EXCAVATING ROBOTIC WASTE
Neo Tokyo & Beyond

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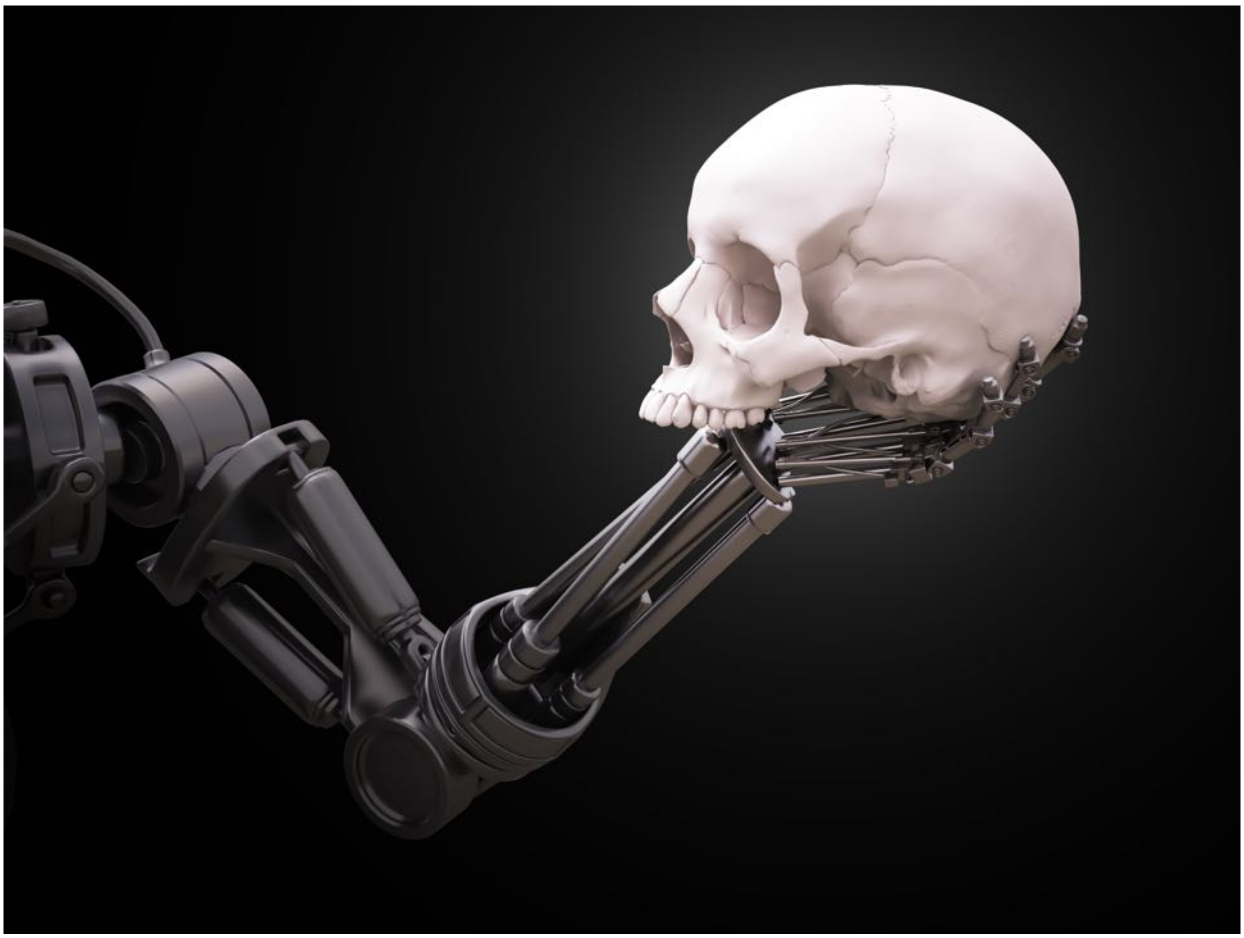
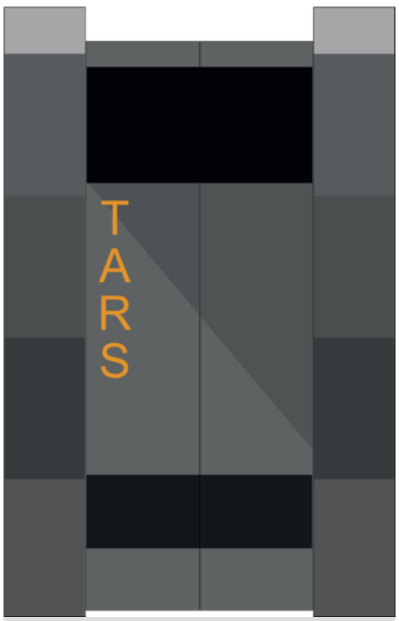


Most people feel a certain ambivalence regarding robots. After years of reading tales about cyborgs and technology-run-amok in dystopian Japanese manga, as well as watching decades of Sci-Fi films—from Fritz Lang's *Metropolis* (1927), *A Clockwork Orange* (1971), *Solyaris* (1972), and *Invasion of the Body Snatchers* (1978) to *Brazil* (1985), *eXistenZ* (1999), *Children of Men* (2006), and *Under the Skin* (2013), I am certainly no exception. What follows is an unconventional opus of organized musings, interpretation, and analysis over robots, resources, space exploration, and what might befall the human species as the planet changes and technology continues along its accelerating arc. Amid all this serious rumination over robots, development, and the implications of environmental and industrial policy in Japan and China in particular, I found myself glimpsing fragmentary lurid scenes from movies or overhearing snatches of dialogue involving robots and the future. It was inevitable that some of those ventriloquist shards would find their way into the present text.

Introduction: Matrix evolutions

In a sector—robotics—that suffers from an abundance of hype, persistent efforts to inculcate buzz, and sometimes desperate attempts to attract capital, it was striking that a project that seemed, at first glance, to be about grabbing attention and creating shock value turned out to be more substantial and thought-provoking. An international team working in a nascent field sometimes described as "evolutionary robotics" in 2021 crafted an early empirical foundation toward building an autonomous robot ecosystem. Such an evolutionary matrix could, in time, be sent to a distant planet, for instance. As a self-regulating, continuously adapting outpost, such a foothold perch could foster conditions to help sustain the eventual arrival of human life on an utterly different world. Given that most planets offer extremely harsh and forbidding environments in which to survive, the robots would have to be robust and adaptable to be able to withstand the bitter, unforgiving extraterrestrial "elements" there—particularly in outlands whose particular climatic conditions and physical/chemical compositions remain little known to scientists. Furthermore, to be able to endure over time, the robotic matrix would need to be recyclable. The last point is of particular significance here, and I return to this question of material recovery and material conversion below.

Matrix (1999), general excitement on board the Nebuchadnezzar after Neo's kung fu upload: **"MORPHEUS IS FIGHTING NEO!"**



TARS robot from Interstellar (2014):
"EVERYBODY GOOD? PLENTY OF SLAVES FOR MY ROBOT COLONY?"

The project, called Autonomous Robot Evolution (ARE)—comprised of a team based at several UK universities and the Vrije Universiteit Amsterdam—involves creating a menagerie of varied robots within a self-contained test setting.

