Complementing Human Labor with Robotics: Progress, Barriers, and Policy

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Abstract

Substitution of capital in the form of automation and robotics has led to widespread, long-term job losses for non-college educated American manufacturing workers. We make the case for greater emphasis on the deployment of *collaborative* robotics, or "cobots," which have the potential to complement rather than replace manual labor while still increasing productivity. Drawing on both our own technical research and that of others, we examine the current state of cobot deployment and demonstrate how well-designed job tasks, paired with carefully integrated cobots, can preserve employment opportunities while enhancing efficiency. As the integration of workers and cobots takes place, manufacturers could realize much larger gains in productivity, less expensive job turnover, and a safer, healthier workplace. Finally, we outline strategic policy measures aimed at redirecting investments to balance manufacturers' demand for productivity with ensuring stable employment and earnings for blue-collar American workers affected by technological and trade-driven disruptions.

Keywords: Labor policy, trade and automation, tariffs, collaborative robots (cobots), worker displacement, labor augmentation.

1. Introduction

> *If the United States doesn't find ways to combine new machinery with better-trained, more-skilled and more-adaptable workers, the country risks more pain for manufacturing, the traditional provider of high-wage, stable jobs.* —D. Acemoğlu [2]

Manufacturers have increasingly turned to automation and robotics under enduring pressure to boost productivity. The recent trajectory of technological change in manufacturing reflects what Schumpeter termed "creative destruction," whereby added technology (capital) has led to improvements in productivity, while also resulting in widespread layoffs, plant closings, and loss of desirable jobs for mostly blue-collar, non-college graduate workers [15, 17, 7, 8, 22, 87]. While contemporary discourse on emerging technologies is often dominated with dire predictions of continued worker displacement due to new technology such as robotics and artificial intelligence [62], some remain skeptical [73, 24]. The introduction of technology in the workplace does not necessarily mean that job displacement, or the loss of demand for labor, is inevitable [76, 87, 2, 3].

In this paper, we argue that emerging *collaborative* robot technologies, which we will refer to as "cobots," have the potential for increasing productivity by augmenting manual labor, rather than replacing it. Our analyses include multiple, interdisciplinary perspectives on the state of cobot deployment based on our own technical research and that of others, and policies to promote such. We show that well-designed jobs and carefully integrated cobots can help avoid the decimation of work for manual labor. With thoughtful integration of workers and cobots, a manufacturer could realize a much larger gain in productivity, less expensive job turnover, and a safer, healthier workplace. Here, labor is not displaced from the work it used to perform, or from the new work that the increased productivity creates—it just does them better in concert with new technology. In turn, widespread productivity benefits lead to higher wages, rising consumer welfare, and stronger economic growth with this collaborative approach, which is quite different from the historical labor displacement approach that has dominated technological change in manufacturing.

While today's powerful industrial robots are typically isolated for worker safety, cobots are, in fact, designed to be alongside people in the workplace. Cobots are engineered to work safely alongside humans, with their speed and power adjusted to enable effective collaboration, allowing each to focus on tasks suited to their strengths. While repetitive motions and awkward positions can strain human workers over time, cobots are built to do such tasks so that people can focus on dexterous, non-repetitive tasks and complex decision-making. Figure 1 illustrates such complementarity in an application at a Ford automotive assembly plant where the cobot carries a heavy tool, and the worker positions and supervises the application of the tool during the installation of shock absorbers. Such applications reduce physical strain over manual labor [64] and substantially improve productivity, as workers are able to supervise multiple cobots [48]. Existing trends show processes like this will become more common, indicating that manufacturing tasks—rather than the entirety of jobs—will be automated and exist alongside other tasks that cannot feasibly be automated [84]. How might this technology lead to enhanced productivity rather than, simply, net displacement of labor? We address this question by considering the current state of cobot technology and design, alongside growing social and political interest in how policy can shape cobot integration to optimally enhance the economic well-being of workers [18, 67].

Technological advancements in robotics, assisted by artificial intelligence (AI), have the potential to enhance productivity and augment worker capabilities without necessarily displacing jobs. Autor [16] indeed argues that automation-driven productivity gains, particularly through AI, have the potential to increase the value of human labor by expanding opportunities for task-based contributions. While the early rollout of AI seems to have taken the same automation path followed by other digital technologies of the 1980s–2000s, [5] finds that AI-adopting firms tend to slow their hiring of complementary non-AI workers more than they increase hiring of AI specialists—cobot integration need not follow this path. By automating undesirable or inefficient tasks while preserving those requiring human expertise, cobots enhance occupational productivity and worker performance. This integration can reduce workplace injuries, extend career longevity for those who might otherwise be compelled to retire, and increase overall labor productivity as workers adapt to new technologies [76].

