National Sword—that is what China named its policy. In July 2017, China notified the World Trade Organization that effective January 1, 2018, it would ban imports of 24 materials, including post-consumer plastic and mixed paper. In November 2017, China further announced that effective March 1, 2018, it would impose a new quality standard for all allowed paper, paperboard, and metals. It would accept only shipments of recyclables that were 99.5% pure—only 0.5% of impurities would be permitted.

National Sword hit two weaknesses in the U.S. recycling industry that most Americans didn’t know existed. First, most U.S. materials-recovery facilities or MRFs (rhymes with “Smurf”)—which sort recyclables—are “single-stream” systems, and a purity standard of 99.5% is unattainable. Second, most U.S. mixed paper and newsprint plus certain plastics (numbers 3 through 7) are not milled—melted or otherwise processed—here at home into feedstock raw materials for making new products. Few such domestic mills exist. Instead, most U.S. recyclables were separated, crushed, baled, and loaded onto container ships headed across the ocean.

Industry Reeling
China’s announcements—intended to improve its air quality and reduce pollution—sent the worldwide recycling industry reeling. In 2016, that country alone consumed more than half of the world's recycled paper and plastic. Indeed, China had been the largest consumer of U.S. recyclables for years. In 2016, the U.S. exported some 41% of paper, much of it going to Chinese mills. Nor is it alone: some years, the European Union exported 95% of its plastics to China. The immediate response was to reroute shipments to other Asian nations, such as Cambodia, Malaysia, Taiwan, and Vietnam. But by the end of 2018, those nations also rebelled. Like China, they welcomed recyclables clean and pure enough to be milled into useful feedstocks, but not what in some cases seemed little better than garbage. Meantime, China cracked down on illegal smuggling of the banned materials past its borders, scanning containers with X-ray machines and opening containers that could not be scanned, and mandating pre-shipment inspections before recyclables left an exporting nation’s port. Additional stringent regulations have been rolled out for 2019.

Great Idea
At first, a few decades ago, exporting U.S. recyclables to China seemed like a great idea...

By the first Earth Day in April 1970, a dedicated core of true believers realized that when you throw something away, there is really no “away.” Discards had to go somewhere, sometimes to an incinerator but most often to a dump (now called a landfill). To be sure, used clothes could be donated to thrift shops, old cars could go to junkyards, and glass beer and soft drink bottles could be returned for deposits and refilled. However, by 1970, beverage distributors were phasing out bottle washing as they continued shifting from heavy glass to lightweight, one-way glass bottles, marked...
The breakthrough was the development of multimillion-dollar separation equipment that today can stand up to four stories high and occupy 50,000 to 200,000 square feet. Agitating screens separate cardboard from other paper, glass, and debris. Drum magnets select out steel cans from a conveyor belt, while rare earth magnets—which induce eddy currents in non-ferrous metals—repel aluminum cans over a barrier to another conveyor belt. As plastics speed by, high-resolution near-infrared optical sensors determine their composition, activating air jets that separate bottles by type.

These high-tech behemoths enabled single-stream recycling: garbage separated from recyclables, but all recyclables be separated from other garbage such as clamshell takeout containers, which most MRFs cannot process. Photo: NOAA. BELOW: Multi-stream recycling means people must separate materials into different bins. Photo: Trudy E. Bell.

“No Deposit, No Return, Not To Be Refilled.” As beverage distribution moved from local bottling plants to regional or national distribution facilities, bottlers light-weighted their containers even more by switching to aluminum cans and plastic bottles.

But glass, like steel and aluminum cans, could be melted down and reformed into containers or other products, just as uncoated paper could be pulped and used for paper or boxboard. Why not give such materials second life rather than a one-way trip from mine or tree to landfill?

Early Recycling
Early household recycling required consumer commitment. By the 1980s, depending on the municipality and its waste-management company, households could be required to wash food cans, remove the paper labels, and crush the cans with the sharp-edged lids inside; separate glass bottles by color (clear, green, and brown) and plastic bottles by number; and tie newspapers into bundles. Each type of item had to be placed out on the curb in a separate open bin or box (no plastic bags), which were emptied by collectors into multiple-compartment recycling trucks.

This system—called either source-separated or multiple-stream—results in the cleanest recyclables ready for milling. However, there were objections. Some municipalities found the specialized trucks and manpower needs expensive. And too many consumers found the elaborate sorting burdensome, so they refused to comply, sneaking recyclables into ordinary garbage headed for the landfill.

The high cost and low compliance not only slowed the universal adoption of recycling across the nation. They also lowered the calculated return on the projected cost of building mills to process recyclables into feedstocks for creating new products, discouraging capital investment.

Perfect Solution
The 1990s brought two independent developments whose combination seemed to offer a perfect solution.

Consumers would recycle, it seemed, only if recycling could be made as simple and convenient as the act of tossing something into the trash. But simplifying the process at the consumer end monumentally complicates separation at the recycler’s end.