Physical robots are 3D printed, drawing on an extensive toolkit;[1] furthermore, each physical robot has a digital avatar that undergoes extensive and rapid simulated evolution in the matrix's mainframe, or "grey matter." In this arena of what might be called "unnatural selection," new generations of robots are then "conceived" and "born" of this combination of physical and digital problem-solving, combining and building on those traits that are most successful in the test field.[2] Swiftly sequencing through successive generations while engaging with unfamiliar conditions on a new world, the matrix might yield a robot that crawls on many limbs, or uses wheels or tracks, adapting all the while to its surroundings. Perhaps it might scoot or slither in articulated sections. Because the matrix operates

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[1] M. F. Hale *et al*., "Hardware Design for Autonomous Robot Evolution," *2020 IEEE Symposium Series on Computational Intelligence (SSCI)*, 2020, pp. 2140-2147, doi: 10.1109/SSCI47803.2020.9308204.

[2] "We're teaching robots to evolve autonomously," *The Conversation*, 21 February 2021 (https://theconversation.com/were-teaching-robots-to-evolve-autonomously-so-they-can-adapt-to-life-alone-on-distant-planets-153159/, accessed December 2022)

ROBBY ROBOT CARRYING UNCONSCIOUS BLONDE, FORBIDDEN PLANET (1956)

independently of human control, solutions to such exoplanetary challenges would likely go beyond what human controllers could conceive of themselves. The matrix could be sent to distant outlands decades or perhaps centuries in advance of human arrival, providing optimized support available for whenever humans might embark upon their sojourn there.

So far, so far-fetched. Discourse on interplanetary travel, not to mention involving robots, tends to take on an exceedingly speculative tone, and this bot-populated space yarn is no exception. Nevertheless, elements of this seductive droid narrative bear some discussion. For instance, the technology for setting up the robot matrix might precede the technology for successfully transporting human pioneers (or refugees) by many years, meaning that the intervening time could be used productively to progress the aim of settling anew in cruelly inhospitable exo-terrain. The robots could begin building shelter that would safeguard the matrix while at the same time providing an emergent base for a laggardly human landing party. In such a shelter, terrestrial plant life, perhaps even insects and animal life, could be encouraged to flourish in order to provide oxygen and sustenance for eventual human consumption. In the meantime, the rotting of dead matter, etc., would produce carbon dioxide in order to help support the new flora. Robot builders could be joined by robot caretakers and robot groundskeepers, who would allow this Eden to go through its own evolutionary generations before humans arrived to enjoy the fruits of robot labor.

CUE LEGENDARY CYBORG “BIRTH” SCENE FROM GHOST IN THE SHELL (1995).

Such is the stuff of future dreams, not to mention fertile material for forward-thinking screenplays, dystopian manga/anime, and Sci-Fi novels, many with specific reference to Japan. The idealized, just-so, romanticized quality is familiar, even *de rigueur*, in discussions of space exploration and terra-forming of exoplanets. In order to engage in such futuristic rhapsodizing, it becomes necessary, even desirable, to skip numerous thorny stages where current technology falls short or where the expense of such ventures could only be justified if the very survival of the human species were much more clearly and presently hanging in the balance.

FURRY ROBOT, RO-MAN, FROM ROBOT MONSTER (1953).

SERVICE ROBOTS AMID MANICURED GROUNDS ON SPACE STATION, ELYSIUM (2013).

Yet what is clear from an outside, contrarian’s examination of the sector is that the creation of a more sustainable system for recycling space-faring robots could also be used to benefit life on Earth. Our current infrastructure for producing, using, discarding, and sometimes recycling and remanufacturing computers, appliances, and other devices involves a great deal of destruction, pollution, inefficiency, and toxic residue. A better system for (re)production of robots—a waste stream that is sure to grow exponentially in the coming years—could offer eventual environmental and material benefits of terrestrial scale. Yet there are also more profound implications; future-tech developments like these could also furnish a roadmap in order to help transform the very pathways along which electronic waste (or "e-waste") currently languishes, more often than not, in a range of settings, particularly in the Global South.

> *Handsome, creepy David 8 android from Alien: Covenant (2017):*
> **"NO ONE UNDERSTANDS THE LONELY PERFECTION OF MY DREAMS. I FOUND PERFECTION HERE. I CREATED IT."**

Excavating robotic waste involves grappling with, and hopefully reducing, the amount of waste generated in the first place. It also prioritizes repair—a far more "eco" way of coping with unwanted electronics, as I explain—over mass disposal and mass recycling. This piece highlights facets of the recycling challenge by furnishing examples and lessons drawn from my longstanding ethnographic research into e-waste scavenging hotspots in places like South China (e.g., Kirby 2019a); the Tohoku disaster zone after the record 2011 earthquake and tsunami (e.g., Kirby 2022, Kirby 2019b); and broad efforts in Japan and Europe to craft an aspirationally circular system of material conversion by way of "the shredder economy" (Kalimo, Lifset et al 2012) (e.g., Kirby 2018, Kirby 2011). Such real-world examples, as extreme as they may often seem, not only give a sense of the environmental challenge facing the planet but also provide empirical evidence of ways that material conversion might eventually operate within configurations like the ARE matrix.

These pages offer a nonstandard merging of the ethnographic and the programmatic. The intermittently forward-looking or speculative dimension of the present account is not only (arguably) evocative but productive, given the emergent and multifaceted nature of robots, both real and imagined, and their deployment in contemporary Japan and other tech-fixated societies; this intermingling here of case studies and ideology, of evidence and imagination, of analysis and anxiety, is part and parcel of droid discourse across the robot-strewn terrain of our sci-fi-informed tech future.

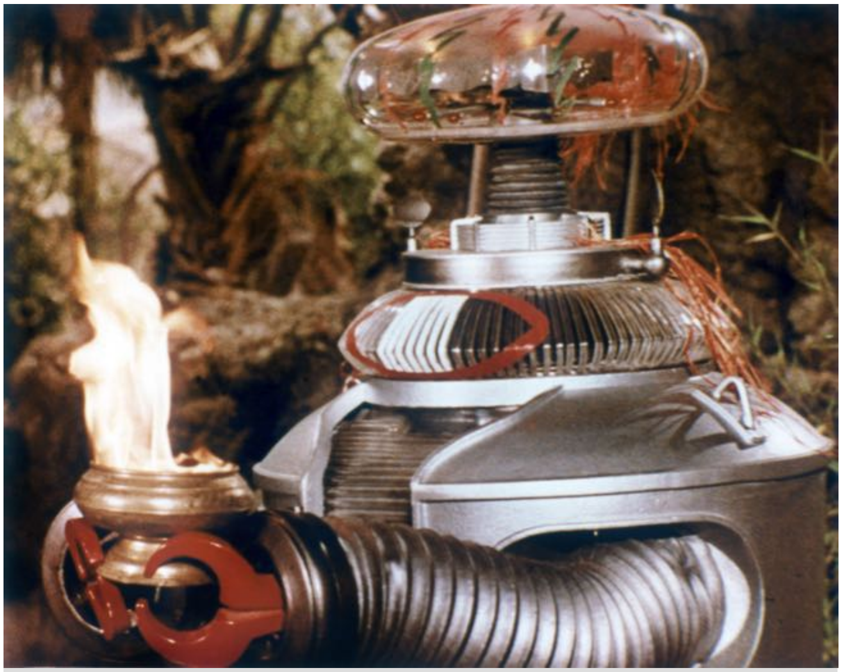
First, it is useful to consider how popular culture and other representations of the robotic imagination have informed how autonomous machines are interpreted in areas of the industrialized world.

