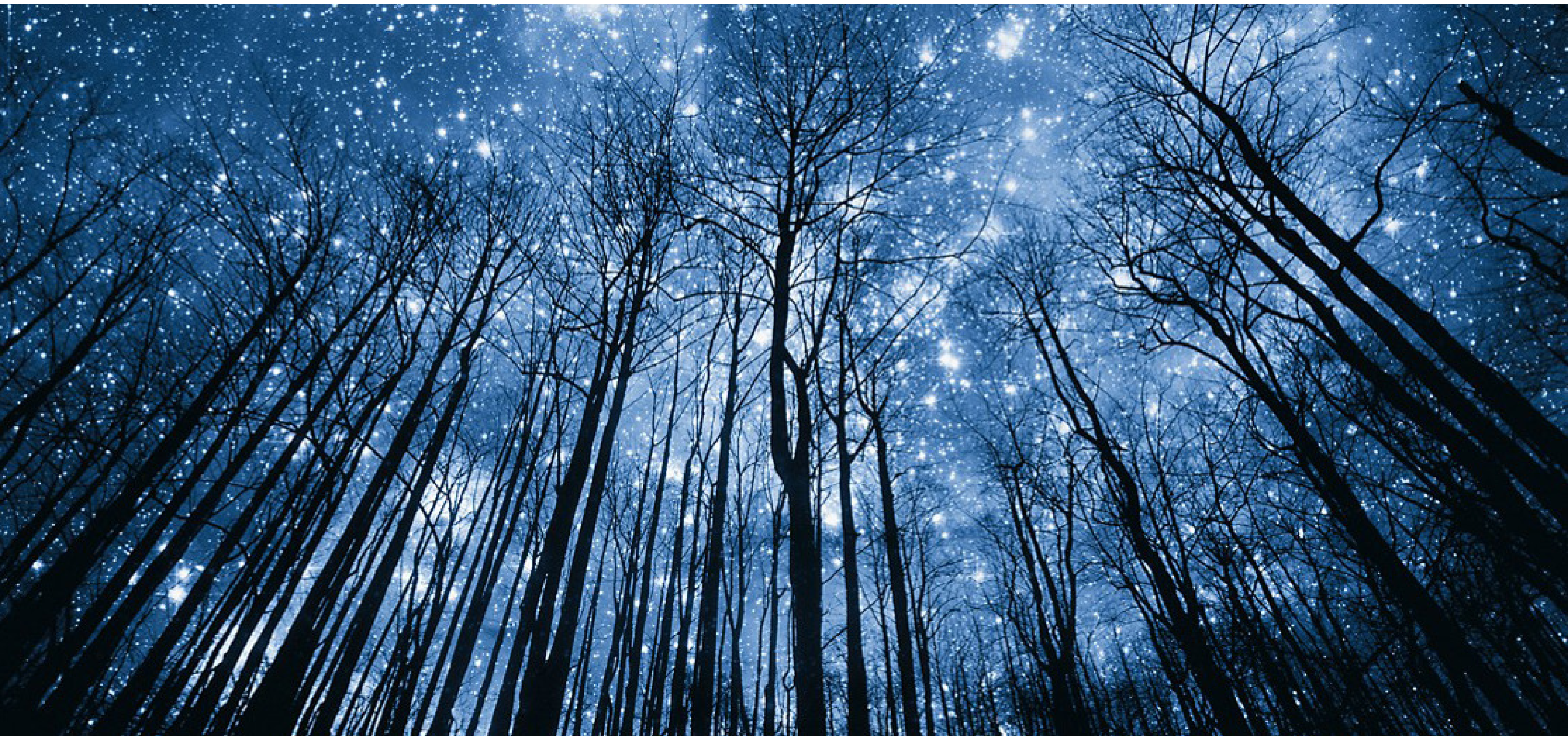
DELL Technologies

RESCUING RECYCLING



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Knowledge Sharing Article

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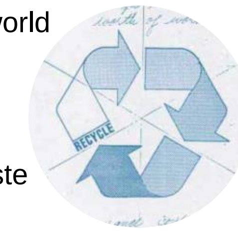
I first heard about recycling from my parents with their stories of how Americans supported their soldiers in World War II. President Roosevelt in early 1942 formed the War Production Board, and part of their mandate was to conserve and recycle scrap metals, rags, rubber, and paper.[1,2] The recycled material was turned into ammunition, bombs, gas masks, life rafts, and more.

The first official Earth Day occurred on April 22, 1970. It set aside a day for world appreciation and help our environment by conserving energy, planting trees, and recycling. That year, university student Gary Anderson introduced us to the three-arrow Mobius loop that symbolizes an infinitely flowing circle of waste reduction by reuse, over and over again.[3]



Recycling helps conserve Earth’s raw materials, and when we can reclaim waste stream items to make new products, we also lower carbon dioxide and methane emissions. We grew up with that familiar recycle logo adorning products and containers as we did our part to reprocess recycled paper, glass, aluminum, plastic, and more into fresh newsprint, bottles, cans, and other items. We are taught to reuse, but if that is not an option, we try to recycle.

The premise is childishly simple, but the execution is devilishly complex. Instead of cutting down trees, mining ore, and pumping oil from the ground, employ seemingly magical ecosystem-aware approaches to reduce garbage in landfills, cut back on incineration, and create new products from old ones. Materials such as glass, aluminum cans, and paper are relatively easy to repurpose. Plastic poses a problem as its quality degrades when reheated and shaped into new products. Recycling can save energy, reduce air and water pollution, and conserve Mother Nature’s limited resources.

With recycling bins in schools, businesses, venues, our homes, and more, we all got the message and did our parts to be environmentally friendly. But something happened on the last day of December 2017 that changed all that. Recycling as we knew it died.

This article is about the recycling dilemma we all face and how technology can rescue it. Much of what we recycle today still ends up in landfills alongside our garbage, or even worse, in our waters, jeopardizing our planet. I will address what can be done to tackle the modern set of recycling problems and explain how computer science concepts like Neural Networks (NN), Artificial Intelligence (AI), and other disciplines will help us care for our planet.

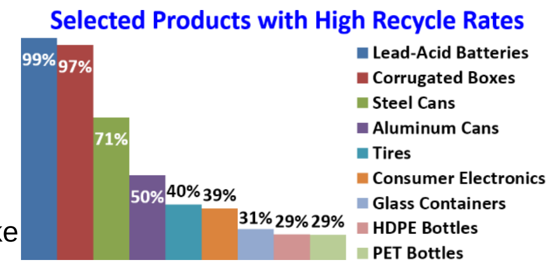
Introduction

Caring about our planet means many things to us. Conserving natural resources, reducing waste, cutting greenhouse gas emissions, saving energy, and more are all our responsibility as citizens. Recycling is one of those responsibilities, yet its feel-good story has had many twists and turns. If we couldn't reduce consumption or reuse items, then we should try to recycle them.

We learned the broad recycling categories of glass, paper, metal, plastic, and electronics. Many of us cleaned and even separated our glass into clear or colored groups. By the 1990s, people were getting lazy. In many towns, separating glass into individual bins gave way to single-stage collection. Consumers could put everything recyclable into the same bin. At Newark Airport, recycling bins have specific openings for plastic bottles, cans, and paper, yet all three drop into one plastic bag. It is left to the Material Recovery Facility (MRF) to separate the items for shipment to manufacturers for reuse, and sometimes to other nations for manual sorting by cheaper labor.

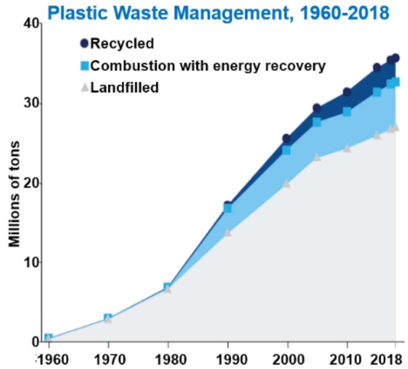
Apathy and carelessness crept into the effort. For example, some airport travelers put their used coffee cups in the paper opening believing the MRF will figure it out. This is sometimes called "wishcycling". They don't know dirty items like coffee cups are not recyclable since it is not easy or profitable to remove the contamination, and instead items often wind up in a landfill.[4]

Contrary to popular belief, while we put plastic in the recycle bin, it has a low recycling rate and much of it goes into a landfill. Plastic is difficult to recycle with today's technology.[5] Bound books, plastic forks, and Styrofoam are also likely not recycled. Some items, like car batteries, have a high recycling rate due to the deposit paid when a new one is purchased.



