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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/350/6265/1242/suppl/DC1
Supplementary Text
Figs. S1 to S8
Tables S1 to S3
References (*36–61*)
Data Files S1 and S2

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EDUCATION

Democratizing education? Examining access and usage patterns in massive open online courses

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Massive open online courses (MOOCs) are often characterized as remedies to educational disparities related to social class. Using data from 68 MOOCs offered by Harvard and MIT between 2012 and 2014, we found that course participants from the United States tended to live in more-affluent and better-educated neighborhoods than the average U.S. resident. Among those who did register for courses, students with greater socioeconomic resources were more likely to earn a certificate. Furthermore, these differences in MOOC access and completion were larger for adolescents and young adults, the traditional ages where people find on-ramps into science, technology, engineering, and mathematics (STEM) coursework and careers. Our findings raise concerns that MOOCs and similar approaches to online learning can exacerbate rather than reduce disparities in educational outcomes related to socioeconomic status.

For nearly a century, technologists have promised that new broadcast media will bridge resource gaps between students in more- and less-privileged environments. "With radio the underprivileged school becomes the privileged" was the promise in the 1930s (*1*); in the 1960s, boosters declared that television would "make available to these young people instruction of a higher order than they might otherwise receive" (*2*). In the first years of the 2010s, technologists have heralded the possibility that massive open online courses (MOOCs) can "democratize education" (*3–5*). Previous generations of broadcast and interactive technologies—film, radio, television, personal computers, Internet access, and Web 2.0 platforms—have yet to fulfill the promise of educational parity (*6*), and these new claims from MOOC advocates warrant empirical study. In this study, we took advantage of the data collected from MOOC students about their demographics and course performance—generally unavailable in studies of broadcast technologies—to present a portrait of registration and completion patterns in 68 courses offered by Harvard and MIT on the edX platform.

Our analytical framework was guided by Attewell's argument that the "digital divide," the gap in education technology opportunities between students from different backgrounds, is best understood as two divides: one of access and one of usage (*7*). More- and less affluent students not only have different levels of basic access to emerging technologies; they have used them for different purposes with different levels of support from mentors. Historically, digital divides of usage have compounded digital divides of access. Surveys from the National Assessment of Educational Progress in 1996 and 2011 showed that students from schools serving mostly affluent students were more likely to use computers for simulations or modeling; by contrast, students from schools serving low-income students were more likely to use computers for drill and practice exercises (*8*, *9*). Comparable patterns have been found across the sciences and other subject areas when comparing schools with similar computer–student ratios serving students from different backgrounds (*10*). Attewell found evidence of similar patterns of computer usage at home, where the academic benefits of home computers were greater for children from affluent families (*11*).

These patterns extend into the era of free Web tools as well. Reich and colleagues examined the use of freely available wikis—platforms for collaborative Web publishing—in U.S. kindergarten to high school (K–12) schools in the late '00s (*12*). They found that free wikis were more likely to be created in affluent schools, and in these schools, wikis were more likely to be used to support collaborative problem-solving and new media literacy. In schools serving low-income students, wikis were more likely to be used for teacher-centered content delivery. This research suggests a potential paradoxical effect of free online-learning resources: They can disproportionately benefit the affluent—people who have the social, financial, and technological capital to take advantage of new innovations, including those that are free.

The earliest research on MOOCs hints at similar kinds of patterns. The majority of registrants in MOOC courses already had a college or graduate degree, and some studies have found a positive, substantively modest correlation between a student's level of education and course completion (*13–16*). We built upon these studies with a much richer demographic portrait of students across a wider range of courses.

Socioeconomic status (SES) denotes one's social and financial resources, and it is typically viewed through a combination of measures (*17*).

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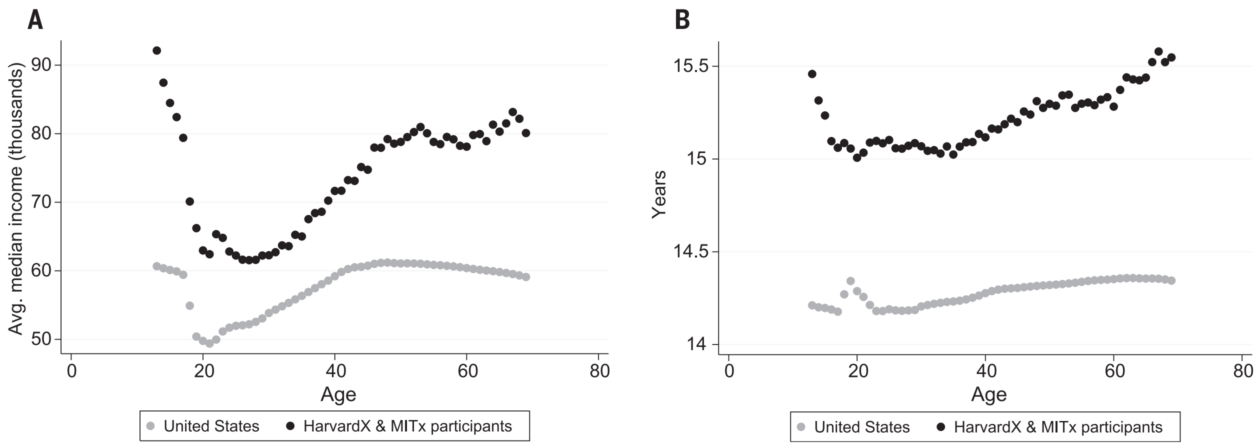

Fig. 1. Neighborhood income and educational attainment differences between MOOC participants and the U.S. population. (**A**) Average neighborhood median income. (**B**) Average neighborhood educational attainment.

