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BinIt: Revolutionizing the Recycling Industry with Computer Vision, AI, and Deep Learning

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Introduction

Raghav Mecheri spent the summer of 2021 staring at images of trash. Mecheri, then 21 years old, had dreams of revolutionizing the waste-processing industry by training computer vision models to recognize the items that end up in industrial waste-processing facilities. He believed that this process would improve safety and reliability across the recycling supply chain and enable greater reuse of materials. There was one enormous obstacle: He couldn't just download a massive set of waste images from Flickr. "There are no images of trash on the internet," he said. "Nobody builds this stuff for fun, right?"[1]

So Mecheri and his cofounder James Bollas persuaded waste-processing facilities along the East Coast of the United States to let them set up cameras across their sorting lines. They promised to generate free consulting reports in exchange for industry feedback on the usefulness of the data they were providing. The idea was that the cameras would monitor the facilities' conveyor belts as they inched below carrying unsorted materials, transmitting snapshots to the cloud.

Mecheri and Bollas purchased the first cameras on Amazon and installed them by hand. They also took responsibility for fixing the hardware when it went offline. Mecheri recalled learning of a downed camera at 1:30 a.m. on a Saturday, grabbing a slice of pizza and bottle of water at a nearby bodega, and catching a 2:30 train on Amtrak's high-speed Acela line from New York to Boston, where he arrived at 8:00 in the morning to fix the problem. He took the train back home the same evening.

Once activated, the cameras sent images from inside the facilities to Google Cloud, and Mecheri's team wrote a script that retrieved randomized subsets of images into a Jupyter Notebook on their computers. Then, Mecheri and Bollas painstakingly audited each image by

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hand, and compared it to the output from an early version of their AI platform. That dataset eventually grew to more than 5,000 images.

That initial batch of photos—a tiny sample size compared to the 50 million-image library they'd collect by mid-2023—provided the base for BinIt's computer vision platform today. "It did not do very well at all," Mecheri said of the trial. "But it was enough to get us customer feedback and buy-in, which was worth its weight in gold."

Mecheri's startup was not the first to use computer vision in the recycling industry. He hoped he'd be able to break away from the pack by developing a fast, highly automated process that could be adapted for the broad spectrum of materials handled across different types of waste-processing facilities. The key would be to create robust, custom models for each customer, adapting their technology to meet their individual needs.

Background on the Recycling Industry

OVERVIEW

When an empty soda can gets tossed into the correct (blue)[2] waste receptacle at a New York City apartment building, it's already beaten the odds. Across the five boroughs, just 28 percent of aluminum cans make their way into the recycling system, according to a 2013 residential waste study by the Department of Sanitation.[3] Citywide, more than half of recyclable materials thrown out from apartments and homes wind up in a landfill.[4] For commercial enterprises like restaurants, office buildings, and universities, the numbers are slightly better: About a quarter of all business garbage is diverted from the landfill, though the city estimates that number would rise to 75 percent if systems for composting and recycling collection improved.[5] Nationwide, the numbers are similar: In 2017, 94.2 million tons of municipal solid waste generated by Americans were recycled and composted, out of 267.8 million tons total.[6]

From the blue waste bin, the soda can is picked up either by city sanitation workers, who handle residential recycling, or by private trash haulers, who handle commercial waste. Businesses pay an average of $12.08 per cubic yard[7] for these services.

The public and private haulers drive their trucks to hauling barges[8] or directly to recycling plants, also known as material recovery facilities (MRFs), pronounced "murfs."[9] In Brooklyn's Sunset Park, an 11-acre MRF[10] on a pier collects 15,000 tons of commercial and residential recycling each month.[11] Other types of non-MRF recycling plants that fall under a broad banner of facilities called intermediate waste-processing facilities, or IWPs, include construction and debris recycling facilities, electronic waste processors, and textile recycling plants.