Scientists believe our environment's trapped greenhouse gases impact our climate. They claim we could decrease the episodes of droughts, flooding, and other disasters if we could reduce harmful fossil fuel emissions. Only one-third of 37 million tons of household recyclable material is recovered in the US with the rest incinerated or becoming waste.[6] If everything was recycled, greenhouse gases associated with creating virgin materials would be reduced by 96 million tons, saving 154 million barrels of oil, and adding 370,000 new jobs. The goal is to increase the recycle capture rate and value by expanding the market for processed recycled commodities. Five challenges face our domestic recycling system: contamination, low collection rates, limited markets, low profitability, and limited decision-making information.[7]

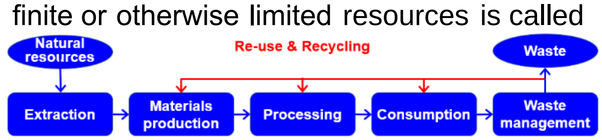
Not to pick on plastics, but even with US recyclable plastic rates increasing, the amount of it reaching landfills is staggering. Invented in the mid-1800s, there are 27 million tons of it in landfills, and it takes hundreds of years to decompose.[8] Only 3 million tons were reabsorbed into the manufacturing cycle due to the difficulty and cost of turning it into a desired commodity. Worldwide, the plastic recycling rate is only 9%.[9]



My pet peeve is the Keurig coffee pod. This ubiquitous small, foil-sealed, single-serve K-Cup cartridge of coffee grounds and a filter makes one cup of coffee.[10] To recycle it, the consumer must separate the recyclable #5 polypropylene cup, discard the aluminum foil top and filter, and compost or put the wet grinds in the trash.[11]

Keurig's success is part of the 1970s single-use packaging revolution that gave rise to the popularity of plastic straws, aluminum soda cans, milk jugs, and more. Single-use plastics account for 40% of all plastic waste and 40 billion K-Cups were used in 2021.[12]

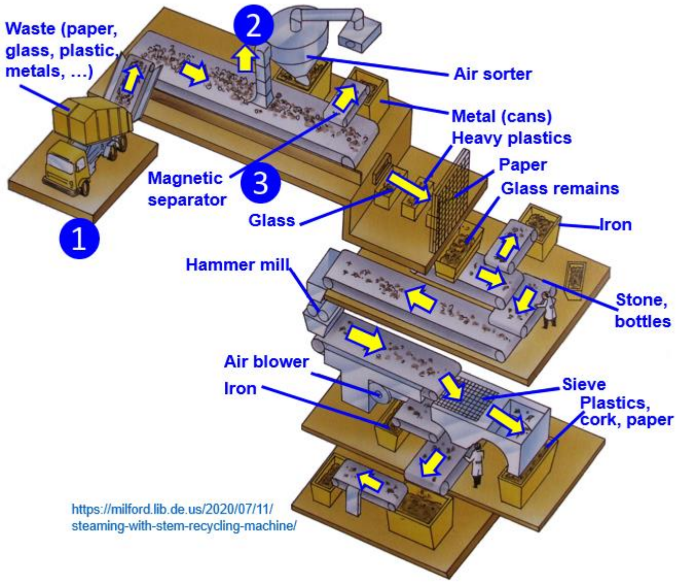
The latest effort to raise awareness of our planet's finite or otherwise limited resources is called the circular economy.[13] This economic industrial model calls for the elimination of waste by **reuse** and **repair of recycled items** as shown in **red**. Encouraging makers to build reusable products, such as allowing them to be repaired or updated at a sensible cost versus discarded, would require fewer virgin resources. In contrast, a linear economy takes in raw materials, makes products, and disposes of old ones. A smartphone is a great example – the software can be updated, but it is impossible to upgrade the hardware, except for perhaps the battery.



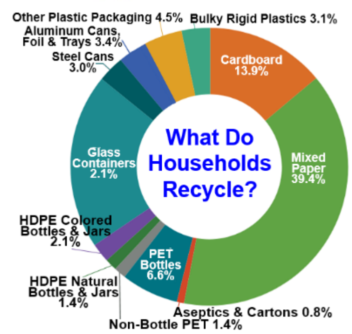
How are Items Recycled?

The simplicity and convenience of single-stream recycling was a "nothing for us to sort no brainer" breakthrough. The strategy worked. Recycling rates rose from 10% in 1985 to 32% by 2018.[14] As a comparison, Germany's multi-stream recycle effectiveness was 56%.[15]

Blue bins are emptied by collection trucks that bring the recyclables to the MRF. Commercial recycling contains a different blend of materials than curbside pickup and it includes more cardboard, plastic film, scrap metal, and building materials such as wood.[16] The material is put on a conveyor belt where employees and machines with screens, magnets, pressurized air nozzles, and computers sort items into categories. Some of the material, such as greasy pizza boxes, can't be repurposed without a great deal of expense, so it goes to a landfill.



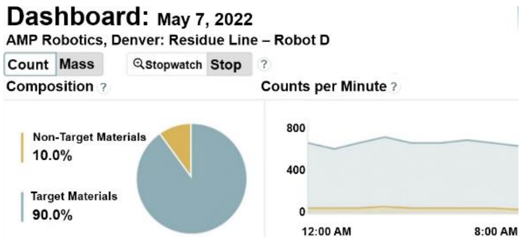
A few of the 600+ MRFs in America can process a truckload of materials in under an hour.[17,18] ① Commingled material is spread flat on a conveyor belt and passed through sorting stages. ② Plastic bags can jam up machinery, so they are removed first and processed separately. ③ Steel cans are removed by magnets, followed by glass, aluminum, paper, and plastics. As different techniques and technologies improve, the sequence order can change.



Households predominately recycle paper and cardboard (53.3%), followed by glass (20.4%), various plastics (19.9%), and aluminum and steel products (6.4%).[19] Given the mix, it is worth noting that some of these items are recycled an infinite number of times while others have a limited recycle lifespan. The analogy often used is the expectation of reheating a slice of pizza in a microwave oven.[20]

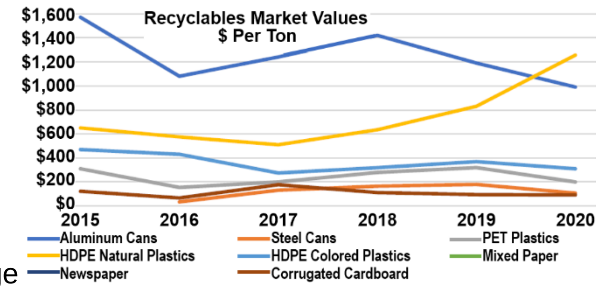
The robot is one of the newest recycling innovations. The latest software machine intelligence allows them to move beyond older industrial tasks such as car frame spot-welding. They now handle complex recycling jobs where thousands of different items on a conveyor belt must be accurately identified regardless of whether they are whole, crushed, crumpled, dirty, turned on their sides, or contain rotting food. They also learn to identify and handle new items that hadn't existed when they were first bolted together. When networked, perhaps through the cloud, robots can collectively share database image updates without a coding change.

The recycling industry is also adopting software tools to help run the MRF and make better business decisions. Every day, materials conveyed through a facility potentially represent hundreds of thousands of dollars in revenue. The goal is to keep baled products such as these to the right, as pure as possible, automate monitoring, coordinate maintenance tasks to maintain productivity, and help market materials based on local trends and composition.

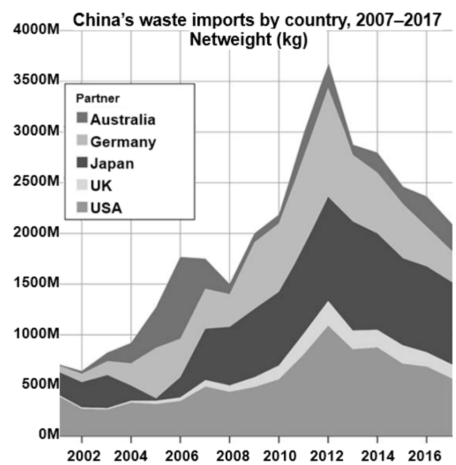


AMP is a company that makes recycling equipment. Their Clarity Software-as-a-Service (SaaS) cloud-hosted program receives precise real-time AMP Robotics data on sorting operations.[21] The MRF activity is shown on its dashboard to the left.

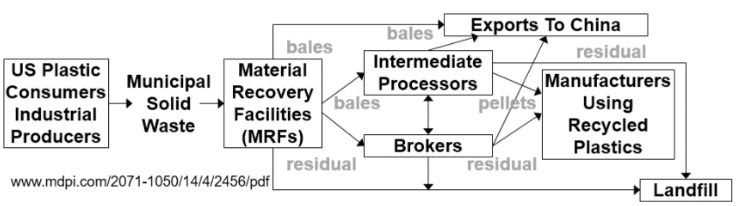
China – The Day Recycling Changed



We feel good knowing we are helping the environment, but recycling is also a big worldwide business that depends on the existence of a profitable market. Like any commodity, the price paid by recycling dealers varies. As this chart shows, commodity prices are volatile, and a change of a few percentage points can determine if a material is profitable to the MRF or loses money.[22]



Up through 2017, China was the world's largest recycling market. Domestically unable to produce enough raw material to meet its manufacturing demand, it bought recyclables from around the world. For nearly thirty years, US MRFs shipped half of their recycling output to China, and in 2016, China purchased over 500,000 US shipping containers worth of recyclables.[23,24] Chinese competition kept prices high and their labor costs were much lower than America's. Transportation costs were low as ships unloading Chinese goods at American ports would otherwise return with empty containers. With China accepting



America's exports of plastic, paper, metal, and more, there was little MRF incentive to innovate sorting and cleaning efforts.

Meanwhile, China's pollution problem was getting worse. As the world was transitioning towards commingled recycling, contamination became a big problem. Blended plastics that were difficult or impossible to separate into purer forms were becoming common. Impurities in bales of recycled materials imported from around the world ended up in their landfills and resulted in increased water and air pollution.[25] A 2015 study found millions of tons of plastic waste were flowing into the Pacific Ocean annually from China's shoreline. While not exclusively a Chinese problem, the Pacific Ocean garbage patch now occupies an area the size of Texas.