The high cost and low compliance not only slowed the universal adoption of recycling across the nation. They also lowered the calculated return on the projected cost of building mills to process recyclables into feedstocks for creating new products, discouraging capital investment.
China liked the idea, because some recyclables (notably steel, plastics, and mixed paper) were cheaper raw materials than refining from ore, crude oil, or trees—enough to allow China to pay some U.S. MRFs from $100 to $1,000 per ton for bales, depending on the material and the market conditions. U.S. recyclers liked it, because it not only deferred the need for capital investment to build mills at home but also generated income.

From 1980 to 2015, though, the amount of U.S. municipal solid waste increased by 73%. Moreover, it became overwhelmed by plastics, most of which do not biodegrade. Virtually all the plastics ever made have been manufactured just since 1950. According to the United Nations, at the present growth rate of plastics production, the industry worldwide is on track to “account for 20% of the world’s total oil consumption” by 2050.

Simultaneously, single-stream recycling is becoming a victim of its own success. Although well-intentioned consumers vaguely know that not all plastics are recyclable, they practice what the recycling industry curses as “wish-cycling”—throw all plastics into the recycling bin and “let them sort it out.” Problem is, manufacturers’ introduction of new plastics and plastic products outstrips the pace of the recycling industry’s ability to handle them.

Industry Headache
Quick plastics 101: Plastics are based on many different petrochemical resins, with the six most common indicated by the number 1 through 6 inside a triangle stamped on a product, while 7 is used for all other resins and combinations. Most municipalities recycle beverage and detergent bottles and jugs made of No. 1 (PETE or polyethylene terephthalate, also called PET) or No. 2 (HDPE or high-density polyethylene). Many will not accept items made of plastics 3 through 7, whose composition can also include a wide range of chemical additives (e.g., flame retardants, pigments, plasticizers, stabilizers).

Contamination is a major industry headache: ranging from liquid residues in unrinsed containers to what-were-they-thinking non-recyclables (“We’ve had garden hoses, plastic kiddie swimming pools, hypodermic needles, even full propane tanks and live shotgun shells,” said Dan Schoewe, operations manager of the Republic Services MRF in Oberlin, Ohio). But by volume, the worst contamination comes from the wrong kinds of containers. For example, to-go coffee cups, juice boxes, flexible pouches, and K-cups include metal foil, paper, or more than one type of plastic, which cannot be separated.

As manufacturers introduced more products with non-recyclable plastics at the same time cities and counties were adopting single-stream recycling, contamination levels in bales increased. Most single-stream MRFs today produce bales that are 97% free of contaminants such as foam cups and food waste: a ton of mixed paper, for example, might include 3% or 60 pounds of plastics or other materials. But plastics are so lightweight that such a contamination level could result in a volume of plastics too great for a paper mill to handle. Plastic films or sticky labels that get into the hydropulper are likely to clog the parts of the
machine on which paper or paperboard is formed. So China balked.

But wait, there’s more.
The fastest-growing category of municipal solid waste (3 to 5% per year) is electrical and electronic waste: anything with a battery or plug.\textsuperscript{10} Such e-waste ranges from large appliances (like refrigerators, washing machines, air conditioners), photovoltaic panels, and medical equipment to personal computers and mobile or wearable devices.

In 2016, 44.7 million metric tons of e-waste was generated globally; discarded mobile phones alone amounted to 435,000 metric tons—20% more mass than the Empire State Building. Yet, less than a fifth of e-waste was recycled.\textsuperscript{12} E-waste is increasing every year, because electronics have a finite and ever-shortening lifetime: anymore, five years is long for a desktop computer, and many smartphones are replaced every year or two.

Technical Challenge
Recycling e-waste is a technical challenge; a single printed circuit board can incorporate more than a third of the periodic table, including precious metals (e.g., gold, silver, platinum, palladium) and other high-value metals at concentrations higher than in mineral ores. E-waste includes rare earths (in magnets, speakers, vibrators, hard drives)—elements the Department of Energy has classified as critical to national energy security.\textsuperscript{11} Additional elements (e.g., cobalt, lithium, yttrium) appear on the Defense Logistics Agency’s list of materials of strategic importance.\textsuperscript{27}

Although backyard recyclers in Asia use acid baths to recover gold, silver, palladium, and copper,\textsuperscript{26} comparatively little industry attention has been devoted toward reclaiming useful substances from printed circuit boards. Long-term, the rate at which valuable materials are discarded in e-waste raises questions of depleting reserves of materials of military significance or economic sustainability. Given that most of the world’s cobalt comes from the Democratic Republic of Congo, for example, The Economist recently asked: “Can the world produce enough cobalt for electric vehicles?”\textsuperscript{18}

Existing consumer economy is linear: resources are extracted from the ground, manufactured into products, used by consumers, and—too often after just a single use—are discarded as waste. Although the literature differs widely in calculating recycling recovery rates from U.S. residential municipal solid waste, all are dismal, ranging from 23% to as low as 12% (percentages are significantly higher for institutional, commercial, and industrial scrap and waste, but percentages for most materials are still under half).\textsuperscript{20,24,19}

Discarding more than three-quarters of plastics and e-waste—or anything else—is a colossal waste of resources. It is also a loss of big money: e-waste alone in 2016 was estimated at 55 billion euros worldwide—more than the 2016 GDP of most nations. This landfilled e-waste included some 18.8 billion euros (over $20 billion) in gold!\textsuperscript{4}

Reduce Future Waste
“Recycling delays, rather than avoids, final disposal,” noted one analysis.\textsuperscript{15} “It reduces future plastic waste generation only if it displaces primary plastic production,” that is, production from virgin stock—petrochemicals in the case of most plastics, but also mineral ores or trees for other materials. Therefore, an increasing number of voices are calling for full-scale re-envisioning of the entire economy—moving from a linear economy to a circular economy.