Emerging AI technologies can be used independently or in conjunction with cobots to further augment their intelligent capabilities, promising to further increase productivity. Although conventional robots primarily offer high-payload, high-precision work in caged, and highly predictable environments, cobots rely on increasingly advanced, AI-based sensing, planning, scheduling, and reasoning technologies to offer more flexible, adaptive, and "human-like" capabilities. Using computer vision methods, cobots can not only maintain a high level of awareness of the work environment [88], but they can also recognize and plan according to the actions and intent of human co-workers [51]. The emergence of generative AI further adds to the capabilities of cobots, enabling them to interact with co-workers using natural language, and enabling engineers integrating cobots to more easily program them and operators working alongside cobots to modify or troubleshoot errors in the programming of the cobot [65]. This evolving human-cobot collaboration aligns with early visions of "man-computer symbiosis" [70], where technology assists workers in expanding their roles rather than replacing them. Evidence suggests that new technologies increase productivity much more consistently when they assist workers, enabling them to perform their jobs better and allowing them to expand into new, more sophisticated tasks [8, 2, 3, 56].

By engaging cobots as collaborative helpers rather than as replacements, manufacturers gain flexibility, productivity, and lower turnover in many otherwise routine jobs [32]. But to reach this goal, employers will have to take a longer and broader view of what return on investment (ROI) means in a human-centered system [44, 28]. For decades, advances in information and communication technologies, as well as industrial technology, have contributed to the reduced share of income accruing to routine labor (Figure 2) [58, 33], reduced manufacturing employment [97], and increased the return to wealth for capital owners [77, 87]. The continuation of past automation trends, however, is not an inevitability. Instead, we must consider how to foster more *positive* collaborative automation systems that increase productivity and enhance career trajectories, enabling workers to develop expertise alongside emerging technologies like cobots.

What design and policies would best facilitate such a transformation? A shift toward human-centered cobotics that avert the most disruptive consequences of unchecked automation will require a strategic policy approach informed by the current state of these technologies, challenges, and design potential.

2. Current and Future Possibilities: Promise vs Barriers

To think about current and future possibilities of a society where cobots are more widely integrated, we draw on our own cross-disciplinary understanding of where the current technological and design challenges are found, and where in the labor market the effects are likely to be felt first. Opportunities for expanded integration can be seen in several proven instances of productive cobot deployment.

In this section, we review the promise and challenges to greater integration of cobots into the production processes among employers and workers, and the institutional and economic actors that can affect these processes.

2.1. How the Integration of Cobots Affects Workers

To begin, we should consider which workers have the potential to be most impacted, their experiences with cobots, and how this might affect the content of their work. This perspective emphasizes that the effects of technology on workers are not just limited to wages and employment, but also job content and job quality and economic stability [1, 74]. Next, for workers to be willing to engage with collaborative robots and new technologies, we consider the design and policy challenges in overcoming the initial reluctance to work alongside cobots—even in cases where robotics have the potential to restore and enhance workers' current jobs. For instance, many potential improvements to job quality take place through reductions in injury or strain [80].

Where can we expect to find the jobs that are most likely to be exposed to cobot technologies in the future? Work by [71] shows a wide potential impact of cobots across industries, demographics, and geography. The intensity of geographic impact is reproduced in Figure 3, and shows an uneven distribution across states nationally. They also find that workers currently in the occupations most likely to be exposed to cobots are younger, shown in the lower panel of Figure 3. Policies that emphasize training for changes in workplace technologies are poised to be more effective when people are younger, as trainees benefit most when there is a longer future work horizon ahead of them. They might also be able to more easily adapt to such changes. On the other hand, income and education levels are lower for those working in jobs with high cobot potential, meaning more investment in sectoral training to utilize cobots may be required, particularly if the cobots require skills such as familiarity with computer programming. While the types of occupations most likely to see cobots are more physically demanding and employ younger workers, cobots will, by design, perform many physical tasks, thereby transforming the occupation. As the human contribution shifts away from some of the physical components, we expect to see greater opportunities for people who were previously limited in their ability to work in these occupations due to age or physical restrictions. Given our aging demographics, this is a welcome development.

Just as the potential for exposure to cobots will be uneven, the perception of and experience with cobots in the workplace will vary and how they are received will be consequential. Recent papers by [82, 81] examined the impact of robotization on work meaningfulness, autonomy, competence, and relatedness, which are essential to motivation and well-being at work across a wide swath of EU nations spanning 2005–2021 and found a consistent negative impact of robotization on perceived work meaningfulness and autonomy over this period. They also found that workers with routine tasks experienced an even greater negative effect of robotization than the median worker in terms of declines in their autonomy, competence, and relatedness. On the other hand, this research also argues that utilizing technology as a tool for independent work can still help workers maintain a sense of autonomy, competence, and relatedness in industries and job roles that adopt robots. If firms have mechanisms in place to ensure that humans and machines cooperate, rather than compete, well-designed cobots can uniquely help improve workers' well-being as well as productivity.