To clean up poor villages smelling of chemicals and burning garbage where laborers performed the sorting, China introduced Operation National Sword.[26] In January 2018, recycle imports were limited to a nearly unattainable contamination rate of <0.5%, a big drop from their previous 5-10% level.[27] They also banned 24 categories of scrap materials, unsorted mixed paper, and low-grade plastics. China had been the most popular world recyclable destination, and Sword effectively stopped soiled and contaminated objects from reaching their shores.[28] In 2019, the ban expanded to include 16 other materials and cut the number of waste import licenses.

Sword created a worldwide crisis. MRFs were in chaos as China's plastic imports dropped by 99% and recyclables piled up at docks. Recyclers around the world sought out other nations to purchase these commodities. Through 2016, US scrap plastic was sold to 78 countries as shown by this partial destination chart, including the uninhabited Australian Heard and McDonald Islands.[29] Before 2018, mixed paper sold for $155/ton, and after, $10/ton. More recyclables began to land in Thailand, Vietnam, Malaysia, and Indonesia, but they also eventually stopped their imports.

US Plastic Scrap Exports Jan-Jun 2016	**Metric Tons**	**Pct%**
China	365,586	38%
Hong Kong	322,157	34%
Canada	217,947	23%
Vietnam	31,750	3%
Malaysia	18,598	2%

National Sword was viewed by some in the US as an act of aggression, eventually leading, in part, to then-President Trump levying tariffs on Chinese aluminum and steel brought into America. China retaliated by placing tariffs on various US goods and materials.

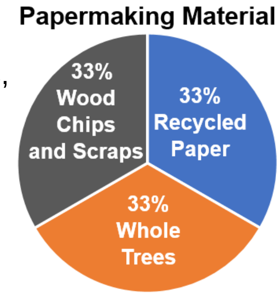
The US and others were forced to rethink their domestic recycling programs as overseas markets shrank. MRFs hired more workers and introduced more automation to help purify the recycling stream, but the cost was high and it took a toll on the market price for various commodities. Communities that had been paid for their recyclables were now paying MRFs to remove them, and the cost became burdensome. For example, Stamford Connecticut earned $95,000 from its 2017 recycling efforts, and by 2018, it was paying $700,000 to remove them.[30] Some communities had to stop their recycling programs and instead rely on landfills.

National Sword is viewed by some as a disaster for landfills and the planet. Offshoring our recycling represented reduced labor costs, cheap transportation, and unloading material that could not be recycled. It also allowed companies to resist sorting and equipment modernization. Others saw it as the start of a new planet-wide opportunity to rescue the recycling initiative through concepts like quality sorting and phasing out single-use plastics.[31] It marked the end of addressing tomorrow's packaging streams with yesterday's recycling technology.

Recycling Basics

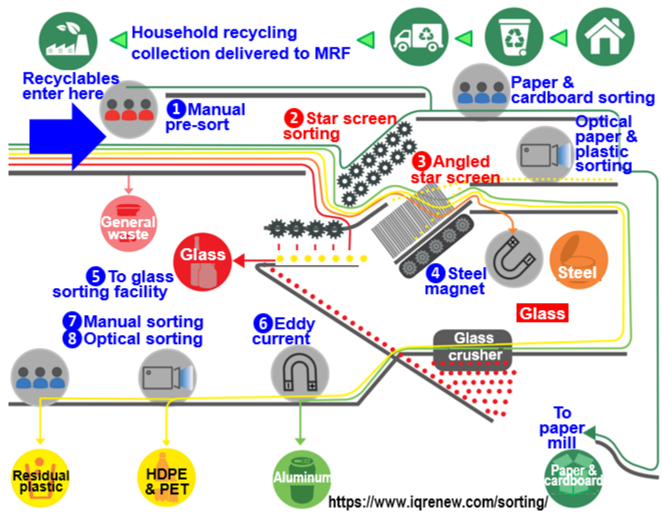
Paper

Paper is a sheet of cellulose shredded plant fiber (wood) formed into a standard size. It is one of our greatest inventions, and to make it from trees, wood is turned into pulp. The pulp is diluted in water and passed over a screen until it weaves and forms a sheet, and then dried. According to the US Environmental Protection Agency (EPA), America recycles roughly 2/3 of its paper, and 1/3 of every new paper product contains recycled paper.[32]



This depicts the single-stream recycling process. Paper and cardboard is sorted by hand or through a **series of rotating**

disk/star screeners on shafts in steps ❷ and ❸. To the left are **narrow-gapped disks**. As paper goes uphill, the **gap** is increased. Heavier three-dimension items like jars and cans are separated from two-dimension cardboard, paper, and lighter materials that stay on the belt. From there, paper goods are sorted into bins of newsprint, cardboard, copy paper, phone books, junk mail, and more. Human pickers remove contaminated or unusable paper where it heads to a landfill and takes months to decompose.[33] As discussed later on, paper can also be sorted with infra-red, optical, air nozzles, and more. Recycled paper, like other commodities, is compressed, baled, and shipped to a paper mill.



Paper arriving at the mill is finely shredded and cleaned, screened, and de-inked. Staples, tape, glue, and other foreign substances are removed before going into a slurry vat to thicken and dry. With each step, the fibers get shorter, hampering the bonding process and resulting in a reduced paper yield. After recycling paper 5-7 times, new wood fibers have to be added. The paper can be bleached white with hydrogen peroxide or color added as needed. The mixture is pressed out with a roller and formed into paper and packaged.

Recycled paper consumes 70% less energy than virgin paper and lowers paper costs. Every tree saved means more carbon dioxide is turned into oxygen, so tree preservation greatly reduces greenhouse emissions.[34]

FACT: Recycling 400 reams of paper can save 17 trees.
www.usi.edu/recycle/paper-recycling-facts/

Steel and Tin

It is amazing that today we still talk about cans. Their history dates back to Emperor Napoleon and his need to feed his troops since an army "travels on its stomach."[35] To meet his challenge, a method was developed in 1810 to preserve food in glass jars, which eventually gave way to using unbreakable tin cans.[36] They are generally made from tin-plated steel, are cheap to make, and take on different shapes. Since the early 1960s, some cans are made from non-ferrous metals (do not contain iron) like aluminum.[37]

In the MRF, giant magnets pick up ferrous material for shipment to a foundry for melting and contaminant purification. It is turned into solid sheets and shipped to bulk customers as fresh raw materials. In the US, about 70% of steel is recycled, which includes 95% of the steel in cars and 70% in appliances.[38] Recycling steel and tin saves nearly ¾ of the energy used to create virgin material.

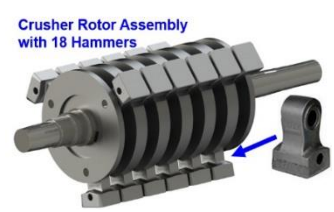
FACT: Steel cans are the most recycled packaging product in the world.
www.rts.com/blog/recycling-facts-statistics/

Glass

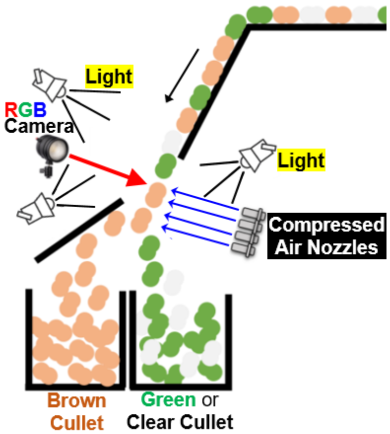
In terms of recycling, glass has much in common with a library book – when you are done with it, return it and someone else can read it. In some jurisdictions, a small deposit ensures the bottle you "borrowed" from the manufacturer is properly returned for reuse.

Glass is made from limestone, sand, and soda ash.[39] A pound of recyclable glass chips (cullet) replaces 1.2 pounds of raw materials. The planet wins when glass is recycled. Melting it does not release CO_2, and a ton of it saves 5 gallons of oil and 714,000 BTUs of energy.[40] Glass can be endlessly reused without any quality loss and new products contain over 30% cullet.[41]

America recycles 40% of its glass while other nations using multi-stream recycling achieve 90% efficiency.[42] Many MRFs sort glass by hand, which works when objects are large and can be handled safely.[43,44] When a truck of single-stream recyclables arrives at the facility, the market may dictate that commingled glass be separated by color. Sorting it into piles such as clear, brown, green, and more, increase MRF costs. Contaminants such as light bulbs, mirrors, and other products containing glass are not easily recyclable and head to a landfill.



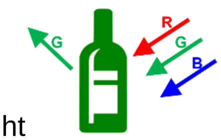
Glass is pulverized by heavy forearm-sized hammers that spin quickly around an axle, breaking the glass into crude cullet particles for future optical sorting. A water mist controls airborne particulates.



A colored glass sorter, such as the one on the right from Tomra, separates brown, green, and clear cullet.[45] Various technologies can be used to detect and sort colored cullet, and the one on the left uses **Red**-**Green**-**Blue** (**RGB**) photoelectric color sensors to detect the intensity of reflected white light off glass shards. A vibrating conveyer belt is often used to distribute the cullet in a thin layer. Non-glass drops into a waste bin.