SPIDER DROIDS CRAWLING AROUND AS SENSORS, *MINORITY REPORT* (2002).

RELATING ROBOTS

Robots—both the actual, somewhat mundane, contraptions themselves and also the lively frieze of droid images that hovers in the capricious imagination of varied publics—comprise a funhouse-mirror reflection of human societies and social change. From space operas to dystopian fables, all manner of fictional narratives involving robots invoke a future where human life becomes engulfed by machines. Robots thus serve as corollary triggers for anxieties over technological development, suspicions over surveillance and automation, and persistent questions over the human mind and whether advanced artificial intelligence is possible or indeed desirable.

It is telling that the world of robots always seems to be on the verge of reality, never quite materializing. This is characteristic of the robotic imaginary, which would collapse—perhaps not unlike a futuristic outpost under machine attack in a standard sci-fi yarn—if people's everyday lives were actually teeming with rudimentary droids that could hardly accomplish basic tasks. The banal experience of the Roomba vacuum cleaner over several days inspires mild boredom, not terror. Indeed, as I discuss below, the actual level of robot development on Planet Earth is so woefully beneath the level of the robots with which we're familiar via popular culture that such breathtaking contrivances, and the weighty questions they raise, will remain out of reach for quite some time longer.



THE B-9 ROBOT, NICKNAMED "BLINKY," LOST IN SPACE (1965): **"DANGER, WILL ROBINSON!"**

Nevertheless, in film and television—and less prominently in literary work and comics/manga—robots serve an important function, allowing us to question what is unique about human experience, offering a contrast between embodied, "meat"-limited mind and emotion on the one hand and artificial capacity and enhanced execution on the other. The mechanized, non-human Other, as presented in a deluge of pop-cultural output, is correspondingly coy, shapeshifting and ambiguous, taking the form of 1) fully mechanical robots (or sometimes pan-machinic AI); 2) different degrees of cyborg (a fusing of human and tech components); and 3) varieties of "synths" created via mimicry of biological and anatomical processes in order to "grow" synthetic beings along pathways separate from humans. It is therefore fitting that the term "robot" derives from a 1920 play entitled R.U.R, or Rossum's Universal Robots, written by Czech playwright Karel Čapek, in which the eponymous subalterns are organic humanoids created in a lab solely for the purpose of work. Čapek's robots are biological entities that pass easily for humans, and are held without volition, freedom, or prospects, to say nothing of rights. (In a further wrinkle, *robota* means forced or compulsory labor and comes down from the Czech word for "forced worker," *robotnik*. The almost homophonous noun *rabota* derives from an archaic term for servitude, itself derived from *rabu*, "slave" [OED, n.d.; Online Etymological Dictionary, 2021].)

"The banal experience of the Roomba vacuum cleaner over several days inspires mild boredom, not terror."

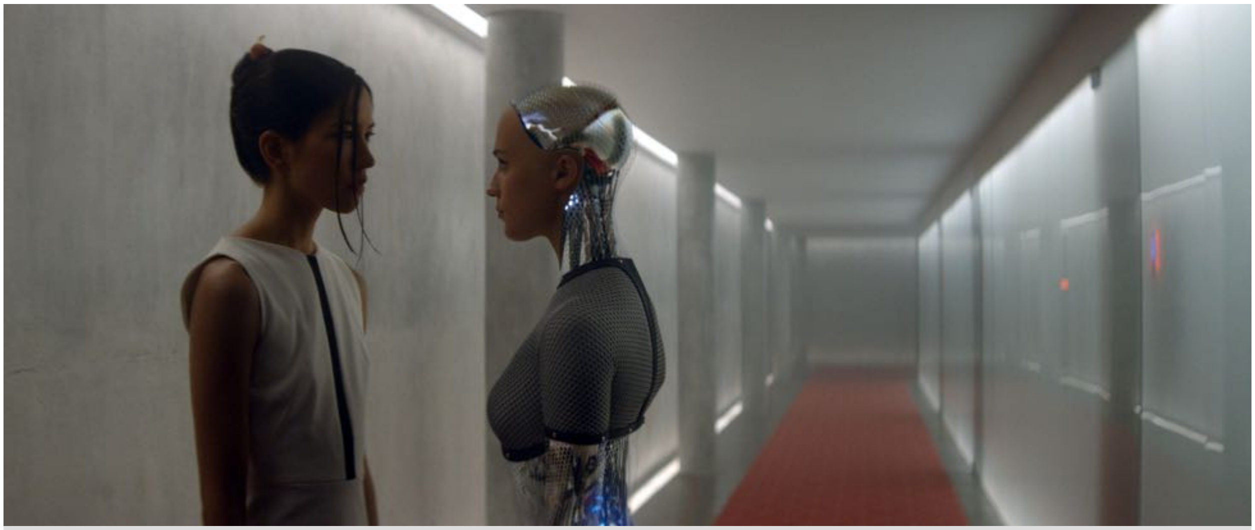
Anticipating a not-uncommon storyline, Čapek's human characters speak of R.U.R.'s robots as not having a soul, but numerous subsequent works have posited a consciousness, identity, or "ghost" that can make robots uncannily human in their conception of mind, claimed personhood, and consciousness (Lem 1977; Asimov 1950; Shirow 1991; see also Putnam 1964, Schwab 2020; cf. *Dark Matter*, created by Joseph Mallozzi and Paul Mullie, 2015). There are even fully virtual AI entities that manifest with a robot-like avatar, like the quirky AI hotel manager with an extremely poor sense of guests' personal boundaries (*Altered Carbon*, created by Laeta Kalogridis, 2018);

or a starship captain's cool, dance-adept "first mate" who provides a high-functioning virtual link to the vessel's systems (*Another Life*, created by Aaron Martin, 2019). Even though the electronics that generate such AI avatars could be conceived of as having similarities to robotic components, the present article is focused on discrete robots' material forms, e-components, and their recycling; for this reason, I leave these virtual/holographic avatars aside here.

Futuristic storylines may choose to "other" robots by making them more overtly mechanical, or they may make them dead ringers for homo sapiens. Each strategy furnishes abundant opportunity to render machines terrifying to human audiences. They may manifest as looming hulks bristling with weaponry, like RoboCop's nemesis the ED-209 (*RoboCop* 1987; dir. Paul Verhoeven) and other "enforcement droids" that boom, plod, and clatter through various SF franchises—or they can be so small as to escape detection, even burrowing into human orifices to lodge inside a person's body (*The Matrix*, 2000, dir. The Wachowskis). Correspondingly, there are filmic robots that can so effortlessly mimic human appearance and tics of communication and expression that their very shapeshifting similitude itself becomes unsettling. In films like *Prometheus* (2012, dir. Ridley Scott), the automat presents as more or less unquestionably "human" until revealed to be comprised of wiring and goop later in the story; in the *Alien* franchise, this android reveal has become a reliable element of the plot formula—see, too, *The Windup Girl* (Bacigalupi, 2009), a novel whose beautiful Japan-made automat has to suffer tell-tale movement impediments (and all manner of other humiliations) until she "jail-breaks" from the software. Back on Earth in relatively sedate-seeming early twenty-first-century contemporary life, the exploits of "dog-soldier"-style robots have gone viral in recent years, including a range of headless, bright yellow-and-black models from Boston Dynamics that can balance when destabilized on ice and negotiate shifting rubble, as well as a humanoid robot, Atlas, that can do a backflip and other tricks. These contraptions frequently creep out human viewers with how adroitly they can perform difficult tasks, but even these creations are unsophisticated compared with most of the autonomous fictional mechs that many people see as representative of robots in popular culture.