The industrial psychology literature also suggests that workers living in more unequal societies tend to view technology as a greater threat to jobs in general. Building from research that societal inequality heightens concerns about status hierarchies and future resource attainment, the literature argues that workers in more unequal societies would tend to view the growth of robots as greater threats than in less unequal societies [94]. And of course, income inequality in the United States is high and has been increasing for decades [49]. Concerns about the effects of new technologies as contributors to inequality are indeed warranted: Researchers have found that the more a demographic group's work has been displaced by automation, the less its real wages have grown from 1980-2016, before the AI boom [7, 87]. More than half of the rise in inequality between high- and low-skill labor over this period can be attributed to automation effects [8]. [69] find that even the threat of automation weakens workers' bargaining power in wage negotiations, dampens wage adjustments, and amplifies unemployment fluctuations. And further, obsolete or high-cost plant closures due to automation and trade effects have created local, long-term and persistent decreases in the employment-population ratio, earnings per capita, and earnings per worker in the affected local economies [50, 41].

It is clear that more work needs to be done, as the impact of the implementation of artificial intelligence (AI) with cobots on workers' experiences remains underexamined. Although AI-enhanced processes and machine interactions can benefit workers (e.g., by assisting with exhausting or dangerous tasks), they can also elicit psychological harm (e.g., by causing job loss, reducing worker autonomy, or degrading work quality). The conditions for robotics to either enhance or threaten workers' sense of identity derived from their work depends on how the technology is functionally deployed—by complementing robotics tasks, replacing tasks, or generating new tasks—and how it affects the social fabric of work [92, 75].

While automation projects in manufacturing often exclusively focus on immediate labor cost savings, as technology advances there is an opportunity to consider the benefits of integrating cobots across broader metrics. As cobots are designed to improve ergonomic conditions for workers, there is reduced strain and injury, and the job is more desirable from a worker's perspective. Both result in less worker turnover and costly training, obtaining higher returns for the worker and for the firm [44]. Using data from the US and Germany, [38] found that the introduction of robots reduced the physical intensity and injury rates of workers exposed to industrial robots in their workplaces. Cobots, in particular, hold promise in reducing injury in jobs that are physically demanding but not fully automatable. [71] find that the occupations most likely to integrate cobots have higher average rates of injury that could be reduced through strategic cobot deployment and design, leading to skill augmentation with little additional training. By reducing ergonomic risk factors, cobots could also contribute to a reduction in opioid dependence, a major public health concern. Both opioid use disorder (OUD) and overdose deaths (OOD) are strongly associated with work-related pain and injury [93]. [14] find that, controlling for observed characteristics of those injured, workplace injury increases the hazard of opioid-related death by almost 80 percent. Hence, meaningful reductions in workplace injuries can save lives.

Some recent deployments of automation, however, have unintentionally intensified workloads for workers and created more adverse safety conditions by sustaining work at a faster than sustainable pace leading to poorer ergonomic conditions, fatigue, greater risk of injuries, increased errors, and unchallenging work [45, 68, 102]. John Howard, Director of the National Institute for Occupational Safety and Health [53] predicts that future "workers interfacing with robots may face work intensification and job displacement..." He warns that "a new 'digital Taylorism' may erode worker autonomy, and lead to work intensification and psychosocial stress." But the situation is not hopeless, as analyses reveal that for some jobs, physical and mental workloads decrease, while for others they increase after cobots are reassigned tasks for optimal productivity [85, 72]. The specific assignment of tasks among cobots and workers is critical for achieving the desired outcome.

2.2. The State of Human-Robot Interaction Design and Worker Reception

On the engineering side, there is much ongoing work aimed at coordination between robots and workers. The prevalence of robots in industrial environments is attributed in part to such advancements in collaborative robot technologies, enabling robots to work close to humans [90]. The rise of teleoperation, involving remote robot control, poses both unique opportunities and challenges for human-robot collaboration in diverse and distributed workspaces. Collaborations involving the teleoperator, the robot, and the local or onsite workers in industrial settings, termed "teleoperator-robot-human collaboration," hold some promise. Recent research has identified opportunities, challenges, and potential applications of such collaborations, which might offer unique benefits, facilitating collaboration among the teleoperator, teleoperated robot(s), and onsite workers across physical and geographic boundaries [61].

Some of our own research takes a hierarchical task analysis approach, rooted in traditional industrial engineering time and motion study, as a foundation for introducing ergonomics considerations of manual work [11, 10]. Work activities in traditional industrial engineering are divided into tasks and further subdivided into actions or therbligs, the anagram named in honor of Gilbreth [96] and is the basis of predetermined time systems utilized in industrial time and motion planning. Although conceived for quantifying task completion times, [39] contended that work activity can be quantified by analyzing multiple variables that consider the worker (e.g., physical capacity, experience, skill, and training), the surroundings, equipment and tools, environmental factors (e.g., illumination, temperature, tools, and loads), and variables of motions (e.g., acceleration, speed, and distance). For example, [40] recognized fatigue due to poor task design. We adapted such a hierarchical framework and expanded it to analyze work systematically and comprehensively across a variety of manufacturing tasks to create a taxonomy of human work to facilitate an optimal allocation of work activities among human and robot workers for productivity, accuracy, compatibility, endurance, and tolerance [72].