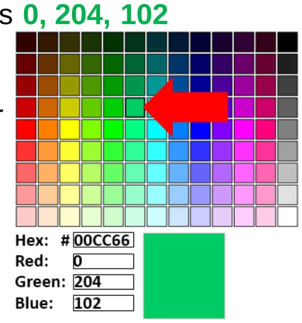
When an **RGB** camera sees a **green** object such as a wine bottle or cullet, only the **green** light is reflected. The absence of a reflection indicates the object is **black**. The ratio of **RGB** reflected light depends on the object's color. Glass is colored by mixing it with metal such as chromium to make it **green**.[46] Other sensors such as X-ray analyzes the element-specific fluorescence to detect coloring and other substances such as zirconium, while near-infrared sensors inspect reflected light for plastic signatures and organic materials.[47]

Object color	Reflected Light		
	Red	Green	Blue
Red	X	-	-
Yellow	X	X	-
Green	-	X	-
Blue	-	-	X
White	X	X	X
Black	-	-	-



A program uses an API such as ***sensor = adafruit_tcs34725.TCS34725(i2c)*** to access an **RGB** camera. It returns a 3-tuple value from an Adafruit (Arduino hobbyist module) sensor on the right. A 3-tuple representing the **RGB** color byte values ranging from 0-255, where 0 is low intensity and 255 is maximum intensity, is returned when the camera focuses on glass. In this example, the values **0, 204, 102** highlighted in **red** show it senses a **light-green** colored glass versus other shades of green and brown.

Green 0, 255, 0	Brown 244, 177, 131
Green 0, 176, 80	Brown 197, 90, 17
Green 0, 204, 102	Brown 153, 102, 51
Green 0, 102, 0	Brown 132, 60, 12



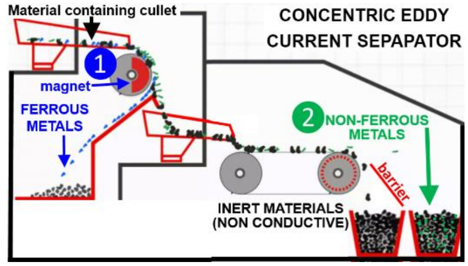
This Python code fragment can read sensor values:

```
# Import necessary modules
import board
import adafruit_tcs34725
# Communicate over default I2C bus
i2c = board.I2C ()
sensor = adafruit_tcs34725.TCS34725(i2c)
# color_rgb_bytes - function returns R,G,B 0-255
print('Color: ({0}, {1}, {2})'.format(*sensor.color_rgb_bytes))
```

```
Color: (0, 204, 102)
```

The ***sensor*** value triggers commands to **compressed air nozzles** as shown in the previous schematic. **Brown** cullet is blown into a farther bin while **green** or **clear** fall into the closest bin.

Additional colors can be accommodated with more bins and accurate air bursts. Cullet sorting can be skipped if the color doesn't matter, such as when it is used in road asphalt.

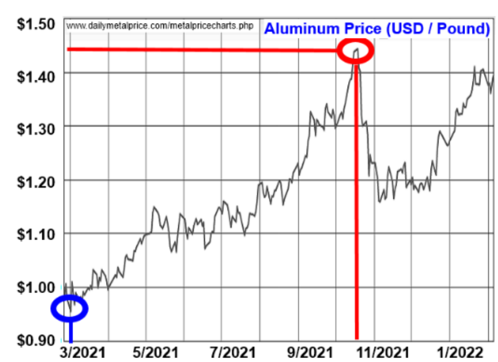


Cullet is scanned for **ferrous metal** ❶ contamination, such as jar lids, using a **rotating magnet**. **Non-ferrous metals** ❷ like aluminum, copper, and zinc are subjected to a rapidly changing magnetic polarity in an eddy sorter. Leveraging "Fleming's left-hand rule" to attain a magnetic field in objects, an eddy sorter separates materials into **inert non-conductive** and **non-ferrous** bins.[48] It can be thought of as a reverse magnet that repels **non-ferrous metals**.

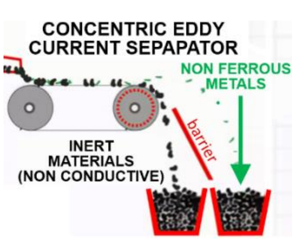
FACT: It takes over 4,000 years for a glass bottle to decompose in a landfill. www.usi.edu/recycle/glass-recycling-facts/

Aluminum

Aluminum is an amazingly strong lightweight material. Easy to form, it resists corrosion and is fully recyclable. The Earth's crust contains 8% of it and is found in bauxite ore open-pit mines in China, Australia, and other countries.[49] The ore is smelted through an energy-intensive process to create aluminum oxide. The US recycles 2/3 of its aluminum and new cans contain over half recycled aluminum.[50] Recycling saves a lot of energy compared to mining it. For example, the energy used to make 20 cans from recycled aluminum would only make a single can from virgin material.[51]



During COVIDs third wave, prices for recycled materials soared as the supply chain crisis worsened.[52] Aluminum market prices jumped 50% in only 8 months from **$0.96/lb** in **March 2021** to nearly **$1.45** by **mid-October 2021**.[53] If you recycle 12-ounce cans for a living, you know it contains about a ½ ounce of aluminum, so 32 cans equal a pound.[54] If the MRF pays you 25% of the **$1.45** market value for a pound of it (they have to make money as well), 32 cans nets you ***$1.45 * 25% = 36 cents*** on **October 2021**. At 50% of market value, you would earn 72 cents for those same cans.



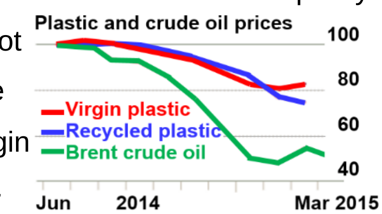
Sorting **non-ferrous** aluminum uses the eddy current method discussed in the glass cullet section to move magnetically charged aluminum into a bin. The material is shredded, cleaned, melted in a foundry furnace at 660°C, and poured into castings or rolled into sheets.

FACT: 75% of all aluminum every produced is still in use today. www.aluminum.org/aluminum-advantage/facts-glance

Plastic

Plastic, and in particular, celluloid was invented in 1855, followed by PolyVinyl Chloride (PVC) in 1872, and popularized by the synthetic electrical insulator Bakelite in 1907.[55] Virgin plastic is mostly made from fossil fuels like natural gas or oil and refined into ethane and propane.[56] When heated, they become ethylene and propylene. With different properties, melting points, and colors, there are thousands of variations. Melted plastic pellets or pliable plastic is used to make carpet, clothing, blow-molded bottles, compression-molded car parts, thermoformed single-use cups, injection-molded meal trays, and extruded straws.[57]

Plastic is always in the news, and for all the wrong reasons. A ton of recycled plastic saves nearly 6,000 kWh of energy and over 16 barrels of oil.[58] With today's expertise, only High-Density Polyethylene (HDPE), Polyethylene Terephthalate (PET), and in some MRFs, Polypropylene (PP) are recycling candidates. It can be recycled just 2-3 times before the quality degrades.[59,60] Even when a particular plastic is recyclable, it may not get processed due to cost and complexity. Virgin plastic is sensitive to oil and gas prices, so if they fall as it did in 2015, makers use virgin plastic.[61] Likewise, when oil prices skyrocketed during the Russian-Ukrainian 2022 war, the price of virgin plastic also rose causing lower-priced recycled plastic to become very attractive.[62] When recycled plastic prices cannot compete, it goes into landfills or even the ocean. Countries like Indonesia have a million tons of plastic in their waters.[63]



One alarming worldwide estimate suggests the ocean will have more plastic than fish by 2050 and microplastics (pieces <5mm long) are finding their way into our food supply.[64] They can be harmful to fish and are in our drinking water and food. One study found a "100g serve of rice typically contains 3.7mg of microplastics" and a microwaved rice pouch had four times that amount.[65] Simply washing manmade microfiber clothing can create microplastics – just look at the captured microfibers and microplastics in your clothes dryer's lint filter.[66]

Recycling plastic requires an understanding of seven Resin Identification Codes (RIC) formulations that manufacturers use in their products.[67] The two in **blue** are the most common and easily recycled. The **yellow** is recycled in some communities. **Red** plastics are harder to recycle and often combined into very different products or classified as waste.[68,69]

Poly**E**thylene **T**erephthalate (**PET** or **PETE**) is lightweight rigid or semi-rigid plastic used in single-use plastic water bottles, polyester or Dacron clothing fibers, resealable food containers, soda bottles, salad dressing bottles, microwaveable food trays, peanut butter jars, and store-bought muffin packaging.[70]

High-Density PolyEthylene (HDPE) is a hard, opaque lightweight plastic that holds a gallon of milk, shampoo, liquid detergent, yogurt, and more. Often used to make pens, planting pots, plastic mailing envelopes, garbage can liners, plastic fences and lumber, outdoor furniture, and grocery bags. Withstands extreme temperatures.

PolyVinyl Chloride (V or PVC) is used to make pharmacy medicine bottles, blister packaging, rigid white plumbing pipes, shower curtains, raincoats, vinyl siding, garden hoses, credit cards, cooking oil bottles, and window frames. It should not be melted or used for cooking utensils.

Low Density PolyEthylene (LDPE) is found in coffee can lids, 6-pack soda can rings, frozen food bags, squeeze bottles, shrink-wrap, vegetable/fruit grocery bags, and dry-cleaning bags. Can be repurposed into floor tiles, brushes, outdoor plastic lumber and furniture, and more.

