• Available in rigid, film, and foamed form	• Poor barrier properties	• Good clarity		• Recyclable[a]	• Requires separating from other waste	• Inexpensive
Polyamide	• Strong • Good barrier properties				• Recyclable[a]	• Requires separating from other waste	• Inexpensive, but higher cost among plastics
Ethylene vinyl alcohol	• High barrier to gases and oils/fat	• Low moisture barrier, moisture sensitive	• Maintains product quality for oxygen-sensitive products		• Recyclable[a]	• Requires separating from other waste	• Inexpensive when used as thin film
Polylactic acid	• Biodegradable • Hydrolyzable				• Recyclable[a,c]	• Requires separating from other waste	• Relatively expensive
Paper & paperboard	• Very good strength-to-weight characteristics	• Poor barrier to light • Recycled content makes it unsuitable for food contact material	• Low-density materials • Easily decorated • Efficient, low-cost protection	• Moisture sensitive, loses strength with increasing humidity • Tears easily	• Made from renewable resources • Recyclable[b]		• Low cost
Laminates/ coextrusions	• Properties can be tailored for product needs		• Flexibility in design and characteristics		• Often allows for source reduction	• Layer separation is required	• Relatively expensive, but cost-effective for purpose

[a]All thermoplastics are technically recyclable and are recycled at the production environment, which contributes to lower cost. As inexpensive materials, post-consumer recycling competes with ease of separating and cleaning the materials.

[b]Recycled extensively for non-food product uses.

[c]Can be broken down to monomer level and reprocessed.

acteristics, marketing considerations (including distribution needs and consumer needs), environmental and waste management issues, and cost. Balancing so many factors is difficult and also requires a different analysis for each product.

Factors to be considered include the properties of the packaging material, the type of food to be packaged, possible food/package interactions, the intended market for the product, and the desired product shelf life. Other factors include environmental conditions during storage and distribution, product end-use, eventual package disposal, and costs related to the package throughout the production and distribution process.

Ideally, a food package would consist of materials that maintain the quality and safety of the food over time; are attractive, convenient, and easy to use while conveying all the desired information; are made from renewable resources, thereby generating no waste for disposal; and are inexpensive. Rarely, if ever, do today's food packages meet these lofty goals. Creating a food package is as much art as science, trying to achieve the best overall result without falling below acceptable standards in any single category.

From a product characteristic perspective, the inertness and absolute barrier properties of glass make it the best material for most packaging applications. However, the economic and safety disadvantages of glass boost the use of alternatives such as plastics. While plastics offer a wide range of properties and are used in various food applications, their permeability is less than optimal—unlike metal, which is totally impervious to light, moisture, and air.

Attempts to balance competing needs can sometimes be addressed by mixing packaging materials—such as combining different plastics through coextrusion or lamination—or by laminating plastics with foil or paper. Plain paper is not used to protect foods for long periods of time because it has poor barrier properties and is not heat sealable. When used as primary packaging (i.e., in contact with food), paper is almost always treated, coated, laminated, or impregnated with materials such as waxes, resins, or lacquers to improve functional and protective properties. In contrast, paperboard is seldom used for direct food contact, even though it is thicker than paper.

Ultimately, the consumer plays a significant role in package design. Consumer desires drive product sales, and the package is a significant sales tool. Although a bulk glass bottle might be the best material for fruit juice or a sports beverage, sales will be affected if competitors continue to use plastic to meet the consumer desire for a shatterproof, portable, single-serving container.

Minimizing Environmental Impact

The impact of packaging waste on the environment can be minimized by prudently selecting materials, following EPA guidelines, and reviewing expectations of packaging in terms of environmental impact. Still, the primary purpose of food packaging must continue to be maintaining the safety, wholesomeness, and quality of food. Knowledgeable efforts by industry, government, and consumers will promote continued improvement, and an understanding of the functional characteristics of packaging will prevent much of the well-intentioned but ill-advised solutions that do not adequately account for both pre- and post-consumer packaging factors. New materials, combinations, and technologies will allow the move from cradle-to-grave to cradle-to-cradle by eliminating negative environmental impact altogether (McDonough and Braungart, 2002).