An authentic circular economy would minimize the extraction of virgin resources from the ground by maximizing the reuse of resources already extracted. In a perfect
A circular economy, nothing is waste, and nothing is wasted. Rather than a one-way trip from cradle to grave, resources continue circulating in the economy—perpetually moving from “cradle to cradle.”

Some recycling already preserves materials: scrap steel, aluminum and glass, can for the most part, be melted down and reused an infinite number of times, reducing the need for mining more iron ore, bauxite, and sand. But many materials cannot be recycled forever. The fibers in paper, for example, get shorter each time paper is recycled, limiting the products able to be made from them—and after six or seven cycles, they can no longer be used at all. Similarly, some plastics can be recycled only once or twice before they must be “downcycled” into products of lower value, which ultimately must be landfilled.

An authentic circular economy would minimize the volume of disposable items made in the first place—ideally, preserving not only the materials, but also the energy of their original extraction and refining, and (where possible) even the function of products. Reuse also minimizes pollution (another form of waste) from the original manufacturing process.

**Refillable Bottles**

Parts of the beverage industry are leading the way to a circular economy by returning to refillable glass bottles. A single sturdy glass beverage bottle can be refilled 10 to 30 times before it chips or cracks. A refillable bottle that makes 25 trips consumes 93% less energy than a single-use disposable bottle. At least 40 dairies around the U.S. and Canada have used refillable glass bottles for years, and now some craft breweries and wineries are doing the same. In September 2018, seven craft breweries led Oregon to launch the nation’s first statewide refillable bottle program, developing a bottle that can be used by any

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**Entire Value Chain**

Another need is reducing the use of plastics throughout the entire value chain. That would mean rethinking the housings of products, returning perhaps to steel or aluminum (which can be infinitely recycled) instead of plastics (which cannot).

To the degree no other material will do, a circular economy means using or formulating more plastics that can be infinitely recycled, or exploring where and how plastic products can be reused in the economy in a way analogous to reusing glass bottles—with an ultimate goal of relying on renewably sourced feedstocks and decoupling plastics from fossil-fuel feedstocks.

A circular economy for e-waste would entail processes for reclaiming high-value metals, strategic materials, and toxins and for reuse and/or safety. The list goes on... Initially, many in the recycling industry decried China’s National Sword policy as ‘the end of recycling as we know it.’ MRFs’ now must pay to have bales removed rather than receiving income for them. “It is the end of cheap and low quality recycling,” declared Antonis Mavropoulos,
Discarded cellphones await their fate at an informal e-waste recycling site in Ghana. Gold accounts for nearly 70% of the value of materials in obsolete or broken cell phones. Photo: Fairphone.

president of International Solid Waste Association (ISWA). “This (ban) will accelerate the collapse of a business model that is efficient in terms of money but not effective in terms of pollution.”

But National Sword also spells opportunities for the recycling industry: in the short term, for example, to pioneer advances in sensor-based technologies to vastly decrease contamination and improve the purity levels of single-stream recycling.

More importantly, it is spurring people industry-wide to think longer term about overhauling our disposable linear economy. “We need to start paying attention and fix this,” stated Michael Dufor, executive director of Northeast Resource Recovery Association. “Don’t make materials we have to throw away; don’t make materials that can’t be reused. The hierarchy is: reduce it first, then reuse it, then recycle it. We [recyclers] are the last line of defense.”

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**Selected references**

Where URLs are not specified, most references can be found online by searching on the title.

1 A list of dairies can be found at http://www.drinksmakinglassbottles.com/all-dairies/

2 An example of refillable wine bottles is at https://www.solidwastemag.com/feature/refillable-wine-bottles/

3 ASTM’s current standard, D7611-13, uses the acronym PETE instead of PET originally used by SPI. https://www.astm.org/COMMIT/d7611/pdf


5 Begin listening at minute 18:40 in a panel discussion held at a Science Café in Concord, NH, in May 2018 https://www.youtube.com/watch?v=j08kxtNp-o


9 “Chinese Customs Department Using X-ray Machines to Check All Waste Containers.” The Recycling Association [n.d., but early 2017].


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**Trudy E. Bell, M.A. (t.e.bell@ieee.org), former editor** for Scientific American and IEEE Spectrum magazines and former senior writer for the University of California High-Performance AstroComputing Center, is author or co-author of a dozen books and 500+ articles. This is her 29th feature for The Bent. She is standing next to bales of plastics 3 through 7 that are stacked outside the Republic MRF in Oberlin, OH, waiting for a market to develop. Photo: Dan Schoewe.