PolyPropylene (PP) comes in colors, has a high melting point, and is dishwasher safe, making it a popular microwave choice. Commonly used for bottle caps, straws, yogurt containers, Tupperware, take-out food containers, and prescription bottles. It can be made into new cutting boards, buckets, car bumpers, and more.

PolyStyrene (PS) is also known as Styrofoam. Popular as packing peanuts and foam, electronics packing material, take-out clamshell foam containers and plastic party cups, CD and DVD cases, and some utensils. Can be transformed by a specialty recycler into insulation but often not recycled.

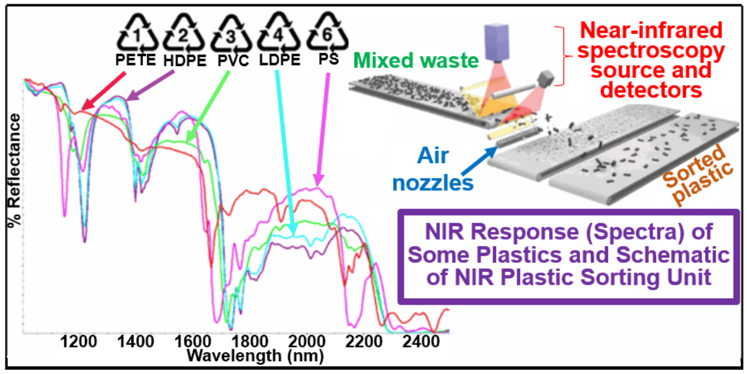
Other - a plastic resin other than those listed above such as bioplastic Polylactic Acid (PLA) or Bisphenol A (BPA) polycarbonate plastic. BPA is a controversial material that some claim is a health hazard.[71] Often found in eyeglasses, power tool housings, car headlamps, and more. Some communities recycle this plastic.

Rigid food packaging that keeps it fresh can be made from twenty unique plastic formulation layers, and the technology to recycle it has not yet been invented.[72] Makers can also change packaging formulations. An MRF's pickers or AI can be trained to put Tide detergent bottles in the HDPE bin. Should Procter & Gamble decide to use a PET bottle, pickers and robots could have a hard time telling them apart. HDPE and PET in the wrong bins cause cross-contamination and degrades their value. Plastic spray bottles could use different plastics for the bottle, cap, sprayer, and label, so it requires separation and processing, such as a mechanical PVC label remover to free it from a PET bottle.[73] To simplify sorting, the recycling industry is exploring new ways to process today's plastics, including those deemed unrecyclable.[74]

Date	PET #1	HDPE #2 Natural	HDPE #2 Colored
Jul-20	$0.083	$0.390	$0.035
Jan-21	$0.078	$0.705	$0.198
Jul-21	$0.273	$1.125	$0.625
Jan-22	$0.185	$0.595	$0.245

This West Virginia chart shows the price fluctuations that affect the success or failure of a plastic recycling program.[75] The red border corresponds with two of the major COVID-19 outbreaks that saw manufacturers greatly reducing plastic product production due to labor shortages. The price per pound reached market lows during July 2020/January 2021 (yellow), with HDPE #2 colored plastic worth only 3.5¢/lb. – not profitable to process. Prices rose dramatically as COVID cases declined with HDPE #2 colored plastic at a relatively high 62¢/lb. as of July 2021, coinciding with a huge increase in demand for recycled plastic (green). The January 2022 period saw another price reduction but less than the initial COVID wave.

Plastic sorting can be the last stop on the conveyor belt. Macrosorting is done by hand to separate whole containers. With microsorting, plastics are chopped up and require the polymer's chemical composition to be identified with a **Near-Infrared spectroscope** (**NIR**). On the right, each RIC has distinct fingerprint spectra wavelengths measured in nanometers. When each piece of plastic is illuminated, an air nozzle sends it into the appropriate bin based on its wavelength signature.[76] This method is not perfect and it has a problem with black polymers that absorb all light, in which case, other approaches are also used. It also runs into issues when distinguishing nonfood-grade HDPE from food-grade HDPE.[77]



NIR Response (Spectra) of Some Plastics and Schematic of NIR Plastic Sorting Unit

FACT: Only 14 recycled bottles are needed to create the fiberfill insulation for a ski jacket.
www.recycleandrecoverplastics.org/consumers/kids-recycling/plastics-can-become/

AI needs to address the newer bioplastic and biodegradable recyclable plastic designed to be better for our planet. Bioplastic is a plastic made from "vegetable fats and oils, corn starch, straw, woodchips, sawdust, recycled food waste," and more.[78] Biodegradable plastics decompose in a composting system. Both would contaminate polymer plastic.

Artificial Intelligence to the Rescue

MRFs sort materials by hand and through conveyor belt automation methods that use magnets, eddy currents, screens, tumblers, air nozzles, and cameras. Pickers at the start of the line remove plastic bags that could tangle the equipment and for quality control at the end as items are sorted into bins.

Working conditions vary by shift and can be monotonous, yet require a degree of precision. The setting is usually not sanitary, and pickers handle "recycled" dirty diapers, syringes, and even dead pets.[79] Infectious items, especially during COVID, can be lethal. A half-full recycled aerosol spray can is hazardous. MRF workers are twice as likely to be injured as other industrial workers and experience high fatality rates.[80] Waste Management Corporation is a large MRF, and before the pandemic, one of their biggest problems was employing 3,000 pickers to work the sorting line.[81] With a pandemic, workers feared being near the recycle stream.

Profitable (and successful) recycling requires items to be accurately separated and processed. Purity is paramount. The sorting has to be done at the lowest labor cost since this “overhead” directly impacts a recycle’s stream profitability.[82] Pickers should also not stand next to each other, especially during a pandemic or when sorting hazardous materials. Some approaches are obvious, such as using a magnet to select steel cans from a conveyor belt, but for people to pick 1 PET and 2 HDPE from a moving conveyor belt requires proximity, training, and machines.

Improving efficiency and profitability requires better sorting – a kind of recycling facial recognition. Many MRFs employ pickers 24x7 to toss items from a conveyor belt into bins labeled with “aluminum”, “plastic”, “steel”, “paper”, and more.

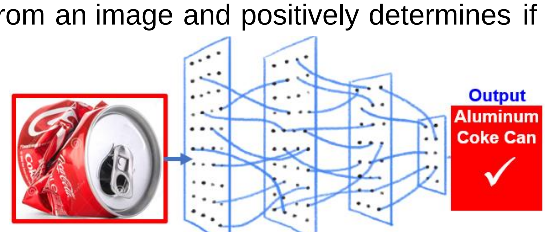
https://www.columbian.com/news/2015/jun/21/recycling-is-stalling-and-the-big-blue-bin-is-one/

The conveyor belt may move at 150 to 600 feet/min. If a picker can reach two feet in either direction, objects move out of reach in just 0.4 to 1.6 seconds.[83,84] If objects are not reasonably spaced, sorting quality suffers and contamination rates increase. The contamination levels that irked China will likely be objectionable to other MRF customers. For example, should greasy pizza boxes contaminate the card stock, the bundles will be worth far less to the MRF.[85]

To improve sorting speed and accuracy, lower costs, and keep workers safe, MRFs are introducing AI-directed robot arm automation. For non-ferrous items, AI-aided computer vision must detect and classify them, similar to facial recognition and self-driving vehicle applications.

Neural Networks

At a high level, AI uses a NN to help make decisions, and there are many types of networks to choose from. Recycling and AI rely on a Machine Learning (ML) Convolutional Neural Network (CNN) that uses a grid of functions that learns to classify objects through image recognition.[86] A camera image from a conveyor belt of recognizable recyclable items is processed by a CNN for similarity classification. It extracts features and logos from an image and positively determines if an object is glass, metal, or plastic. In this case, it is an **aluminum Coke can**, but it could have easily been an egg carton, an HDPE Tide laundry bottle with a PP PolyPropylene cap, or something else.

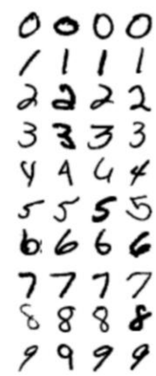


https://data-flair.training/blogs/cats-dogs-classification-deep-learning-project-beginners/

A CNN mimics the human learning process. For example, you might teach a child to say “cat” by pointing to a picture of the animal and saying the word cat. You reinforce that process by saying "Yes, that is a cat," or by correcting a mistake. A CNN learns through interconnected neuron layers and algebraic functions to find big data relationships.

Here is an example of how a CNN understands what handwritten numbers represent. People easily recognize all these digits as "two" since our  brain processes information with over 100 billion neurons.[87] With a camera and a computer, the CNN must learn the characteristics of a digital image matrix of greyscale pixel values.

It is difficult to write a program to read a digit image from a camera and determine with some certainty what number it is. These days, this pattern recognition problem is tackled by a NN. Many are written in an open-source language designed for this purpose called TensorFlow, although almost any language such as Python, Java, or C can be used.[88]



A CNN learns what a digit is, similar to how many children learn to read. It is shown an image, makes a decision, and receives positive or negative feedback at the end. The US Modified International Institute of Standards and Technology (MNIST) maintains a NN image database. It contains 60,000 training and 10,000 test images with a 28 x 28 8-bit (0-255) pixel form factor to evaluate the network's accuracy.[89] A NN program ingests MNIST data, develops rules for inferring what digits look like, and forms the basis for comparing a new image to the database.