Researchers have for some time now considered how robotics and humans can interact most productively [79]. Our work has also demonstrated examples of how such complementarity can be achieved between cobots and workers [12, 60], and others have shown what economic benefits it might offer to employers [2]. An early example is an exploration of how tasks that are currently being performed manually can be allocated to "hybrid" human-robot teams, generating complementary plans that take human and robot capability, cycle time (i.e., the amount of time it takes to complete a unit of production), and ergonomic impact (e.g., physical strain that task imposes on the worker) into consideration [85]. The application of this approach uncovers the types of tasks where the complementarity between a human worker and a cobot can offer performance and/or ergonomics benefits. Specifically, this work found that tasks that involved work that is parallelizable, were repetitive, and included awkward postures for the human worker benefited from the integration of the robot.

An alternative to this allocation-based approach is to provide the human worker with the ability to determine complementarity "on the fly" using an end-user programming interface [47]. In this approach, the human worker plans automated work for the cobot, and during the operation of this automated work, steps in to provide corrections where automation is unable to meet task expectations. An application of this approach to a sanding task has shown that, compared to manual sanding, this form of human-robot complementarity can reduce worker fatigue across different parts of the body by 17.5–36.5% and reduce perceived task load while improving the quality of the work by approximately 6% compared to full automation [64]. This approach can also enable the human worker to simultaneously supervise and correct the work of multiple cobots, which offers much greater gains in productivity [46]. These examples highlight the potential that the introduction of cobots may have on productivity and worker health and demonstrate the different forms that human-robot complementarity can take.

Efficient use of cobots can also help reduce turnover, retain workers, and reduce injuries on the job, leading to less demand for long-term disability applications. [71], also referenced above, develop an index of cobot adoption suitability across occupations and connect this with demographic data on who is currently employed as well as injury rates in occupations that hold the greatest promise for cobot integration. One finding was that the occupations with high cobot integration potential have average injury, overexertion, and total medical treatment rates that are far higher—by many measures almost double. Beyond their potential to increase productivity in working alongside people, cobots can also be designed especially to reduce injuries of workers in these otherwise risky occupations. By reducing many physical demands in cobot-integrated occupations, the pool of people who are both interested in and also more able to do the work can expand. Although cobot design has progressed, several barriers and challenges to integration remain on the worker side as well as on the employer side.

Many young workers eschew trade work and find it unappealing because it is physically demanding, dangerous, and sometimes dirty. This attitude has led to a shortage of manual craft workers in many nations [3]. Americans want meaningful work with economic and job resiliency so they can feel that they are in control of their lives and that they have a say in the direction of their company and worker community. This recent increase in the search for meaningful work is linked to job churn where workers seek jobs for which they are better suited along several dimensions. But as workers find jobs they like and obtain longer tenure with internal job ladders, that churn slows down and productivity, stability, and job satisfaction increase [1].

A key question is whether manufacturing, construction, and other blue-collar, "trade work" jobs can indeed be and are also perceived as meaningful, stable work with the desired attributes listed above. Even with lower formal educational barriers, union and other wage premiums, and urgent hiring and training needs among many employers in manufacturing and construction, worker retention challenges persist. Can this be overcome by giving labor a voice and some discretion over their work as well as an internal pay ladder that rises with their tenure and skill, or by other types of interventions that affect the structure of jobs, also termed "the pre-distribution of earnings?"

Worker acceptance of robots and cobots is an essential design and training barrier to overcome. But it can be done. Studies have highlighted the robot's performance, the additional effort needed to operate cobots, the perceived occupational safety of working with cobots, and psychosocial factors, including fear of job loss, existing prejudices against robots, and openness to new technology, as factors that might affect worker acceptance of cobots [12, 60, 43]. There is also mounting evidence that indicates workers can also feel good about working alongside collaborative robotic assistants, particularly if cobots are designed and integrated in ways that address key limitations, including lack of social interaction [83] and lack of autonomy [99]. Worker acceptance of robots improves when robots use social cues to communicate with workers [34] and when workers take ownership of the robot, for example, by configuring or programming the robot [99].

Field studies of worker acceptance and interaction with cobots that are currently deployed in industry report on the emergence of social relationships between workers and cobots (despite management seeing them as "equipment"), the attribution of human characteristics to cobots, social interactions with the robot, and workers benefiting from social cues designed into the robot [79, 89]. These studies highlight that, while many barriers to widespread adoption and acceptance of cobots remain, careful design and integration of cobots into work environments can overcome these challenges and enable a perception of cobots as essential contributors to the productivity and social fabric of these environments [60].