> "There are numerous possible positions on a continuum between remote human control at one extreme and autonomy and even sentience at the other extreme when speaking of such apparatuses."

In order to capture the full range of contrivances that both already exist and will develop in the coming decades, I use the term "robot" (and "bot," sometimes "automat" or "droid") in this article to refer to autonomous or semi-autonomous synthetic entities that, broadly speaking, engage with, perform tasks (at some stage) for, or coexist with humans. Naturally—as it were—there are numerous possible positions on a continuum between remote human control at one extreme and autonomy and even sentience at the other extreme when speaking of such apparatuses. To advance a discussion of robotic waste here, I use the term omnivorously to include drones, some electric vehicles, and types of future appliances in a capacious category of "robots" when considering tech development, discard, repair, and conversion. Nevertheless, I understand that a tighter classification could offer some advantages. A strong case could clearly be made to fashion a much narrower definition of robot to distinguish between fully autonomous entities with relatively complex problem-solving and adaptation capabilities and, conversely, drones/e-craft which are generally piloted by humans with tighter monitoring and control. This, however, glosses over the question of tech waste, which is a core preoccupation of this article.



EXPLOITED "FEMALE" ROBOTS PLOTTING THEIR REVENGE. *EX MACHINA (2014)*

ROBOT ANXIETIES

A glance at blockbuster film offerings reveals an enduring and popular fascination with synthetic creatures, systems, and devices that become self-aware, become degraded and unstable, become indistinguishable from humans, and/or become hacked, suborned, or appropriated by interested parties. But these robot fables are just as likely to be vehicles for other social anxieties. A brief account here touches on a few well-known examples of iconic franchises in order to help dispense with extensive description.

For instance, the neo-noir masterpiece *Blade Runner* (1982, dir. Ridley Scott) is, like many such futuristic films, concerned with the astonishing ability of so-called replicants to impersonate and ventriloquize humans, comprising a sensitive, though blood-soaked, meditation on personhood and identity. Much of the story involves Decker (Harrison Ford) struggling with his grim job hunting down and assassinating replicants while at the same time falling in love with a replicant and trying to save her from an apparatus dedicated to her destruction.

> "The film also reflects some ambivalence over a muscular killing machine … with a foreign accent wearing American sunglasses and leathers, jacking iconic Harley-Davidson motorcycles from God-fearing citizens, and shooting constitutionally protected firearms while laying waste to American communities."

But the film, made in the early Eighties, is in many ways just as much about anxiety over a rising Japan during its period of high-speed growth and competition with American industry. East Asian iconography litters the film and close scrutiny reveals a disturbing amount of dwarves, apparently presented as an unspoken racist critique. Significantly, the Philip K. Dick story on which the film is based, *Do Androids Dream of Electric Sheep?* (Dick, 1968), has no such East Asian context.

The Terminator (1984, dir. James Cameron), made just two years later, is very much about unchecked technological development, the dreaded rise of machines and their gruesome, crimson campaign to exterminate the human race.

However, made during the height of the Cold War, the film also reflects some ambivalence over a muscular killing machine (Arnold Schwarzenegger) with a foreign accent wearing American sunglasses and leathers, jacking iconic Harley-Davidson motorcycles from God-fearing citizens, and shooting constitutionally protected firearms while laying waste to American communities.

It's difficult to pinpoint what *The Matrix* (1999, dir. The Wachowskis) precisely "means," seeing as it is a self-consciously cerebral mash-up ruminating over choice, control, and Gnosticism across a sprawling plot that depicts humans as enslaved in a world dominated by ruthless and terrifying machines. Nevertheless, the film betrays considerable anxiety over virtual "reality" and the perils of a digital, Web-enabled world.

THE INTRICATE ROBOTIC SLAUGHTERHOUSE OF WESTWORLD

It's even more difficult to position the intricate robotic slaughterhouse of *Westworld* (2016-2020, created by Jonathan Nolan and Lisa Joy), but the series serves as a gory contemplation of corporate greed and humans' capacity for savagery and violence in a space where rules and mores are suspended, as well as providing extensive indication of human attraction to pleasure-bots. Here, as well, humankind is threatened by a machine uprising as the robots become self-aware, hostile, and unwilling to play their humiliating subservient role in an immense Wild West theme park. Nevertheless, much of the plot critiques the monied and professional classes of humans who designed, run, and or visit Westworld and who betray such ignoble traits, whereas the newly emancipated automats exude a kind of naïve purity due to their relatively recent exposure to the "real" world—echoing Stanislaw Lem's *Mortal Engines* (Lem 1977), in which implacable "palefaces" (humans) hunt down fugitive robots who, for their part, submit to death with all the precious dignity of Christian martyrs.

This brief discussion indicates that while robots are a frequent vehicle for anxiety in some popular culture, particularly science fiction, they are not the only source of anxiety. Indeed, films along the same lines as these include a great deal of other elements of legitimate concern, from bioprospecting (e.g., *Avatar*, 2009, dir. James Cameron) and *Gattaca*-style problems of gene-driven inequality (1997, dir. Andrew Niccol) to the character of alien ways of life beyond Earth and the mysteries of inter-species attraction, not to mention human capacity for barbarism. Not to put too fine a point on it, robots might best be described as intensifiers—elements that amplify and heighten ambivalence over human tendencies by offering both a rival source of action and power in the story and a means of stepping outside of the dominant human narrative that so insidiously privileges humans' xenocentric attitudes. Even though robots form a key part of the technology-run-amok theme, they provide a means toward more profound critique; robots thus hold a mirror up to humanity, aping our mannerisms and foibles, yes, but reflecting awkward, even brutal, glimpses of "human nature" that—across a range of works—foreground a portrait of homo sapiens that much of humanity might find unsettling.

"Implacable 'palefaces' (humans) hunt down fugitive robots who, for their part, submit to death with all the precious dignity of Christian martyrs."

This ambivalence notwithstanding, in the year 2022—over a century after Čapek's legacy launched a thousand autonomous ships, fembots, search-and-destroy rovers, and service droids—human imagination of robots remains extremely active. Yet in many ways the machine era has already arrived, with far less exuberant dread. Outside of these dark fictional visions on screens or book pages, human familiarity with machines and devices creeps onward, to the extent that many populations in developed and developing contexts are surrounded by a steady aggregation of technological things—as well as an accumulation of tech-waste. These machines' continued easy presence and materiality in human lives in well-off and less wealthy nations creates a misleading sense of their benign "end-of-life" pathways when discarded. Very much to the contrary, this midden-mound of tech, so ubiquitous as to seem harmless, comprises a serious global problem that the impending robot revolution may do little to help. (I sketch out the global impact of e-waste below.)

"Over a century after Čapek's legacy launched a thousand autonomous ships, fembots, search-and-destroy rovers, and service droids, human imagination of robots remains extremely active."

If, given the above, we consider our willing surrender to the devices we carry and the Internet of Things that is slowly colonizing households and other spaces in which our lives are lived, it is ironic to conclude that humanity is already complicit in the machine takeover that has roiled our collective futurist dreams and wary Sci-Fi fantasia for many decades.