Once the clear bags of recycling are taken off the trucks or the barges, all the material is moved onto the floor of the MRF, where human workers remove large items like bicycles. The remaining items are then transported onto a conveyor belt, where they are ready to be sorted by material type into categories.

The Sunset Park facility, which bills itself as one of the most advanced in the United States,[12] uses a variety of methods to further separate materials into plastics, glass, and metal. Aluminum cans are sucked up off the conveyor belt by a giant magnetic drum.[13] Infrared sensors sort plastics by type. Human workers audit each waste stream to ensure accuracy. Then, the "pure" categorized waste is collected in a dumpster and compressed into a rectangular block more than a meter long on every side.[14]

From there, the facility sells these giant compressed cubes of recycled material for further processing. A bundle of soda cans and foil might be processed into more soda cans, more aluminum foil, or airplane parts. Plastic from bottle caps and laundry detergent bottles may be turned into plastic pipes or trash cans. The bottles used for bottled water, soda, and clamshell containers for grocery store items like salad greens and berries might be repurposed into carpeting or clothing.[15]

The best-case recycling scenario for a soda can or water bottle is for it to end up in one of these bales. In reality, many items are ultimately sent to the landfill because of contamination.[16] Worse, recent macroeconomic shifts have made recycling more expensive as landfills remain cheap. In some places, recycled plastics are burned or landfilled rather than reused.

A MACROECONOMIC SHOCK

The U.S. recycling industry has experienced a seismic shift in recent years. For a long time, the United States exported recyclables to China, which repurposed them into new materials. In 2018, though, China implemented a National Sword policy that raised the purity standards for imports of new recyclables. Prior to the implementation of the policy, in 2016, the United States exported 16 million tons of recyclables to China. Today, the United States ships less than two million metric tons of waste abroad—a steep drop from 2016 levels. The change left U.S. recycling firms scrambling to ship containers of recycling to other countries in Asia and Africa, which in turn implemented their own import bans. An estimated 20 to 70 percent of that discarded material is never reprocessed.[17]

China's policy shift upended the economics of the recycling industry. In Bakersfield, California, for example, the city used to earn $65 per ton of recyclables. After the shift, the city had to pay $25 per ton to dispose of them.

Municipalities struggled to adjust. Without revenue from China, recycling companies raised service prices for cities and towns, which responded by diverting waste or, in some cases, halting service altogether. By 2019, Philadelphia was burning about half of its recyclables in an incinerator, which generated energy but also ran the risk of contributing to air pollution.[18] Deltona, Florida, suspended its recycling program the same year. Some places, like the airport in Memphis, kept the blue and green recycling bins in place to preserve carefully built consumer recycling habits. It was a customer-friendly illusion: Once the bags were collected from the bins, they all went to the same place.[19]

NEW TECHNOLOGIES

By 2023, recycling in the United States was in the midst of a transition. For decades, products could be sold to China at prices that maintained profits for recycling companies and worked for municipalities. Now, recyclables—and plastic in particular—had nowhere to go. For recycling companies, it was more important than ever to run efficient, accurate sorting systems that could keep as much waste as possible out of the landfill.

In recent years, optical sorting and robot technologies have been gaining popularity.[20] Borrowing hardware developed for other industries, like food processing, early movers adapted the technologies for a recycling setting.

The first optical sorters entered the recycling industry in the 1990s.[21] Though they held a lot of promise, they frequently required large capital expenditures and more computing power than was readily available. They were also glitchy, malfunctioning in the dusty atmosphere of the MRF. The technology improved substantially in the 2000s and 2010s, growing more accurate and more durable. By 2020, Waste Management, one of the biggest players in the industry, reported that 40% of its facilities were using optical sorting technology.[22] Despite growing industry adoption and substantial performance improvement, limitations remained. A 2022 article in *Waste Today* magazine reported the machines needed to be recalibrated every one to three months.[23]

In part because of these obstacles, panelists at the 2020 Waste Expo wondered whether the industry had reached "peak optical sorter."[24] MRF operators were turning their attention to a new and exciting waste-sorting technology: robots.