2.3. Institutional and Stakeholder Considerations

There is a role for many actors and stakeholders in bringing about a "cobot revolution." Each may play a role in moving toward a better employee-robotics combination which benefits all parties while providing economic stability and security in an economy centered on people [1]. Alternatively, each may play a negative role by focusing on short-term profits, using technology to put pressure on workers to be unrealistically productive, or setting up adversarial relations between unions and workers. In this section, we briefly outline some of the changing institutions that may play a key role in the deployment of collaborative robotics in manufacturing.

Workers and the Role of Monitoring Technologies. The use of smart technologies that monitor activity in order to optimally coordinate between humans and cobots can lead to significant increases in worker safety, health, and output. But because these monitoring technologies also necessarily measure productivity, in some contexts they could also introduce unwelcome pressure for workers to increase output, possibly overextending themselves due to fear of job loss. Monitoring also introduces legal and privacy concerns. There is evidence that many workers dislike monitoring, citing privacy and feelings of mistrust among top concerns [19, 100, 101]. Such monitoring may, notwithstanding its legality, engender ethical concerns among workers who do not know what the recordings may be used for. There is the risk that employers could use the data collected to engage in potentially unlawful forms of employment discrimination or for strategic gain in liability disputes over workplace injuries. Addressing these concerns is instrumental to the acceptance and success of these systems. But technological monitoring can also help establish evidence of worker productivity which can protect workers. In some industries, e.g., long-haul trucking, monitoring and assistance technology is welcomed by drivers as it can raise their productivity and reduce accidents [37, 54]. Design and implementation must consider the specific aspects leading to these technologies being favorable or not to workers and output, how they can be designed to prevent unscrupulous exploitation of workers, how they shape broader perceptions of cobots, and the legal implications of monitoring technologies.

The Role of Tariffs and Trade Policy The "Free Trade Era" in the US and elsewhere, characterized by rapid policy changes and trade agreements in the 1990s, has delivered broad and significant benefits, primarily through lower consumer prices. The costs, however, have also been high and far more concentrated. Many manufacturing jobs in the US have been displaced—particularly in the labor-intensive textiles and automotive industries—as production shifted to a small set of lower-wage countries. Once-thriving regions have suffered economic decline and population loss. While the overall benefits may outweigh the costs, some economists have grown more circumspect—no longer championing the manifest and unequivocal benefits of free trade, but now emphasizing the adjustment costs to workers and distributional effects. There has been a notable shift in public opinion as well. Most Americans favor free trade agreements but also think that more has been lost than gained through increased trade [27] and consider tariffs acceptable under certain circumstances [86].

By taxing specific imports, tariffs mitigate the negative (and positive) effects of free trade, raising consumer prices but also encouraging domestic production and job growth. If high enough, tariffs could even make some labor-intensive, non-automatable industries viable in the US. Given the relatively high domestic labor costs, technologies like cobots that enhance human labor would become especially appealing.

"Build at home" is a key component of current US industrial tariff policy based on national and economic security and to offset foreign subsidies [13]. These investments are particularly aimed at the EV industry and the semiconductor industry and support a large expansion in manufacturing investment under the CHIPS and Infrastructure Acts [29**?**]. With higher costs leading to decreases in imports from China, there has been a significant increase in domestic manufacturing structure investment (Figure 4; [31]). The question of its effect on US manufacturing employment is still an open issue, with a possible decreased emphasis on EVs owing to a planned expansion of domestic oil and gas drilling, driving down prices of owning carbon-producing vehicles, which may significantly expand the time horizon to realizing the fruits of recent ARP EV investments [30]. Nonetheless, the growth in manufacturing investment presents an opportunity for integrating technologies like cobots that enhance scarce human labor.

The Role of Industrial Labor Unions The recent resurgence of labor unions in automobile manufacturing and related industries has improved workers' futures, but not without some costs. Most manufacturing jobs are full-time jobs with good benefits as compared to "gig" jobs and part-time employment. Unions play a key role in reducing wage differentials and obtaining better and more regular hours for union members, hence avoiding under-employment and stabilizing earnings [21]. Unions also contribute to greater worker voice on the direction of development and how to deploy innovative technologies in the workforce. And they are effective instruments to argue for employer accommodations to protect workers from injury and burnout. Given that the threat of automation weakens workers' bargaining power, reduces wage adjustments, and amplifies unemployment fluctuations, unions could therefore play a large role in advancing policies that protect labor and argue for complementary labor-capital approaches as their recent and continued growth in the automotive and other industries have shown [69].

There is growing interest among non-union workers in joining a union, reflecting a broader desire for greater worker voice—one that could also benefit employers by reducing turnover and increasing returns on investments in employee training [63]. While this could take the form of formal union membership, it could also be realized through employee advisory councils or worker representation on corporate boards. These mechanisms would help institutionalize worker input on policy changes and innovation, fostering trust and reducing the adversarial tensions that often accompany traditional collective bargaining. But labor unions that create a conflictual relationship with employers to automate and not cooperate may not be the best way forward. In contrast with the US, European work councils and labor unions encourage firms to automate while investing in training and upgrading skills so blue-collar workers can advance and be more productive [23]. The recent unionization of Volkswagen in Tennessee, but the failure to win unionization for Mercedes employees in Alabama, suggests that unions involved in US auto manufacturing are not yet strong enough to make large institutional changes in the treatment of workers.