Cyberdine's "Skynet" this is not. Yet to the extent that devices sometimes communicate and move with apparent independence, autonomous or semi-autonomous contraptions may very much resemble a makeshift robotic glimpse of the future. In addition to domestic security and enforcement operations, drones engage internationally in surveillance, airstrikes, and brutal targeted assassinations inside and outside of warzones. "Autonomous" electric cars have more or less driven themselves into and around some jurisdictions. Airborne drones deliver parcels to certain locations and wheeled robots carry grocery shopping down some metropolitan sidewalks. There is vanishingly little cause to think that these trends will peter out over time. Instead, they will likely extend into vast webs of robotic service of varied autonomy—but along a "long tail" timeline. Westworld will remain an engaging, but decidedly distant, dystopian mirage, at least for the foreseeable future.

> "Yet to the extent that devices sometimes communicate and move with apparent independence, autonomous or semi-autonomous contraptions may very much resemble a makeshift robotic glimpse of the future."

This slow progress notwithstanding, in the Covid era, relatively rudimentary robots and drones are widely seen as covid tech conveniences whose time has come. On top of degeneration and obsolescence, the experimental horizons of robotic development mean that autonomous and semi-autonomous devices will be continuously tested at the messy frontier of technological innovation, along with accumulating tech-detritus.

> "*Westworld* will remain an engaging, but decidedly distant, dystopian mirage…"

Next, in light of this futuristic topic, I'd like to discuss challenges with regard to the environment and with regard to material resource use in the coming years. If we are living in a world where drones will increasingly deliver our purchases, monitor our location, and patrol our borders; if we are living in a world where robots will gradually (and suddenly) take on mind-numbing or complex tasks once performed by humans; if we are living in a world where core elements of our daily lives will increasingly become automated, whether due to a pandemic or to other factors, then those in industrialized nations which have tended to export their tech-detritus to the periphery, particularly to the Global South, need to start to think more seriously about what happens to all those devices when they become broken, outdated, or too cumbersome or unloved to remain in their possession.

In short, we need to talk about robotic waste.

URBAN MINING, TOXIC PAYLOAD

A fine, though bracing, way to look at elements of the robotic waste challenge is to sketch out how electronic waste has been handled over the past few decades in key parts of the world which are known for their robust approaches to e-waste conversion (a.k.a. scavenging).

South China's Chaoshan, a region about five hours' drive east of Guangzhou—is a zone notorious for smuggling. Nestled in the dusty Guangdong heartland lies scofflaw, enterprising Guiyu, a community of about 50,000 residents which, in its heyday, attracted a shifting population of as many as 100,000 migrant workers; each year, Guiyu processed up to *20 million tons* of imported e-waste in roughly 5,000 family-run workshops (Chi et al., 2011; Huo et al., 2007).

TOXIC RESIDUES FROM ELECTRONIC WASTE SCAVENGING DUMPED BY THE RIVER IN GUIYU, SOUTH CHINA. (IMAGE: BASEL ACTION NETWORK)

Due to this staggering scale, Guiyu was long viewed as the pollutant world capital of demanufacturing tech devices—or in other words, the toxic, unsavory flipside of the sleek, consumer electronics juggernaut that is all the rage in well-off parts of the world. Not coincidentally, this sizeable node of e-waste scavenging in Guiyu was located near a major concentration of toy manufacturers; there, recovered microchips and other recycled components were sold to be used in the making of dolls, playthings, and other gewgaws both for China's domestic market and around the world, not to mention finding their way into a wide range of other electronic devices, like CCTV cameras. According to the range of Guiyu informants interviewed by our ethnographic team,[3] as well as others (see Minter 2013), repair of devices for reuse or resale was by far the most profitable way to extract value from e-waste. (I return to the significance of repair for crafting a sustainable tech system below.) What couldn't be repaired or scavenged for precious metals and other materials was often burned, buried, or thrown in the river that ran through the community. Ash

"Guiyu became the "love-to-hate" poster child for campaigns against environmental blight in the Global South as well as a symbol of the problems of unsustainable outflows of waste from wealthy countries to disadvantaged communities."

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[3] My main collaborator on this transnational e-waste scavenging research has been Anna Lora-Wainwright, School of Geography and the Environment, University of Oxford. Our research and fieldwork were supported by a timely John Fell OUP Research Fund grant (entitled 'Urban Mining, Toxic Payload') and then by a generous Leverhulme Trust Project Grant. Prof. Li Liping at Shantou University Medical College kindly made our Guiyu fieldwork possible by sharing her research contacts in the area. Professor Li also introduced us to several local students who aided in research collection. During fieldwork in South China, we were joined by then-Oxford DPhil student Loretta Lou. Dr Yvan Schulz subsequently joined our Oxford-based research team from 2017, also funded by the Leverhulme Trust grant.

SCAVENGERS WORKING IN FRONT OF A TOWERING PILE OF E-WASTE COMPONENTS, GUIYU, SOUTH CHINA.

was also dumped into this tenebrous waterway, which became a lifeless, putrescent channel of industrial bile that literally stained the riverbanks black at the waterline.

Partly for these reasons, Guiyu became the "love-to-hate" poster child for campaigns against environmental blight in the Global South as well as a symbol of the problems of unsustainable outflows of waste from wealthy countries to disadvantaged communities. While not unwarranted, this latter characterization was nevertheless complicated by not-insignificant mitigating factors—for instance, many people in hotspots like Guiyu supported the trade and enthusiastically welcomed shipments of electronic waste, seeing them as a munificent boon. Indeed, Chaoshan was awash with tales of bootstrapping Guiyu waste entrepreneurs who had made a fortune by gaining a lucrative foothold in the plastics recycling business. Others hit it big by extracting precious metals like gold, platinum, palladium, and beryllium from circuit boards and other components using crude acid washes (e.g., so-called *aqua regia*, an alchemy usually dominated by hydrochloric acid that dates from the Middle Ages) and other deleterious methods. This is to say that, far from being seen by most local Chinese as a miasmatic hellhole—the prevailing view in a range of wealthy, industrialized democracies via lurid media portrayals—such tales of rags to riches in the waste trade made Guiyu into a locus of opportunistic fascination. Vested local officials and bent police, as well as local gangs, brutally limited the ability of outsiders to set up their own workshops in Guiyu, but local success transformed families involved in scavenging into sought after sources of eligible brides and bachelors who offered the promise of future earnings to in-marrying partners—at least for a time. From about the second decade of the new millennium, a dogged central government campaign to clamp down on conspicuous pollutant activities seen as damaging to China's international image—clearly epitomized by Guiyu—and/or to control successful businesses that lay almost exclusively in local Guiyu hands, led to a reversal of fortunes for local workshops. By 2018, many entrepreneurs had soured on the scavenging trade due to a combination of unwanted government interference in the historically freewheeling sector and a slump in commodity prices, as well as a lack of perceived availability of e-waste of desired quality. Once one of the most reliable money-spinners in the transnational waste trade, albeit with often slim margins—much depended on volume—Guiyu had lost its mojo. The smart money found other opportunities in Chinese communities with a much lower profile and less government and international surveillance than e-waste's most notorious trouble spot had attracted over more than 20 years.

"Such tales of rags to riches in the waste trade made Guiyu into a locus of opportunistic fascination."