MRFs began installing robotic hardware initially developed for other industries like car manufacturing, as they waited for developers to build products specific to the industry. This meant operators faced problems with gripping and sorting, and robotic arms suffered from durability issues in the MRF environment.[25] Despite these challenges, the new technology generated a lot of excitement. By 2019, robotic arms were making twice as many "picks" per minute as their human counterparts.[26]

Industry experts saw robotics and optical sorting as complementary technologies. They saw a lot of promise in the addition of a layer of AI and machine learning technology on these existing systems that could improve accuracy and reduce the need for costly and cumbersome recalibrations.[27] Industry upstarts had the potential to break in by offering software systems that were compatible with existing hardware or by developing hardware that could outperform the current systems. There was also opportunity for AI firms that could address problems that were not adequately solved by optical sorting or robotic arms, an opportunity that BinIt was keen to leverage.

BinIt's Story

EARLY DAYS

It was Raghav Mecheri's 19th birthday when his five-person team won first place in the Columbia Venture Competition's Undergraduate Challenge, tying with a startup that was working on a product designed to help law enforcement instantly identify people under the influence of impairing substances.[28] BinIt's prototype was a waste receptacle that automatically separated recyclables from landfill material.

"The underlying logic was simple," Mecheri said. "Trash in America and trash globally is way too complicated. There are three (or more!) bins everywhere. We have limited visibility into what goes in what bin, and there is plenty of anecdotal evidence that trash is often not sorted well at the source," he added.

When the BinIt team won $25,000, it felt like a lot of money to the teenage members. Then the COVID-19 pandemic hit, and Mecheri found himself attending class via Zoom from his home in India. The five founders soon realized "nobody wanted to pay four figures for a robotic trash can," as Mecheri put it, and turned their attention elsewhere, still committed to spending the grant money on an entrepreneurial venture. They looked into data privacy, file streaming, and file sharing before eventually circling back to waste.

"The world has a fundamental macroeconomic problem, which is that we need greater visibility into recycling," he explained. "Everyone from MRF operators to legislators benefit from increased data on waste streams and visibility into the circular supply chain."

"Often, the last piece of data ever created on a piece of recycling is the credit swipe when someone purchases a six-pack of seltzer at the grocery store," he added. "After the bottle is disposed of, it enters an often opaque supply chain—we wanted to make it more transparent."

The team eventually estimated that creating this level of visibility across the waste-processing industry represented a multibillion-dollar opportunity. Put another way, an AI vision product could save recyclers more than $150,000 per year by reducing contamination, diverting hazards, and improving their accuracy.

The BinIt team quickly saw the parallels between their newfound vision and their prior work in the AI-powered waste-sorting space. Their new idea wasn't too dissimilar from the original prototype—both relied on intelligent software to identify waste material. The difference was that instead of building trash cans to manage the problem at the household level (expensive, unwieldy), they'd work on products for the intermediate waste processors that collected recyclables and sorted them for further processing.

FROM PROTOTYPE TO COMMERCIALIZATION

In 2021, BinIt found its first recycling customers, the material recovery facilities, which agreed to have cameras installed in exchange for biweekly progress reports. BinIt was transparent with those initial customers—the reports had a significant human component and were not fully automated. That was the summer Mecheri spent labeling images of recycling and riding the train from New York to facilities across the East Coast to fix faulty cameras.

By the end of 2021, the team had their starting point: over 5,000 images they had painstakingly labeled by hand with recycling-relevant data (for example, the kind of plastic in the picture). The time had come to use this dataset and their prototype to create the next version of their machine vision platform.

Of the five-person founding team, three were involved in Columbia's Machine Learning research ecosystem. "Making something work was just part of that process at the time," Mecheri said, adding that "behaving like college kids" was a large factor in the company's early progress.