The Role of Business Incentives and Tax Policy Corporate economic structures create incentives to reduce labor costs and increase productivity to generate dividends, raise stock prices, and give high-level employees bonuses based on these actions. These incentives work against the longer-term interests of workers and firms by focusing only on short-term profits and stock prices due to lower taxes on returns to capital [98, 95]. Changes in the relative tax rates on labor and capital could also greatly influence investment in new workplace technologies. Currently, federal and state capital tax rates are much lower than labor income tax rates. The rationale has been that, because capital investments are forward-looking and more "elastic" or responsive to price changes compared to labor, making tax on capital more distortionary and reducing investment. While it is an empirical question, if those assumptions are not accurate and the estimates of capital elasticity are lower than previously thought, taxing capital at a lower rate would not be justified and should not be advantaged over labor. [5] argue that automating capital has been undertaxed and that, instead, technologies that are favorable to workers and increase productivity should be incentivized. If augmenting technologies like cobots were—unlike automating technologies—elastic, this would suggest either favored tax rates or subsidies would be highly effective at promoting their development and usage.

3. Goals for the Economy and Policies to Go from Here to There

The paradigm of technological development that has long focused on replacing human capabilities must cede its place to a mindset focused on expanding human potential [2, 3]. The changes we envision—and believe are necessary—would require a different approach to technology, both from policymakers and corporate entities. The human-complementary approach is not likely to prevail with existing tax and investment policy and corporate attitudes. But policy can help us change the tide [1, 4, 23]. There are hopeful signs, as the policy focus within manufacturing industries has changed from job quantity to job quality, in a quest for stable well-paying jobs with good benefits and a worker say in how technology is deployed [75].

Cobotics could and should be deployed not to replace human work but to augment it, enabling workers to perform more complex tasks, being trained alongside new technologies to increase productivity. If so, the outcomes for workers would reduce financial stress; reduce job instability and uncertainty; and increase earnings stability and earnings ability, accompanied by within-company growth paths of earnings tied to overall and job-specific productivity growth [1]. If indeed the goal is to "choose a path for machines in service of minds" [4], the following policy targets will direct us toward that goal.

3.1. Goal 1. Strategic Investments in Human Capital

Strategic investments in formal post-secondary training and education, coupled with clear pathways to employment, would minimize displacement and promote recovery. US labor markets are very flexible but do not often facilitate connections that both help prepare people for jobs and then link them to these jobs. Employment rates are consistently higher and less volatile for people with higher levels of education, as they assimilate knowledge and both soft and hard skills that are increasingly valued in the labor market [36]. Scarcity of labor can drive wages up, if combined with the right investments in both equipment, cobots, and people. Investment in robots has increased rapidly, but it has not been accompanied by adequate investments in people. However, the workforce remains arguably unprepared for many new tasks, including technical and advanced precision work alongside and with robots [6]. This sort of sectoral technical training, termed "career and technical education" or CTE, can be accomplished through existing and expanded collaborations between community colleges and employers to provide the necessary skills. Additionally, apprenticeships and on-the-job learning can also contribute [59] and be encouraged through tax incentives for firms that provide training in working with cobots and other technologies that enhance human labor, as described in section 3.5, and through place-based efforts we discuss in 3.4.

By adopting these strategies, such technologies can become relatively more attractive than those designed to displace human labor, ensuring a swifter recovery for displaced workers [36]. The US Trade Adjustment Assistance program, which has helped provide wage insurance for workers adversely affected by trade, could be used also to compensate workers displaced by technology [55]. While the effectiveness of TAA has been mixed [91], lessons from it can inform the design of programs that anticipate—rather than respond to—potential disruptions, relying on estimates of robotics exposure [35, 71]. Such programs and policies are widely practiced in Europe and offer models that could be adopted [67].

3.2. Goal 2. Supporting Human-Centered Cobot Research

Tasks where cobots are carefully integrated to augment worker capabilities have the potential to mitigate physically straining work by performing repetitive and physically straining tasks and reduce direct costs associated with worker injuries and lost time, as well as reducing indirect costs associated with reassignments, insurance, and work dissatisfaction. While this is clearly valuable for workers, employers, and society, many technologies come from research focused on more narrowly defined objectives. Increased public funding for human-complementary technology research, recognizing that this is not currently a private sector priority, should be better supported to optimize robotics for all [61]. Innovation in cobotics is currently driven by internal research and development divisions within and investments by large companies [9], and in addition to technological advantage, tax incentives for companies, in exchange with public sharing of advancements, can facilitate industry-driven innovation. As it is now, because not all benefits are internalized, even negligible costs lead to missed opportunities and design approaches that society overall would benefit from. Human-centered design and research that takes an integrated, cross-disciplinary perspective on the place of work-related technologies should be advanced within existing research and funding structures.