China’s ruling party has long seen the Middle Kingdom as a technological superpower in the making, and for over a decade, the Chinese government has seethed at the perceived second-class role that China had come to occupy as, arguably, *the* pivotal nation in the murky, tainted global waste-scavenging trade. Instead of wallowing at tech’s pollutant back end, China fancies itself as the *sine qua non* trading partner on the supply side of high-end technology—though of course China itself produces a great deal of domestic e-waste, and therefore would continue to benefit from an ability to handle large quantities of WEEE via sustainable conversion and recommoditization (e.g., Zhu and Chertow 2016). One reason China became so central to the trade was both the willingness of entrepreneurs to engage in the trade and the de facto broad latitude they enjoyed in disposing of the byproducts of their scavenging work in an often laissez-faire regulatory sphere. The efficiencies were so lucrative that the whole industrialized world had become more or less accustomed to using China as their extraterritorial scrapheap, a welcome destination for their WEEE and a place where workshops would do the dirty work that they wouldn’t countenance taking place in their own countries.

“Exasperated, Beijing began characterizing imports of e-waste and scrap as ‘foreign garbage’ (*yang laji*), vilified as a filthy and pernicious threat to the nation.”

Given the sensitivities surrounding these issues, it was just a matter of time before Beijing took action. Authorities banned several categories of electronic devices and appliances as far back as the year 2000. Yet with patchy surveillance and weak enforcement, millions of tons of WEEE continued entering into China with little impediment, fuelling an expansive informal sector of scavenging and material recovery. Exasperated, Beijing began characterizing imports of e-waste and scrap as “foreign garbage” (*yang laji*) (Schulz 2019), vilified as a filthy and pernicious threat to the nation (*pace* Lepawsky 2018; Davis et al 2018). The central government then implemented a series of high-profile operations from 2013 (given triumphalist names such as “Green Fence” and “National Sword”) in order to quash the illicit activities of this dynamic sector—particularly smuggling and pollutant processing. The campaign escalated in July 2017, with an even more restrictive ban on the transnational trade in scavengeable waste. Notably including all plastics and paper, but also an extensive set of categories of scrap materials, imports of such materials are now forbidden. The ban is even more sweeping than it seems at first glance; since e-waste and other WEEE often contain plastic and a key part of the e-waste trade comprises the conversion of plastic, the ban excludes much imported e-waste, etc., as well (Schulz and Lora-Wainwright 2019).

Moving forward, China has embarked on a strategy to implement formalization of WEEE conversion (Inverardi-Ferri 2017), shaped by an ideological vision of technological “civilization,” (Geall and Ely 2018; Tong et al 2015) but it is still too early to determine whether the shift away from the scavenging mode of production has managed to achieve its stated aims of efficiency, safety, and sustainability. (For example, locating scavenging activities in a dedicated facility, as in contemporary Guiyu, does not, of its own accord, magically eliminate pollutant emissions from conversion activities. Guiyu informants argued quite the opposite—that emissions simply became better hidden.)

In this regard, it is instructive to look at Japan, where an integrated system of largely automated material recovery has existed for nearly two decades. Japan’s vast apparatus of material conversion offers a rough illustration of what authorities in Beijing envision for China in the coming years—though China’s formal sector will likely be considerably larger, due to the nation’s far greater size and the longstanding focus on conversion there. (It is even conceivable that China's system will eclipse Japan's in sophistication of material conversion if the Middle Kingdom finds a way to integrate the expertise and dynamism of its huge population of experienced scavengers, instead of marginalizing and vilifying them.) Following the lead of Japan's successful appliance efficiency-oriented Top-Runner program, the archipelago's e-waste conversion apparatus is shaped by competition. Two rival Japanese tech consortia dedicated to WEEE conversion, encompassing about two dozen high-tech plants between them, compete to have the highest recycling percentage for certain appliance classifications (such as televisions, for which Panasonic claims an 89% material recycling rate).[4] In this way, such highly automated facilities in Japan recycle most of the nearly one million tons of consumer appliances generated annually (Honda et al 2016, 84-89).

"Repair is often the most "eco" way to deal with electronics—it's far more efficient to fix a computer for resale than to break it down into pieces in order to extract tiny amounts of gold and palladium from its circuitry, for example, not to mention more lucrative."

Repair is often the most "eco" way to deal with electronics—it's far more efficient to fix a computer for resale than to break it down into pieces in order to extract tiny amounts of gold and palladium from its circuitry, for example, not to mention more lucrative—but such strategies are unappealing to many established tech corporations. Indeed, it cannot be ignored that expertly repaired televisions and other appliances would take market share away from tech corporations' own new product lines. For this reason, most of Japan's recycling apparatus was relatively disinterested in encouraging repair and reuse (Honda et al 2016, 85-87; Kirby, 2018). Instead, the consortia pursued a familiar cycle of mass-production, mass-consumption, mass-disposal, and mass-recycling that was an extension of Japan's maximalist trajectory from the high-speed growth years of the postwar period. Whatever the positives, the Japanese system can therefore be deemed a considerable missed opportunity.

Be that as it may, Japanese tech companies have embraced the industrial challenge of demanufacturing. Through a combination of careful human prepping and skillfully mobilized mechanical brawn, these companies dismantled, chopped, and classified the WEEE, transforming discarded products back into relatively discrete aggregations of material (e.g., large industrial sacks filled with chunks of aluminum, or steel, next to others into which particular types of plastic fragments had been decanted). The better the materials are classified, the purer they will be and thus the higher their value on the market or to the manufacturer; Panasonic representatives say it manages to use about 20% of its recovered materials in its own global operations, a claim that seems plausible partly because such conversion helps Panasonic's own bottom line. Someday, perhaps this conversion work will be conducted with greater automation, but workers remain integral to the current system. After initial manual human disassembly, most discarded appliances and other electronics are crushed by a giant studded steel mangle. The resulting fragments are then reduced to more uniform size and sorted at high speed on conveyor belts, utilizing clever and time-saving technologies to sort "like with like," such as puffs of air, flotation, magnetism, electrical charge, and infrared sorting. Partly for this reason, the business of high-tech "green" recycling is sometimes referred to as "the shredder economy" (Kalimo, Lifset et al 2012). Yet the vast infrastructure of machines, transport logistics, and human labour that breaks down e-waste goes far beyond mere crushing or "shredding." This enterprise of undoing brings not just destruction but reconstitution, with plastics and

[4] "Recycling Processes," Panasonic PETEC facility online PR, 2021 (https://panasonic.net/eco/petec/process/, accessed December 2022).

metals shrapnelized, separated, melted, compressed, snipped, cooled, crushed, and pelletized in a mutable purgatory of form. This then made them available for recommoditization.

As impressive as these formal-sector technological and engineering feats can be, it's now clear via my research that this sleek, high-tech recycling stream was propped up and sustained by a shadow stream of waste exports abroad, mostly to China. Japan, since the late 1990s, has therefore presided over the expansion of two "waste regimes" (Gille, 2007, 34-5) that worked interdependently—one public-facing and eco-responsible, the other dictated by expediency and profit, operating out of the public eye. Indeed, the shadow trade in scavengeables like e-waste—smartphones, computers, televisions, appliances, old stereo equipment, outdated cameras, and other tech components— created ready channels for licitly exporting materials that the marquee system could not convert as efficiently, as explained below.

"As Yamamoto-san delicately put it, perhaps 10% of the hypothetical cargo might have contained steel mixed with copper—which was difficult for customs inspectors to detect."