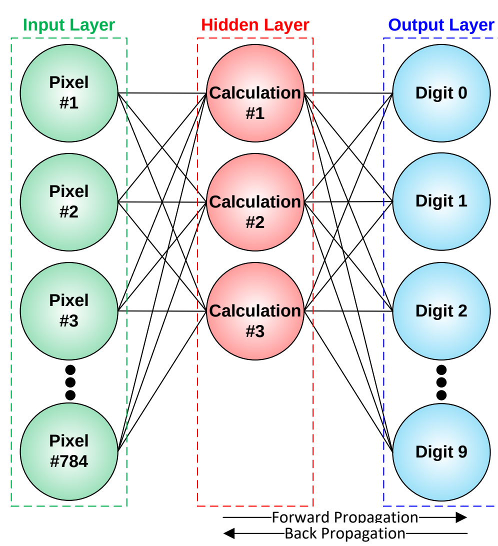
```
0:   0.10%
1:   0.03%
2:  99.91%
3:   0.06%
4:   0.00%
5:   0.00%
6:   0.00%
7:   0.00%
8:   0.02%
9:   0.00%
```

Once it learns the rules, it processes an image like this "**2**". Using a relatively short GitHub program, it predicts with **99.91%** certainty that the number is a two.[90] With much lower certainty, it determines it could be a "0", "1", "3", or even an "8'" at .02%. The more training the NN does, the greater its accuracy.

This is an example of a NN that processes each MNIST

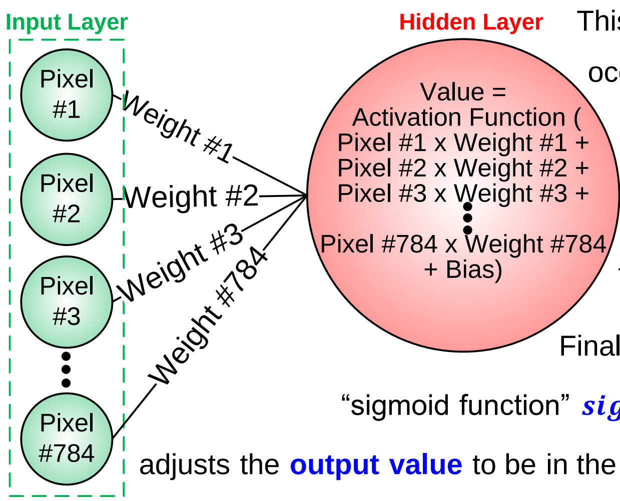
1	2	3	●	●	●	28
29	30	31	●	●	●	56
57	58	59	●	●	●	84
●	●	●	●	●	●	●
●	●	●	●	●	●	●
●	●	●	●	●	●	●
757	758	759	●	●	●	784

28 x 28 greyscale pixel image. The image is encoded as 28 rows of 28 pixels as shown to the left. Each of the 784 **pixels** is mapped to its assigned 784 **input layer** neurons on the right. The greyscale pixel value ranges from white (0.0) to black (1.0), with grey values in between.



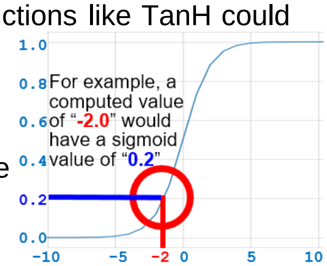
Data flows from the **input layer**, through channels to the **hidden layer**, and to the **0-9 output layer** neurons – this is called ***forward propagation***. The number of **hidden layers** defines how many computation perceptrons it has, and the perceptron assigns the pattern a value. You can think of a perceptron as an information processing node. The example above has one perceptron since there is one **hidden layer**, and it consists of three processing neurons. It is also called a two-layer network – we do not count the **input layer** since computations are not occurring there. Complex *deep neural networks* have many **hidden layers**.

Each path between the **input** pixel and the **hidden layer** is initialized with a random **weight** from -1.0 to +1.0, representing the importance of the source node to the connecting node. In the example above, there are 2,352 weights between the **input** and **hidden layers** (784 x 3).



This diagram shows the basic calculation that occurs in every **hidden layer** neuron. Each pixel's greyscale value (between 0.0 – 1.0) is multiplied by its pixel's weight and summed for each of the 784 pixels. A bias value constant is applied to the **input** and added to the sum.

Finally, an activation reduction function, such as a "sigmoid function" $\boldsymbol{sigmoid\ function} = \frac{1}{1 + e^{-(weight\ x\ pixel\ value + bias)}}$ adjusts the **output value** to be in the range of **0.0** to **1.0**. Functions like TanH could be used, but sigmoid produces a good estimate for the scanned digit. For example, if the **hidden neuron** had a value of **-2.0** (X-Axis) after multiplying the weights by the pixel values, and adding the bias, the sigmoid treats the new **output value** as **0.2** (Y-axis) as shown to the right.



With our digit "**2**" example, we expect the correct **output layer** answer to be [0,0,**1**,0,0,0,0,0,0,0] giving us the values to the right. During the network's test period, if the **output layer** produces an incorrect value, such as the test of digit "**2**" having a value of 0.3%, a backpropagation is performed in all layers, resulting in the adjustment of various weights and biases. This is how the NN "learns". When all test values are processed and the correct digits have a high likelihood of being correct, the NN is ready for production use with new images.

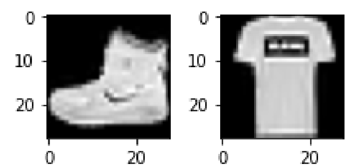
```
0:  0.10%
1:  0.03%
2: 99.91%
3:  0.06%
4:  0.00%
5:  0.00%
6:  0.00%
7:  0.00%
8:  0.02%
9:  0.00%
```

As mentioned, it is important to randomize the weights and biases. If they were all set to the same value, then each neuron would be computing the same value, the backpropagation would be identical, and the network would not learn.

This is an MNIST summary of the learning computations:

1. Feedforward.
2. Compare the output with the expected output.
3. Determine the amount of error.
4. Adjust parameters running the operations backward.
5. Repeat the calculations.

Neural Networks for Recycling



Similar to the MNIST database of number images, there is also a set of 28 x 28-pixel Fashion MNIST images of shoes, T-shirts, and more such as these to the right.[91] In a similar vein, Stanford University students created a GitHub TrashNet database of 2,527 **RGB** color

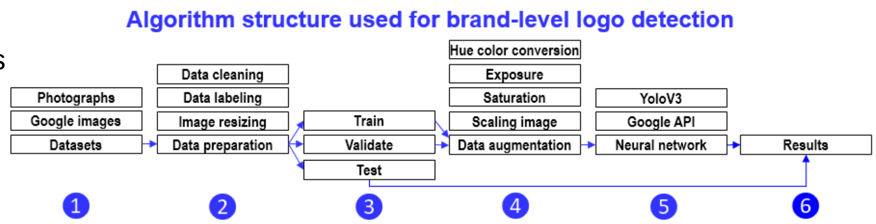
images as shown to the left. Used for recycling and trash, they resized the images to a higher resolution of 512 x 384. TrashNet has 501 glass, 594 paper, 403 cardboard, 482 plastic, 410 metal, and 137 trash images.[92] Even with these images, matching is still a hard problem to solve.

TrashNet forms the basis for training a recycling NN. Using a deep neural network with thousands of images, an AI vision system instructs an x-y-z Cartesian coordinate robot sorting arm, like this one from AMP Robotics, to pick up an item.[93] The system understands pixel depth and directs the 300-pound multi-jointed arm where to pick up the item. The term robot is from the Czech "*robota*" meaning "forced labor."[94] This spider-like one imitates human hand-eye coordination.[95,96]

Computer commands instruct stepper motors to rotate a precise number of steps, causing a segment to move forward, backward, left, right, up, or down. The robots can use a compressed air-powered **suction grabber** to pick up a squashed water bottle or a mechanical hand to pick an Amazon carton. Camera-fed computations spot recyclable objects in real-time similar to the way we do, and even make determinations about objects it has never seen before. Robots place glass in a glass bin and PET plastic in the appropriate bins over a hundred times per minute. "Smart" ML recycling robots can achieve a 98% accuracy rate.[97]

Training is the key to AI recycling accuracy. The chance of correctly sorting an item is extremely high if its image is in the database. Recycleye, a U.K. company that makes ML tools useful to tracking and automated waste sorting, maintains a 2.7 million image "WasteNet" database in the Microsoft Azure cloud for training purposes.[98]

ML robotic systems can detect labels, color, texture, brand, size, and other attributes for ease of processing. Rotational transformations and image updates are added to its database for future identification. Popular items found in the database are Coca-Cola (allegedly the world's largest plastic polluter) and Pepsi (allegedly the second largest European plastic polluter) bottles.[99] This is Recycleye's summarized object classification and identification brand logo architecture:[100]



1 The model uses internet-supplied logo images from various angles.
2 Non-logo images are removed such as ingredient labels, and the logo is bound to an image grid.
3 Training, validation, and test datasets help define the NN weights.
4 Data undergoes resizing, hue color conversion, saturation, and exposure changes.
5 NN processing of conveyor-belt camera inputs.
6 Coca-Cola achieves a 91.3% brand accuracy and 92% for Pepsi.