The team was well aware of how difficult it would be to train a deep learning vision model from scratch. These models are typically based on deep neural networks—powerful predictive algorithms that often comprise millions, if not billions, of parameters. Developing such a model from scratch would necessitate substantial engineering resources, both in terms of computational power and workforce. This would mean both an enormous capital raise and considerably delayed deployments.

Instead, therefore, the team decided to leverage transfer learning, a powerful technique that would allow them to use an existing, open-source computer vision model and adapt it to carry out a specialized task. They sought advice from other startups that worked on tasks like automated traffic violation detection and analytics for manufacturing. "I think shedding this belief that you're building something unique from the ground up helped us move a lot quicker," Mecheri said. "In a way, your novelty does not come from the ability to build something unique, but it comes from the ability to build something quickly, iterate on it, and acquire some kind of nuance or perspective that is unique to both you and your industry."

The team used Python augmented with open-source deep-learning libraries to fine-tune this model employing the images they had collected and manually labeled. Powered by an array of GPUs provided by cloud providers like Amazon Web Services (AWS) and Google Cloud Platform (GCP), the BinIt team worked through their junior year at Columbia to build an initial production-ready Machine Learning model. "It didn't do very well at all initially," Mecheri said of the first effort. "We kept iterating on that process until we had something that worked well. Our current approach has evolved considerably, but transfer learning got BinIt v1 off the ground. "

BINIT'S FIRST CUSTOMERS

Thus far, BinIt was providing its services for free, but, armed with its nascent model, the company looked to have a real path to commercialization. "That's when the conversation got a lot more real," Mecheri said of the founding team. They were all set to graduate in 2022 but were starting to go their separate ways. They sat down and had what Mecheri called a "very clear and surprisingly civil" conversation about their long-term priorities. Eventually, three of the five cofounders transitioned into advisory roles, going on to pursue PhDs, found another company, and work in private equity. Mecheri is the current CEO, and James Bollas is the chief technology officer. Their team has since grown to nine people, based in New York, London, and Berlin.

The original business model was straightforward: They'd purchase the cameras themselves, then install them and collect a monthly per-camera subscription fee from each facility. The first month's subscription revenue paid for the hardware, and the remaining months supported the rest of the business.

The BinIt team continued refining the product and the underlying technology, responding to customers' feedback. At one point, as they were attempting to train their models to identify a plastic substance called polypropylene, the system began seeing the material all over the place. Customers were livid—the dashboard wasn't useful if it was constantly flashing false alarms. As it turned out, the model had begun identifying polypropylene in Coca-Cola bottle caps. It wasn't wrong, but the bottle caps were everywhere. The incident led the BinIt team to introduce a feature that gave clients access to their own image library so they could investigate similar issues in real time by viewing a given conveyor belt, camera, and time stamp. "Either that builds confidence in our outputs, or you can report the frame and tell us we've messed something up—it's the best way to get better!" Mecheri said.

ANOTHER MAJOR TRANSITION

BinIt's second major pivot started with a fire. Mecheri was installing a camera at a material recovery facility when he heard a massive explosion. A nearby conveyor belt was engulfed in smoke, and flames leaped around them. Mecheri and Bollas looked at each other, unsure of what to do. Within a minute or two, a maintenance person arrived. "Get out, can't you see the fire?" Mecheri recalled him screaming.

The fire had been started by a lithium-ion battery. Hidden batteries make their way into material-processing facilities in products like laptops, electric scooters, and e-cigarettes.[29] These highly volatile batteries explode when they are punctured or overheated, and fires can also be caused by aging or defective products.[30] Worse, the batteries are difficult to detect with a camera or the naked eye because they're small and compact. The facility staffer called them "the industry's biggest problem," and in that comment the BinIt team sensed an opportunity. Soon, their research revealed that out of the 600-plus facilities that accept curbside and single-stream recycling, over 200 had a fire in 2022. "As somebody who grew up in a family of fire safety entrepreneurs, I knew we could do better as a sector," Mecheri said.