The Japanese public-facing system is a clever mix of ecological imperative and PR, set up to elevate certain high-profile products as "national champions" in the French style.[5] While the marquee system handled standard appliances and other predictable components, the shadow stream enabled the difficult recycling work to be exported to other countries, notably China.

Yamamoto-san, a seasoned executive at a major Japanese recycling and smelting company, explained to me how the system worked. Of course, much of it came down to what he called the "separation cost" of conversion, which was much higher in Japan. For example, a plasma-screen television bought within the past decade would be sent to a dedicated, highly automated facility, like PETEC, and recycled to a high standard (see Kirby 2018). By contrast, an old VCR-style videotape player, once very common in Japan, would follow a very different path with much less scrutiny. A typical year before 2018 or pre-Covid would see brokers visiting Japan from places like China, looking for scrap. Now-obsolete VCRs, for example, contain metals that appeal to scavengers, but the small motors inside each VCR are an unwieldy mix of copper and steel. This means that each motor has to be cut apart and the copper separated before these can go to smelters. (With arms spread and an exaggerated facial expression of mock disgust, Yamamoto-san blurted out, "Steel smelters *hate* copper!" to a young female PR representative and me in a sleek but sterile conference room near Akihabara.) The separation cost for such work is prohibitive in Japan. It's hard to imagine any Japanese company choosing an above-board approach to this kind of conversion work, which is difficult and involves much expensive manual labor with very little reward. But this is precisely the kind of demanufacturing work that an e-waste Mecca like Guiyu specialized in for many years: high volume, slim margins, and relatively minuscule labor costs. Take a typical large, pre-2018-crackdown shipment of iron-mixed-metal scrap from Japan to China, for example. As Yamamoto-san delicately put it, perhaps 10% of the hypothetical cargo might have contained steel mixed with copper—which was difficult for customs inspectors to detect. When it arrived in a scavenging destination like Guiyu, however, the separation cost was much more manageable because labor there was very cheap; the VCR motors and transformers could be cut open and broken down manually.

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[5] Where France aggressively promotes Airbus mega-jets and Areva's EPR third-generation nuclear reactors in high-stakes bilateral negotiations, Japan pushes an image of efficient competency with electronics that adds to the lustre of smart televisions, computers, air-conditioners, and so on.

Japan's trade with China has long existed in an administrative murk that has suited Japanese interests. At the crux of this trade is the, for Japan, highly favorable manner of defining what counts as waste and what, conversely, counts as a valuable commodity. Once something (a vending machine, an electronic dictionary, a microwave oven) is designated as waste in the Japanese system, it falls under the dictates of a strict series of mandated controls, including regulations stipulating the types of trucks that can handle the material, a manifest system to account for its progress through different stages and intermediaries, codes that designate the kind of facility where it can be stored and handled, and so on. By contrast, according to Japan's regulatory framework, if a waste product (such as discarded stereo equipment, old-style boxy televisions, superannuated appliances) is purchased, for nearly any amount of money, it is considered a commodity, not a waste. (In the Japanese system, according to Yamamoto-san: "If you pay money for something, it has value. If you want … PCs from my company, the borderline is whether we pay money or we receive money.") Such material can then be exported, even to a jurisdiction with generally low environmental standards and enforcement. This is markedly different than the approach followed by the EU, for example; in Europe, anything containing mercury, a neurotoxin, must be handled with care, no matter what its status as a commodity. So for a hypothetical Japanese company meeting with a hypothetical Chinese scrap broker, both parties get what they want. The Japanese company gets rid of waste that is difficult and expensive to process. The Chinese broker gets quality e-waste that can be extremely lucrative to scavenge in a zone with much lower separation costs.

This Japanese approach is, in effect, a form of magical thinking. Instead of confronting the waste trade in reality-based, macro terms that would take account of the holistic effects that toxins have on people and the environment, Japan chooses to play semantic games. There is an instructive analogue in international law. According to a similar logic of human rights, an alleged criminal in one jurisdiction often cannot be extradited to another country's jurisdiction, for instance that of the USA, where s/he would likely face the death penalty. The Japanese policy of allowing the sale of waste as a commodity to overseas e-scrap brokers is to pretend there is no capital punishment, no extradition, and indeed no criminal.

When I propose a different system for robotic waste, I engage in a degree of abstraction. Robotic waste is essentially e-waste, despite how it might be commonly conceived. However, robotics as a sector remains at a very early stage, with relatively low production volumes. There is an opportunity here to carve out a different pathway for robotics and robotic waste so that more sustainable practices are programmed into the sector from an initial stage. If robotics labs can, early on, be encouraged to rely more on repair than disposal/replacement, then when the sector expands, down the road, robotics might continue along a much more sustainable trajectory than has generally existed for standard WEEE.

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Embedding this set of practices in robotics would be a big environmental win. However, going hand in hand with the messiness of e-waste is the enduring quandary presented by waste conversion. "Urban mining" is never completely free of emissions and leakage, and with Guiyu-style scavenging this has been far from the case, as I have explained. Is it better to engage in messy urban mining of e-waste, even if far from pristine, or is it preferable to avoid scavenging and engage in traditional underground mining to extract the same materials from ore? The former approach may offend environmentalists and others, but if urban mining can be gradually made cleaner and provide a sizable percentage of material like copper—which is lucrative and easily recycled—then digging up ore in "virgin" ground can perhaps be avoided, or at least postponed. A few timely examples include plans for Pebble Mine, whose proposed site on Alaskan tundra would have threatened prized salmon spawning grounds (NYT, 9 September 2021); and the so-called Twin Metals project, whose proposal to mine in a national forest watershed could well have been disastrous for Minnesota's 1.1 million-acre Boundary Waters Canoe Area Wilderness, located just downstream (Washington Post 26 January 2022; Minter 2013). Clearly, WEEE conversion needs to be made far less noxious, particularly in industrializing nations in the Global South. It should also probably be made much more efficient, drawing on industrial ecology principles, no matter where it occurs. But whatever percentage of copper can come from conversion of existing waste (e.g., urban mining, also known as "above-ground mining") would help prevent Arcadian idylls like these, or even ordinary communities, around the world from being depredated by extraction vehicles, toxic emissions, and parlous mine tailings. Introducing such principles into a relatively new sector like robotics could potentially create substantial benefits and also showcase a practical dimension of sustainability in a grounded manner that would facilitate greater impact.

Crafting robotic waste ecosystems

From the above description of real-world recycling processes, a.k.a. scavenging, in East Asia, we can put forward some premises. 1) To start with, lasting sustainability doesn't simply happen on its own. Without a robust regime of laws, regulations with teeth, inspections, and penalties, sustainable e-waste conversion is unlikely to flourish in a place where cheaper, easier, and more pollutant methods can be relied upon, not to mention routine smuggling of imports from abroad. 2) Next, context matters. Good-faith efforts to inculcate eco practices in varied socio-political settings must include taking account of history, culture, and actual conversion practices on the ground, not whatever buzzwords and circulating attitudes happen to be in fashion. Japan has spent decades inundating public discourse with eco-rhetoric over sustainability and resource use, both domestically and internationally. In this way, Japan has been able to self-curate its desired image as a leading nation promoting best-practice environmental policy and forward-thinking sustainability, a reflection of its aspirations on the international stage. (This is also a logical response to spending much of the postwar period as a global environmental villain [Huddle & Reich 1987; Broadbent 1998; Avenell 2017].) Yet even Japan has been engaged in the aforementioned shadow trade in difficult, dirty, and/or (maybe) dangerous (or *sankei*, a.k.a. "3K"; *kitsui, kitanai, kiken*) e-scrap being sold to other countries more or less under the table for convenient export. 3) Circularity is a seductive conceit often invoked by stakeholders, but it is rarely ever a description of a true sustainable system. Industrial ecology and so-called zero-emissions remain more common as aspirations of eco-efficiency rather than descriptions of successful environmental engineering at scale. 4) Refurbishment of electronics represents a productive way forward, however daunting and elusive beyond limited workshop-style operations. Indeed, repair is often far more efficient than shredding—as explained above, fixing a smartphone is far preferable to disassembling and crushing the handset to extract tiny amounts of precious

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metals therein, with all the eventual pollutant externalities such operations bring. But as yet, there are not so many examples of meaningful eco-recovery and repair of electrical and electronic components.