3.3. Goal 3. Modernized Occupational Policy

Update and modernize Occupational Safety and Health Administration rules to create safeguards (i.e., limitations) on the use of worker monitoring that leads to layoffs, and by increasing reporting of hazards by employees and employers. These updates could incorporate incentives to reduce injuries, by means of increasing employer penalties for injuries and rewarding employers for reducing injuries on the job. Proactive surveillance for occupational health and safety hazards can not only prevent injuries but reduce the costs associated with lost work time and reassignments. Ergonomics tools for hazard surveillance utilizing AI, computer vision, and sensor technologies offer a means for detecting hazards that are more vigilant and less demanding of employer resources. Policies for monitoring physical stress and strain should be updated to accommodate smart devices.

3.4. Goal 4. Improved Place-Based Investments

Policies promoting the integration of human-centered technology should expand on or redirect recent targeted programs, such as the 2022 CHIPS and Science Act's regional tech hubs program and the 2017 Tax Cuts and Jobs Act's Opportunity Zones. As larger companies seek to reduce supply chain risks by investing closer to their customers, these programs have further encouraged revitalization in areas affected by disinvestment due to trade and technological changes [78]. Much of this new investment targets communities that suffered the worst impacts of plant closures in recent decades, some of which are gaining a disproportionate share of new investment and job creation [57]. Not all such communities have benefited, and there are both notable successes and failures [42, 41, 20]. Many of these subsidy-driven initiatives have spurred significant new investments in plant and equipment [29]. However, such policies must be carefully designed to ensure that subsidized investments promote technologies that enhance human work and skills rather than further displace them, aligning with training recommendations from above.

3.5. Goal 5. Promoting Worker Voice, Training, and Collaborative Agreements

Policies that facilitate the integration of cobots in the workplace should seek to promote worker interests and voice, while at the same time avoiding unsustainable cost increases or encouraging full automation. This can be achieved by encouraging collaboration through various forms of worker representation and productivity-linked agreements. A collaborative approach, as demonstrated by Germany's industrial unions, enables companies to embrace and adapt to technological advancements while maintaining competitiveness by improving both productivity and wages. Actively promoting collaborative investment, however, also requires policies that would align the training needs of people and employers. This should include more tangible incentives for investment in human capital to complement human-centered cobot technologies. While unions can advocate for training and upskilling programs that enhance labor value and reduce the risk of automation-driven displacement, such initiatives are not always in employers' immediate interests or financially viable. Firms could be incentivized to provide these programs through tax deductions, alongside training initiatives coordinated through the Workforce Innovation and Opportunity Act (WIOA).

3.6. Goal 6. Improvements to Tax Policy

Capital income is almost always taxed at lower rates than earned labor income in the US and in other advanced economies at both the personal and corporate levels [52]. These differences in tax rates distort the relative prices of labor and capital, and the artificially lower cost of capital relative to labor unambiguously increases demand for capital as a substitute for labor [58]. Along with [24], we would argue for equalizing the effective marginal tax rates between labor and capital (via corporate income tax), in addition to allowing deductions for human capital investments (through such training as mentioned above), to promote parity. In doing so, more investment would be directed towards enhancing human labor—including technologies such as cobots—and away from technologies that displace or automate human labor.

4. Conclusion

Cobots hold significant promise for enhancing productivity through complementarity with human workers rather than displacement. At the same time, there are potential barriers to greater integration of cobots in the workplace. On the worker side, the effects go beyond wages and employment, extending to job quality, autonomy, and well-being. Cobots appear poised to impact industries unevenly, often affecting younger, lower-wage workers in physically demanding roles while simultaneously offering a chance to expand job opportunities for people who previously could not perform such work and reduce injury. Acceptance and effective deployment of cobots hinge on both thoughtful engineering design—such as ergonomic task analysis, teleoperation, and adaptive end-user programming—and institutional factors like union participation, business incentives, and worker training. Policy choices around trade, taxation, and regulation influence whether cobots become tools for augmenting human labor or instruments of intensified workload and job displacement. Ultimately, successful cobot integration depends on creating an environment in which the interests of workers and employers are more aligned to balance immediate cost savings with long-term social and economic benefits.

We believe that we have begun to make the case for strategic policy incentives and redirection of investments to meet manufacturers' thirst for more productivity and promote the interests of American workers following several decades of loss of jobs, earnings, and wages due to changes in technology as well as trade [26]. A shift in how technology is developed and deployed, moving from a labor-replacing focus toward expanding human potential, will require strategic investments in human capital—through post-secondary education, apprenticeships, and tax incentives for workforce training—to minimize displacement and increase workers' adaptability. Offsetting economic losses and ensuring future technological advancements that preclude repeating past displacement should be central to our policy goals moving forward [25, 66]. Support for human-centered robotics and cobot research would help ensure that technologies are designed to complement and enhance human capabilities rather than replace them, while improving job quality and reducing workplace injuries. Modernizing occupational safety rules, providing wage insurance and training for workers, and refining place-based investments are all necessary to ensure the benefits of new technologies are felt broadly and do not come at the expense of only some groups. Strengthening worker voice, fostering collaborative agreements, and equalizing the tax treatment of capital and labor would also encourage growth that promotes human-complementary innovation and shared productivity gains.