The BinIt team began researching technologies that could detect lithium-ion batteries within waste streams, finally settling on X-ray technology. Adding X-ray machines to their product line would mean incurring significant capital expenses to purchase each 2,000-pound device. The old software as a service (SaaS) subscription model wouldn't absorb those costs. In 2023, BinIt decided to sell the X-ray machines as a hardware product alongside a software subscription. "Today, we're what I call a 'hardware-enabled software business,'" Mecheri said.

Mecheri saw the products as two sides of the same coin. "They both look for things that shouldn't be there and help people identify those things, so that they can eventually be removed. They just look for different things with different levels of accuracy."

With the addition of the hazard detection product, BinIt was poised to expand rapidly. BinIt Hazard (their X-ray product) was already drawing attention from clients for its potential to put a stop to the dangerous and expensive fires caused by hazardous materials, and Mecheri was convinced he could use this as a springboard to expand the company's horizons to compliance and broad-spectrum material feedstock data for the recycling sector:

> We believe that the next generation will spawn a plethora of category-defining business—especially as the supply chain grapples with the inevitable transition from linear to at least partially, if not completely, circular.

THE CHALLENGE

BinIt's success or failure would depend on its computer vision models' performance in two key tasks. The X-rays had to readily identify hazardous contaminants like lithium-ion batteries, and they had to do so both quickly and accurately. A single devastating battery fire resulting from a BinIt technological error could ruin the company's reputation in the relatively concentrated industry. At the same time, the cameras had to provide high-level, actionable insights into facilities' sorting operations, enabling managers to save money and reduce landfill waste. In other words, the cameras were only useful if they paid for themselves.

The company would not thrive without high-performing computer vision models. But in order to deliver customized AI software to each client while also scaling up, BinIt had to find a way to move from hand-labeling individual trash images to producing sophisticated new models at a rapid clip. The model BinIt had trained based on the initial image set they had hand-labeled was useful, but it was far from perfect. Furthermore, the team quickly realized that using a single model wouldn't cut it. They found that every facility was different, and that there would be considerable advantages for an ability to deploy distinct, personalized models to every client.

Despite these challenges, Mecheri was optimistic. He felt the excitement among customers who were eager for lithium-ion battery detection, and he was confident BinIt's technology could leapfrog its competition. In mid-2023, he embarked on another funding round, ready to take BinIt to the next level.

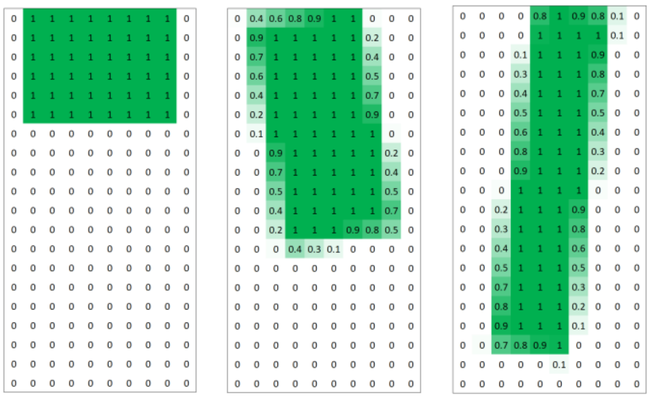
A Simplified Example

To better understand the technology underlying BinIt's business model, we shall consider a simplified example that mirrors many of the challenges BinIt faces in its algorithms.

In this problem, a camera captures monochrome ("black-and-white") still images of objects in a recycling facility. These objects need to be sorted based on their lengths, so that they can be sent to the right machine.