To maintain a sustainable society, consumers must rethink their purchasing and convenience expectations as well as their material and energy usage to interact more intelligently with the world in which they live. **FT**

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REFERENCES

EPA. 1989. The solid waste dilemma: An agenda for action. EPA530-SW-89-019. Environmental Protection Agency, Washington, D.C.

EPA. 2002. Solid waste management: A local challenge with global impacts. EPA530-F-02-026.

EPA. 2006. Municipal solid waste in the United States: 2005 facts and figures. EPA530-R-06-011.

Hunt, R.G., Sellers, V.R., Franklin, W.E., Nelson, J.M., Rathje, W.L., Hughes, W.W., and Wilson, D.C. 1990. Estimates of the volume of MSW and selected components in trash cans and land fills. Report prepared by the Garbage Project and Franklins Associates Ltd. for the Council for Solid Waste Solutions, Tucson, Ariz.

IFT. 1991. Effective management of food packaging: From production to disposal. Inst. of Food Technologists scientific status summary by K.S. Marsh. Food Technol. 45(5): 225-234.

Kiser, J.V.L. and Zannes, M. 2004. The 2004 IWSA directory of waste-to-energy plants. Integrated Waste Services Assn., Washington, D.C.

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

Identifying Constraints and Their Impact

Constraint	Design Feature It Led To	If There Were No Constraint

Criteria Ranking Form

Rank	Criteria

Brainstorming Summary

Some teachers like to use a form like this for groups to summarize key ideas from their brainstorming session.

Team members
What is the problem you are considering? Answer in one sentence.
What are your notes from the brainstorming? Only one team member records the notes.
After brainstorming, take a picture of the workspace or save your sticky notes. Then answer the following questions. What were three specific issues or aspects of the problem? Re-Engineering Packaging What were the four to six design ideas that appeared most often during the brainstorming session? Biomimicry and sustainability; structure and function; material science What are at least four key features of your design? Describe them in words or sketch them.

Initial Design Plan

Teams should complete this form after they have identified constraints and criteria and settled on their solution, but before doing any building. The Initial Design Plan is their entry ticket into the building phase and provides evidence of planning and connecting back to the design space.

Team members and job titles
Criteria: List the top five things your team must keep in mind to develop a good solution. List these criteria in order from the most important to the least important. Use a Design-Ranking Form to complete this section.
The solution's four most important features: 1.
2.
3.
4.
The solution's least important feature: 5.
Constraints: What limitations and requirements must the solution meet? List no more than six constraints.
Design statement: What will your team do to develop a solution for the problem? You may draw a sketch, or create bullet points or paragraphs to create a clear picture of your plan.

Meeting criteria: How will your proposed solution meet the identified criteria? Specifically name the criteria and the ways they are being addressed. Use the list form to complete this section.

Science concepts: List any science concepts you need to understand and apply to meet this challenge.

1. Re-Engineering Packaging

2.

Additional background information: Identify any data, statistics, cultural, or historical information you may need to research.

Anticipated problems: What issues or roadblocks will your team have to overcome to succeed? For example, how or where will you get materials? How might a scaled model inaccurately represent the actual product or solution? How do you plan on getting the information or product to the end users?

Final Design Summary

This form brings students back to the initial design space and asks them to summarize how their planned prototype evolved into a solution.

Group name:

Team Member	Job Title or Responsibilities

Problem statement (Name your challenge.)

Criteria: On the left, list the top three criteria that your team developed and listed on your Initial Design Plan. Fill in the spaces on the right to show how you met each criterion.	
Criterion	**How We Met It**

Constraints: On the left, list three constraints listed on your Initial Design Plan. Fill in the spaces on the right to show how you met each constraint.	
Constraint	**How We Met It**

Final design product or solution: Give a detailed description or make a detailed drawing. Label drawings to highlight the important details.

Re-Engineering Packaging

Modifications or changes: List any significant changes from your Initial Design Plan. How is your final version better at meeting your design goals?	
Change	***Why* or *How* It Is Better**

Most significant concepts: List the two or three ideas that you used the most when designing your solution.