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5. Supplementary Figures

FIGURE 1: A cobot application at a Ford Motor Company's assembly plant in Cologne, Germany. In the application, the cobot carries a heavy, air-powered tool, which the worker positions during the installation of shock absorbers in Ford Fiesta model cars. (Copyright: Ford Media Center, permission pending.)

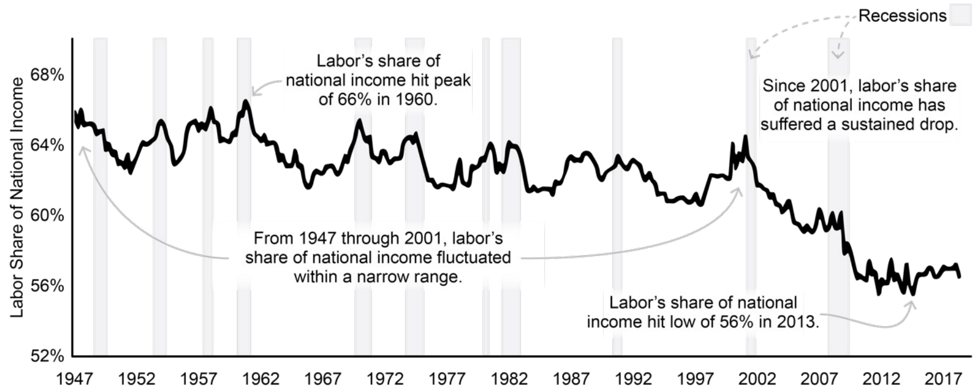
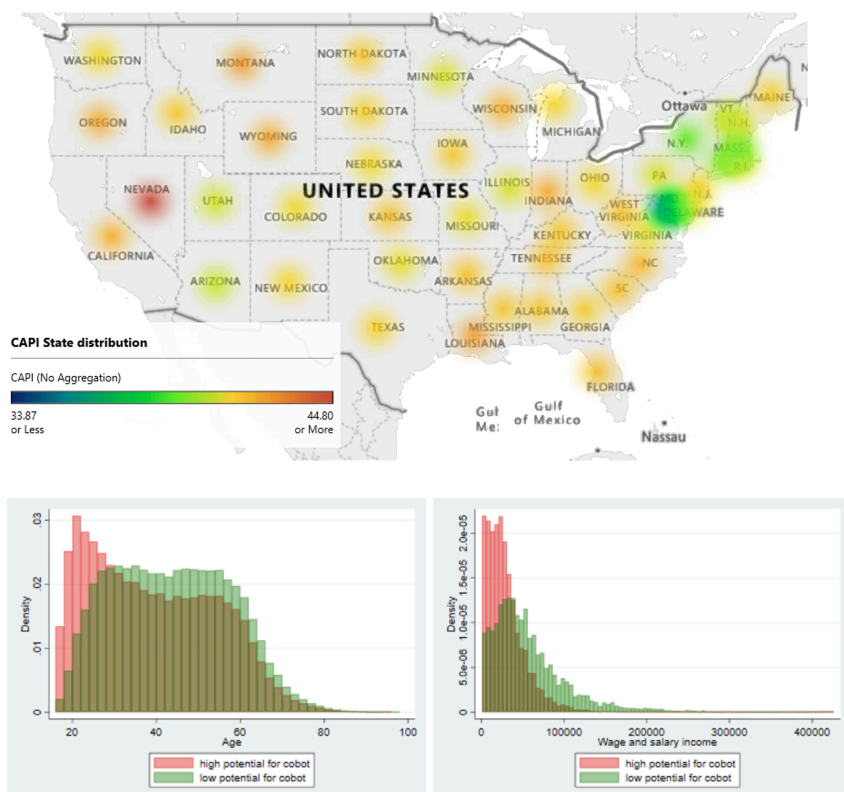


FIGURE 2: Labor share of national income. (Adapted from [58]; data source: Bureau of Labor Statistics.)



(a) age

(b) income

FIGURE 3: *Top:* geographic distribution of cobot-exposed work. *Bottom:* age (a) and income distribution (b) for people in jobs with high- and low-cobot exposure. (Source: [71]).

Figure 4: Surge in real total manufacturing construction investment after the passage of the CHIPS Act and IRA. (Adapted from [29]; data source: FRED Total Manufacturing Construction Spending, monthly at a seasonally adjusted, annualized rate using FRED Price Index of Materials and Components for Construction).