The images are divided into 200 pixels, arranged in 20 rows and 10 columns; each pixel is represented by a number between 0 and 1, where 0 indicates pure white, and 1 indicates opaque black. The camera is set up to ensure the bottom edge of the object is always aligned with the top of the image, but the picture may be slanted, and images may have different thicknesses and lengths.

The three images below display examples from this dataset, with each pixel value converted to a shade of green. The image to the left is shortest and thickest and is oriented head-on. The image at the center is slightly thinner and longer and slanted in one direction. The image to the right is thinnest, longest, and slanted in the other direction.



To decide what machine each of these objects should be sent to, our algorithm will need to determine each object's length—it would need to automatically determine that the object to the left is short, the one in the middle is of medium length, and the one to the right is long.

We will consider how an algorithm like BinIt's might be used to do this. It is worth noting that because of the simple structure of this problem, more traditional techniques might work here, too, but we will use neural networks. We will look at a small set of training data, use it to train our neural network, and see how it might be used in practice.

Before class, ask yourself how you might train a computer to carry out this task—if you had to convert your intuition to a simple set of instructions, what would they be?

Exhibits

Exhibit 1: Sketch of the Prototype that Won BinIt the Columbia Venture Competition

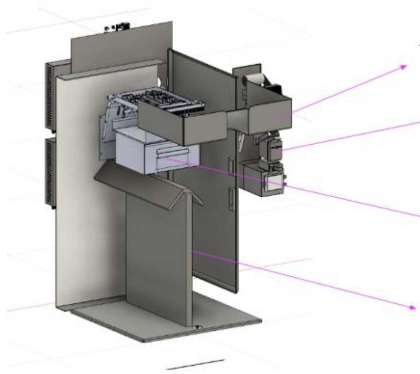


Exhibit 2: Installing a Camera in the MRF

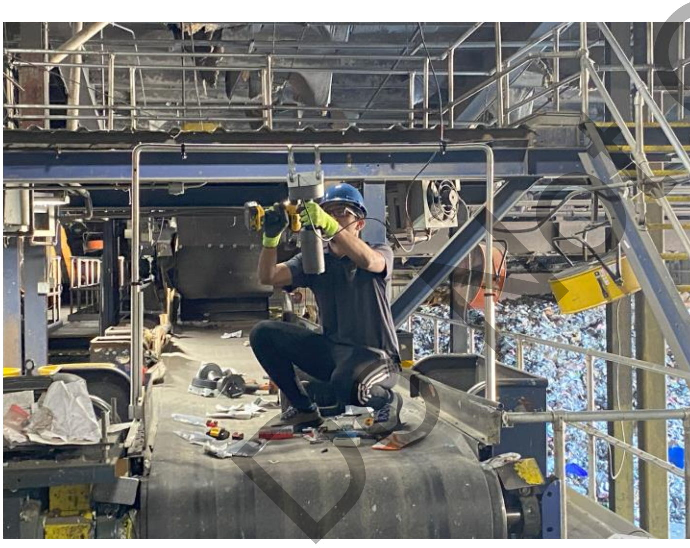


Exhibit 3: BinIt's Camera in Action

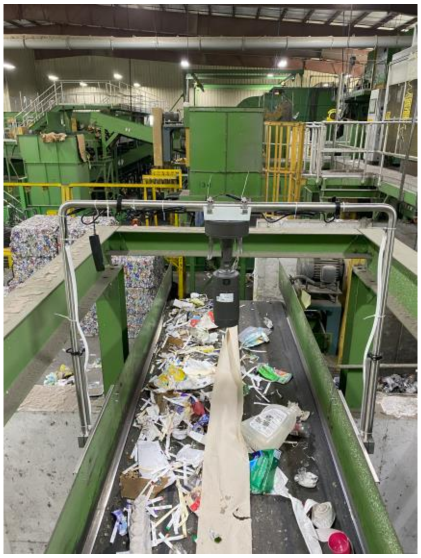


Exhibit 4: BinIt's Algorithm in Action

Endnotes

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