One telling case of repair that touches on these four premises is Apple's Daisy robot (debuted in 2018), designed to disassemble and recycle iPhones. In a convenient irony, Daisy, which resembles more of a transparently sealed factory-kiosk than a discrete robot, was partially constructed with parts from Liam, the first iPhone recycling robot (which debuted in 2016) (Verge 2018). This and other iPhone scavenging helps facilitate the sale of refurbished iPhones, for a lower price—usually about 15% cheaper—with components that come from other iPhones (sometimes referred to as Certified Refurbished). But much of what is recovered from the two Daisies—one operating in California, the other in Amsterdam—can, in turn, be converted and reconstituted to manufacture new components. For instance, cobalt recovered from the recycling can be rechanneled into new battery manufacture; tungsten is another in-demand element, used for durable casings, that is collected and reincorporated into further products. Yet even within the Apple iPhone universe, these operations remain far out of proportion to the scale of the challenge: at full capacity, each Daisy can recycle about 1.2 million iPhones a year, while 233.9 million iPhones were shipped in 2021 (Statista 2022). This improbable ratio doesn't count the billion-plus iPhones already in current active use, either; furthermore, many households and institutions have other old, abandoned phones lying around. Even with DIY e-repair evangelists like iFixit offering manuals and tools to consumers willing to take matters into their own hands, the prospects for a sustainable, repair-driven revolution in electronics so far remain dim.

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The Autonomous Robotic Ecosystems (ARE) project, described at the opening of this article, is one initiative that sketches out a pathway that could pioneer a different, more positive approach. To be clear, the actual recycling of robots is not an emphasis of the existing ARE studies, to say the least. The UK- and Netherlands-based scientists responsible for the ARE projects prefer to dwell on the more novel theoretical and technical side of the robotic matrix, the problem-solving and design "evolution" of the ARE apparatus, while the actual recycling involved is little more than an afterthought—recycling at its most rudimentary level. (Some ARE scientists did not respond to numerous queries in autumn and winter 2021 to expand on these research questions or explain their methodology further.) Yet over time, whether or not by this team of scientists, the technological side of the recycling challenge will necessarily move forward. Advances in the production of electronics, the continued modularization of components (like microchips and capacitors), and tailored engineering of mechanical devices—such as further stages of sophisticated 3D-printing—will likely create sustainable efficiencies in how robots can be produced, with an eye toward eventual dismantlement, recycling, and reproduction.

Yet it is the potential applications for such a robotic matrix that are also enticing. The challenge of human interplanetary exploration—possibly as a response to the prospect of civilizational collapse, perhaps just as a billionaire's pet project—may help focus and capitalize efforts to craft pioneering technologies in order to make the "evolutionary" recycling of robotic waste a workable objective. This, along with the growing environmental interest in making efficient use of discards—or finding cheaper "certified-refurbished" types of cutting-edge smartphone to buy, as the case may be—may well help reorient some of the more out-of-whack elements of our species' remaining time on Planet Earth.

Conclusions

The boundaries of what is considered "e-waste" have for some time lain unhelpfully narrow. For instance, the satellite debris, wrecked or partially damaged spacecraft, and abandoned rocket components that currently orbit Earth are called many things—space trash, space junk, orbital debris, "offworld rubbish" (Lepawsky 2016)—but are materially indistinguishable, for the most part, from e-waste. Given its increasing density and concomitant hazard to operating satellites and space mission launches, perhaps entrepreneurs will someday succeed in collecting and converting this rich form of electronic waste, just as space-oriented multi-billionaires hope in the future to replace pollutant terrestrial mining with demolition and ore-extraction of comets, asteroids, and other heavenly bodies.

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By sharp contrast, excavating robotic waste stands as a similar, though much more achievable and reality-based, eco-technical goal. In a relatively new sector, sustainable principles that yield efficiencies, including repair, can be introduced to the design and manufacture of robots. And with the assumed robust development curve of robotics in the coming years, the impact of such sustainable principles could prove considerable. Significantly, many scientists and engineers who populate robotics labs are lifelong tinkerers. Based on my ongoing research on robotics, people who are designing and testing robots have, at different stages of their careers, depended more on repair when there was a problem with the robots they used—until, for example, their more advanced career stage made them too busy, and time-consuming repairs were too impractical. It's impossible to say whether such conditions will make a difference, but hands-on experience with repair appears to represent fertile territory for inculcating eco principles—such as making robots, from the beginning, more easily dismantle-able, with components that are pre-designed to be recycled efficiently. Moving forward, the potential for nurturing a sustainable approach and emphasis on refurbishment of robots is non-trivial, as is the prospect for growth and expanded impact.

Thus, the creation of a more sustainable system for recycling the future's space-faring robots that are destined one day to explore distant outlands can also be used to benefit life on Earth in the here and now. The implications for making progress on near-term goals related to air and water quality, energy transition, and climate crisis are promising. Yet maybe the biggest question-mark hovering over such a proposed change is humans' prodigious affective capacity, one of humanity's most reliable markers of species difference. A

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scientist named Joo-Ho, who runs a lab in Kyoto, chose to hold onto a robot, CE3, that he had used in five years of experiments rather than discard or recycle the apparatus (as Apple's Liam robot had been cannibalized to construct Daisy). The more the lab workers had engaged with the robot, the more they had considered it a "friend" for whom they felt "sympathy." As Joo-Ho explained, "The robot worked very hard for us—it's a very complex emotion"; he went through a sort of a grieving process in dealing with the retirement of his reliable research subject CE3. After keeping the bulky superannuated robot for eight years on a shelf in very tight storage space in his small lab, Joo-Ho said he was arranging for a colleague to take on CE3—specifically, a former student who had more lab space and a similar willingness to hold onto the robot rather than toss it on the proverbial scrapheap.

Excavating robotic waste may involve both urban mining and a willingness to dig a bit deeper into what makes us human. As a species, we may well develop the technological and logistical capacity to (re)produce robots sustainably at scale and to avoid deleterious externalities. Efficiencies and green advances in robotics could, moreover, influence the larger resource economy of the global electronics trade, vastly multiplying their impact. Yet this aforementioned robotics lab's experience suggests that we may have a further considerable affective hurdle to surmount if, over time, we come to develop feelings for the very robots that, for decades, we have feared as terminators, automat trackers, killer fembots, enforcement droids, and ruthless Sentinels. Should this curious eventuality come to pass, it will likely usher in a period of productive coexistence, even partnership, as machines offer their non-senescent spans and expendable utility to humankind's mortal toolkit. If so, the hand extended to help save the planet and indeed the species may well be coated in silicon.

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