Key to the Success

Accuracy, cost, and speed are critical to AI robot sorting. With only an infrared or hyperspectral image analysis of materials beyond the infrared or ultraviolet ranges, plastic water bottles and salad clamshells appear to be made from the same material.[101] Without AI, a scrap buyer may not want to risk product purity, and expensive or slow solutions affect the MRF's profitability.

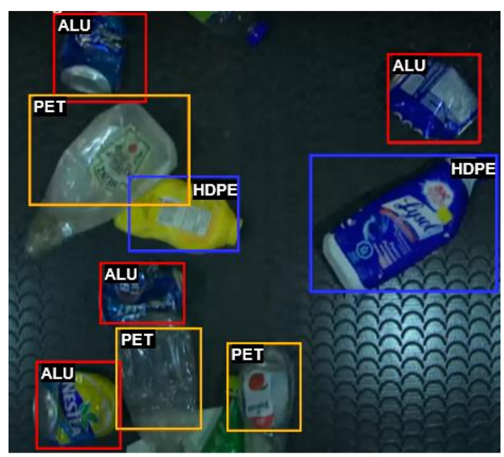
Pickers had been the only game in town, and they were truly amazing. Their stereoscopic eyes operated at 30 frames-per-second with dual-ambidextrous arms and hands that picked objects with ease. With little training, their brain differentiated between items as the conveyor belt whisked by. Some could grab two or more similar items in one effort. Their downside was their scarcity, salary requirements, and hit-and-miss quality. When pickers tire, quality went down along with their picks per minute. If they were ill or hungover, it could be a bad day at the MRF.

AI robots sort 80-140 items/min, reach over 90% accuracy and can achieve a profitable Return-On-Investment in three years.[102] They do their tasks without risk to life but are not cheap, with the AMP Robotics lease starting at $6,000/month.[103] MRFs expect to reduce sorting costs by 70% and many buy multiple robots to save money on sorting and improve quality control.[104,105]

Cost is a function of processing speed, machine cost, upkeep, reliability, and other variables. In a simple example, a picker's annual $30,000 salary costs the MRF perhaps $39,000 with benefits, supervision, training, supplies, insurance, overhead, and other costs. If a robot picks 120 items/min and operates nearly 24/7, it can easily replace 3 shifts of 3 workers which costs the MRF $351,000/yr. Over 5 years, the MRF would spend $1,755,000 (3 workers x $39,000 x 3 shifts x 5 years = $1,755,000) in salaries and benefits. The robot costs are roughly $6,000 x 60 months = $360,000. Robots require maintenance and likely cannot run 24 hours a day, but a 5-year, roughly 80% savings is significant. The MRF would lease more machines.

The AI sorting approach can be enhanced with more high-resolution images and categories. Similar to a number NN, a recycling NN requires training and retraining when new items are detected or by quality assurance checks that require refinement of the learning network. For example, here are three different Tide laundry bottles made from two different plastics. On a moving conveyor belt, a human and an optical scanner would have trouble choosing the correct bin. The four products to the left have various plastic formulations, and only AI-assisted networks, near-infrared, or hyperspectral imaging could guarantee a high accuracy rate to insure a pure plastic bale.

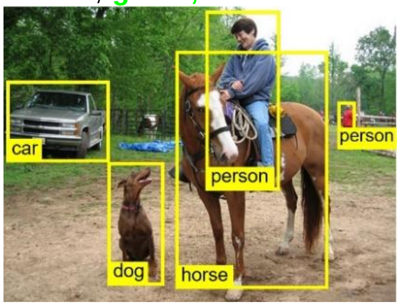
Computer vision object detection finds an item, classifies it, and calculates its coordinates. To the right, randomly oriented items achieve a lower accuracy and take more time to individually identify than aligned ones, so a process enhancement to separate and optimally arrange them makes for faster NN calculations. One technique is singulation, and conveyor belt technology from companies like Intralox separates stacked objects such as these **red**, **green,** and **blue** plastic bottles to the left, or overlaps like these green, brown, and clear bottles that need to be spaced further apart to achieve a higher rate of detection.[106]



Another refinement requires computer vision to crop and resize an image.[107] With a NN, accuracy increases when images have the same orientation and resolution. Some of the approaches to computer-automated matching include images cropped at the center or a random point. It also helps when items are illuminated similar to database objects.

The result is a system that spots an item and correctly identifies it. No system is perfect, and that's where the learning aspect of the system is constantly refining its accuracy.[108]

Some implementations must process recyclables even faster. This can be achieved with a Region-Based Convolutional Neural Network (R-CNN). Similar to the **red**, **green,** and **blue** plastic bottle example, the dog, horse, car, and people are bound by yellow rectangles in this R-CNN picture that detects and defines multiple objects in a single image.[109] At a high level, an algorithm creates sliding windows that examine and optimize the multiple individually sized rectangles.[110] This is computationally intense, but can greatly improve a robot's sorting speed.



As discussed, management software also plays a critical role in this cost-optimized, high-quality world of recycling. The ability to get real-time data from the recycling center allows operational decisions that optimize profitability and improve product quality. Some software suites specialize in "buy/sell" financials, inventory control, understanding the amount of material the MRF is processing, international and domestic order management, and other functions.[111,112]

On The Horizon

Recycling technologies change as breakthroughs are realized. Their approaches are different as they all try to improve upon a complicated process and bring to the forefront new, more efficient ways of helping the planet. Some focus on reducing the sorting time since recycling volumes are higher than ever before. Others focus on cost or reducing contamination to ensure the purity of MRF streams. Manufacturers are also trying to simplify and eliminate unnecessary packaging or make the packaging they do use more environmentally friendly.

It is a relatively straightforward process to recycle steel, aluminum, glass, and paper. The biggest challenge recyclers face is with plastics. Some plastics are not recyclable with today's technology and others face a limited lifetime. Instead of cutting up plastic into small pieces and using **RGB** approaches to separate it, scientists are exploring chemical ways to turn the recycled plastic into infinitely recyclable plastic, fuel, and food – yes, food.

Chemical Recycling

Plastics are made up of polymers (repeating blocks of small monomer particles.)[113] Chemical recycling breaks the monomer links so they can be deconstructed and recovered, and made into higher-value chemicals. It is the length of the bonded monomer chain that gives plastic its softness (plastic wrap) and hardness (PVC pipes) properties at various temperatures.

This approach allows the plastic to be infinitely recyclable, just like aluminum. It repurposes difficult or uneconomical plastics back into the supply chain, regardless of color or composition. It can even work alongside classical plastic recycling allowing certain items to be processed mechanically and others processed chemically. However, chemical recycling has historically been expensive, energy-intense, and produced only a limited set of new products.

Chemical recycling uses **chemical**, **thermal,** or **catalytic** conversion processes to turn scrap plastic into something more useful:

- **Chemical conversion**, aka **depolymerization**, **chemolysis,** or **solvolysis** creates monomers using chemistry, solvents, and heat, removing contaminants along the way. The new plastics are of similar quality to virgin materials.[114] The process is best suited for PET and certain synthetic fibers like nylon.[115]
- **Thermal conversion**, aka **feedstock recycling**, uses high heat to break polymers into simpler molecules using either **pyrolysis** or **gasification**. **Pyrolysis** converts plastic into a solid, liquid, and gas by applying high heat (350–600°C) above its decomposition temperature without oxygen.[116] Removing oxygen prevents incineration-related combustion by-products from forming. **Gasification** uses some oxygen and even higher heat (800–1200°C) to create syngas. The process works for all plastics and can produce chemicals, fuel, or fertilizer. **Gasification** is more popular than **pyrolysis**.[117]
- **Catalytic conversion** simplifies **pyrolysis** to break down polymer chains with less heat and time.[118] Useful with contaminated and mixed polymers, it uses barium carbonate and combinations of aluminum and silicon as catalysts.[119] IBM's new volatile catalyst uses a blend of chemicals, pressure, and heat above 200°C to process plastic with dirt, labels, or glue. It can also ingest carpet, toys, and cotton and polyester clothing to create balls of natural cotton and polyester powder.[120,121] Other approaches use cheap iron as a catalyst. They microwave an iron-plastic mixture for 60 seconds to generate a ten-fold increase in valuable hydrogen and carbon nanotubes.[122]

Plastic Food

Two scientists found a way to convert scrap plastic into protein using a food “generator.”[123] Their system uses pyrolysis to convert PET polymer into monomers to form an oily substance. The material is fed to synthetically altered bacteria that create new bacteria that are 55% protein. They believe a machine could be built that allows us to put our plastic waste and non-edible biomass into a hopper to create a nontoxic protein powder safe for human consumption.[124]

Alternate Single-Use Materials

Nearly 98% of single-use plastic comes from virgin fossil fuel.[125] Footprint, an Arizona company, creates plant-based packaging to replace single-use plastics.[126] Using compostable single-use molded containers made from cellulose, recycled cardboard boxes, agricultural waste, and wood fibers, their brown-fiber clamshells and trays biodegrade in only 90 days versus 400 years for plastic.[127] They also make recyclable, compostable, and biodegradable cups and microwave-safe bowls. Footprint products cost a bit more than plastic. To keep a cellulose cup fresh, companies like NewKiv make a biodegradable corn-derivative PLA bioplastic microwaveable cling wrap for your molded container.[128]

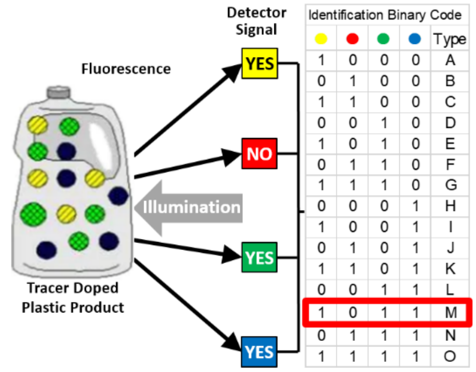
Fluorescent Markers

The difficulty in sorting plastic is trying to determine with high accuracy what type of plastic it is. What if the plastic could inform the sorter through a simple scan of an intelligent label? That is the idea behind permanently marking the outside of a container with an invisible fluorescent dye coding system. A project called Plastic Packaging Recycling using Intelligent Separation technologies for Materials (PRISM) enables high-speed MRF optical sorting systems.[129]

Marked with invisible fluorescent **red**, **yellow**, **green**, and **blue** colors, the manufacturer encodes the polymer composition to indicate food-grade and non-food packaging. The markings are only visible when illuminated by ultraviolet light. This invisible plastic recycling barcode encodes combinations of PP, PS, Linear Low-Density Polyethylene, and PET.

PRISM food-grade clear plastic would have a DR-1 red marking and the non-food colored package would be DY-1 yellow. Food-grade colored plastic would get both DR-1 and SC-1 cyan. To the left is a test run of various color codes under a UV light showing various plastic compositions.

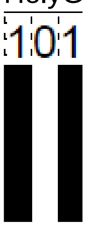
As items move along a conveyor belt, ultraviolet light illuminates the PRISM label and with color-coding as shown to the right, its plastic formulation. An air nozzle sends the item into the correct plastics bin. PET accuracy exceeds 96% for one pass and 99.6% for two passes.[130] Plastic sorting time is greatly reduced, accuracy is very high which avoids contaminations, and the cost is very low.



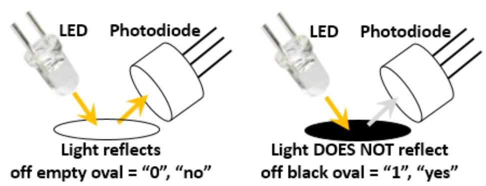
Digital Watermarks

Fluorescent markers are one way to encode recycling information onto an item. Europe's HolyGrail project embeds or prints invisible digital watermarks on items that are visible to MRF sorting cameras. The postage-stamp-sized coding system identifies the packaging information with 98% accuracy and without needing expensive NIR spectroscopy or AI. Even difficult multi-material packaging is easily processed through supplied encoded recycling information.[131] No matter how crushed the object gets, the code is still visible to the camera, allowing for the easy separation of a lemonade bottle from a laundry detergent bottle.

HolyGrail's method is similar to a barcode.[132] Traditional barcode labels use white and black



marks as binary-coded information. A photodiode interprets reflected light off white stripes as a "0" and no reflected light from black stripes as "1" as shown. There are many coding methods, such as a



Quick Response (QR) code. QR alignment squares, highlighted in red, are for scanner orientation. QR encodes thousands of bits of binary-coded recycling information data in a two-dimensional matrix. HolyGrail uses ultraviolet ink to print or stamp black-light readable codes all over the plastic.

These invisible **digital watermarks**, as shown to the right, behave like a consumer **standard barcode**, but contain information on the manufacturer, type of plastics, multilayer composition, stock-keeping unit (SKU), food vs. non-food usage, and more. They make sorting efficient, accurate, and less expensive than a picking operation. The coding is being explored by over 130 companies such as industry giant Procter & Gamble.[133] Consumers can also scan the invisible codes with their smartphone camera to find out everything they need to know about an item's recyclability.[134]

A New Plastic Designed to Be Recycled

Mechanical recycling produces inferior plastic compared to virgin plastic. What if it was reengineered to be recycled and not made from petroleum? Researchers have formulated a new infinitely recyclable plastic called PolyDiKetoenamine (PDK) that can be used to make a wide range of products.[135]

It is recycled in an acidic solution that breaks it down into its original monomers and separates it from additives.[136] It is built by combining monomers into long polymer chains like other plastics. **Virgin PDK** is still expensive at **$45/kg** and it generates a high **86 kg** of CO_2. For market acceptance, it needs to cost near virgin **HDPE** or **PET** at **$1/kg** and **2-3** kilograms of CO_2.[137] **Recycled PDK**'s story is better as the cost drops to **$1.50/kg** and only **2 kg** of CO_2, making it viable. A goal is to make it from microbe fermented plant material and not fossil fuel to lower its pollution profile.[138]

Plastics	Cost/kg	CO2 kg
HDPE Virgin	$1.00	2
PET Virgin	$1.00	3
PDK Virgin	$45.00	86
PDK Recycled	$1.50	2

Government Direction

Governments worldwide are encouraging more recycling and less waste. As landfills grow and air and water quality diminish, cities like Seattle, New York, and Paris are introducing legislation to reduce waste and encourage reuse and recycling. The EPA notes the US recycling rate has dramatically increased from only 7% in 1960 to 32% in 2018, but more can be done. Some municipalities enacted charges for recycling items to reduce and reuse them to lower the MRF burden.[139] Others are looking to fund MRFs or provide subsidies and tax incentives.

A "bottle bill" is a law allowing distributors and retailers to collect a small 5-10¢ refundable deposit on marked beverage containers. The goal is to encourage consumers to be responsible for their glass bottles, aluminum cans, and PET bottles. The legislation addressed issues that arose in the 1950s and 1960s where no-deposit containers were adding to litter problems. Up to that point, soda and beer were sold in refillable and reusable glass bottles.

Many states have tried adopting a bottle bill, but only 10 states succeeded: Massachusetts, California, Connecticut, Hawaii, Iowa, Maine, Michigan, New York, Oregon, and Vermont.[140] Michigan has an 89% redemption rate.[141] Environmentally concerned consumers in other states encourage their representatives to explore this legislation and the Congress has before it a National Bottle Bill "S.984: The Break Free from Plastic Pollution Act" under review.[142,143] Many beverage makers have opposed bottle bills while encouraging recycling.[144]

Progress is being made on waste management, recycling, and sustainability fronts. Customers and employees demand sustainability. New technologies are redefining and improving the waste management field. Growing populations and increased regulations are driving organizations and citizens to make recycling and reuse practices key parts of their business.

Fast-Food Reuse

We are witnessing the end of some of the egregious environmentally impacting fast-food practices. Burger King is testing the reuse of deposit-fee packaging returned to the store after a safety cleaning.[145] Starbucks began using partially recycled paper cups in 2006, phased out plastic straws, and is testing personal and single-use deposit recyclable cups.[146,147] McDonald's has pledged by 2025 that all of their "guest packaging will come from renewable, recycled, or certified sources with a preference for Forest Stewardship Council certification."[148]

Less Packaging

Manufacturers have been following a trend to reduce the amount of packaging in their products since it decreases material and shipping costs, and is better for the environment. The ubiquitous Poland Spring water bottle is a great example. Their bottles use 60% less plastic than in 1990. In 2020, a bottle contained 20% recycled PET, increasing to 25% in 2021. Their goal is to reach 100% this year in their commitment to a circular economy.[149]

While the "less packaging" movement uses less raw material, produces less CO_2, and is pro-Earth, the saying "every decision has a consequence" is also true. With less material needed to make an item, it takes more recycled bottles to create a ton of PET, and it is less profitable for the MRF to process each unit. A point can occur where manpower overhead, energy consumed to process, and other costs outweigh the recovered value. If the MRF doesn't increase the price per pound of recycled PET, it could become more cost-effective for them to send it to a landfill. While the purpose of the package is not to recycle it, recyclability must be a consideration.

Conclusion

Recycling is among the many pressing issues of our time and our planet requires we do a better job of it. It is constantly under scrutiny and vacillates between hope and reality. Improvements are being made, but there are still wide gaps between what can and cannot be recycled, and what can be recycled profitably. America alone generates 300 million tons of waste a year and only 25% is recycled, with one out of three aluminum cans ending up in a landfill.[150]

It's time to rescue recycling by reinventing it. New efficient technologies and innovations from fields like computer science and chemistry hold great promise to tackle the sorting and recycling of material. We can accurately analyze and get information directly from the recycle stream and apply new ways to convert it into products. At the same time, the private sector needs to reduce our dependence on fossil fuel-based packaging, especially with single-use plastics, and tackle the global waste problem by making packaging environmentally friendly. Many manufacturers are committing to include more recycled content in their packaging. Consumers need to waste less, reduce contamination, and adopt a “reuse before recycle” mentality.

Cost and purity are big themes when we develop plans to rescue recycling from its current trajectory. Tactically, we need to design MRFs that economically and autonomously sort and recover materials that are in demand and welcomed by the marketplace. Strategically, we need to end the confusion about what is and is not recyclable, help build a robust marketplace, and modify our behavior as a society to bring about a circular economy. Technology plays a big part in reshaping our recycling approach. We can make great strides in solving this problem and it won’t take much to improve upon the world’s 9% recycling rate. If done smartly, we can reduce our landfill use, save energy and natural resources, and help rescue the oceans and the air we breathe. Recycling can pay for itself and each step along this path will help the planet.

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