In this study, we used three indicators for SES: (i) parental educational attainment, (ii) neighborhood median income, and (iii) neighborhood average educational attainment. When signing up for edX, students were asked to provide their mailing address, and for U.S. MOOC registrants, we used this address to identify each student's census block group, a "neighborhood" of ~1500 people for which we have census data about median income and educational attainment (*18*). Although more direct measures of family income or wealth are preferred, these neighborhood-level measures have proven useful in other studies (*19*). We are particularly interested in adolescents age 13 to 17, for several reasons. First, these are the years that have traditionally been critical for students finding an on-ramp into postsecondary science, technology, engineering, and mathematics (STEM) education and careers. Also, MOOC advocates have identified K-12 students as a promising target population for MOOCs (*20*, *21*), and universities and MOOC platforms are increasingly targeting this population with their offerings (*22*). Pragmatically, these students likely live at home with their parents, and our three measures probably identified an individual's SES with greatest fidelity in this age range.

In the 2012–2014 academic years, Harvard and MIT offered 68 free courses and modules on the edX learning-management system, which attracted 1,028,269 unique participants (individuals who entered the courseware of one or more courses) (*16*). Our study examined 164,198 unique participants from the United States who reported an age between 13 and 69 and provided a mailing address that we could match to a census block group, which represented 57% of U.S. participants in this age range (table S1). Because many participants registered for multiple courses, these students accounted for more than 200,000 participant-course observations. We compared the demographic characteristics of U.S. MOOC participants to the U.S. population to better understand the digital divide of access. This comparison can be understood as a case-control study (*23*), with edX enrollees as cases and a synthetic set of one-to-one matched controls by geographic area, with the assumption that controls were unlikely to be enrolled in edX, given the large population size. We then examined how measures of SES predicted course completion to understand the digital divide of usage.

Table 1. Differences in MOOC participation and certification likelihood attributable to a one–standard deviation increment in SES variables. Values are odds ratio plus or minus 1 SE. An odds-ratio of 1 means equivalent odds. For age 13 to 69 regressions, the sample sizes are ~232 million for participation and 201,225 for certification. For age 13 to 17 regressions, the sample sizes were ~20.5 million for participation, 8481 for neighborhood-SES certification models, and 2112 for parental education certification models. See supplementary materials for model specification details. Robust standard errors clustered at the course level are used for certification models. All coefficients are statistically significant ($P < 0.01$).

SES variable	Age	Participation	Certification
Neighborhood income SD = $30,536	13–69	1.44 ± 0.003	1.06 ± 0.014
	13–17	1.59 ± 0.012	1.13 ± 0.026
Neighborhood education SD = 1.27 years	13–69	1.95 ± 0.005	1.07 ± 0.022
	13–17	2.09 ± 0.024	1.32 ± 0.049
Parental education SD = 2.92 years	13–17	2.97 ± 0.086	1.28 ± 0.114

We first described differences in neighborhood characteristics between HarvardX and MITx participants and the U.S. population as a whole. For individuals of all ages from 13 to 69, MOOC participants lived in neighborhoods that are more affluent and have higher average levels of educational attainment (Fig. 1). We found that, on average, MOOC participants resided in neighborhoods where median household income was $69,641 dollars, which was $11,998 dollars above the neighborhood national average of $57,643 (table S2). When we restricted our comparison to individuals aged 13 to 17, the difference was $23,181 (table S2). We found large differences in neighborhood educational attainment across all age groups as well.

We conduct a variety of sensitivity analyses (presented in the supplementary materials), which suggested that this finding was robust and persisted at the individual level (fig. S4). Specifically, we found that the positive relationship between neighborhood SES and MOOC participation persisted across courses and within states, counties, and census tracts (table S6); survey respondents appeared similar to nonrespondents with respect to our measures of SES (tables S7 and S8); alternative demographic data sets and neighborhood identification approaches produced similar estimates; and participants also tended to live in more densely populated neighborhoods (tables S9 and S10), which suggested that MOOCs do not disproportionately serve the geographically isolated.

Predicting MOOC participation as a function of neighborhood SES allowed us to interpret these differences in terms of participation likelihood. The results of logistic regression models are shown in Table 1, where the odds of participation are estimated in terms of a one–standard deviation change in the predictor. Interpreting these results in dollars, we predicted that an additional $20,000 in neighborhood median income increased the odds of participation by 27%. Each

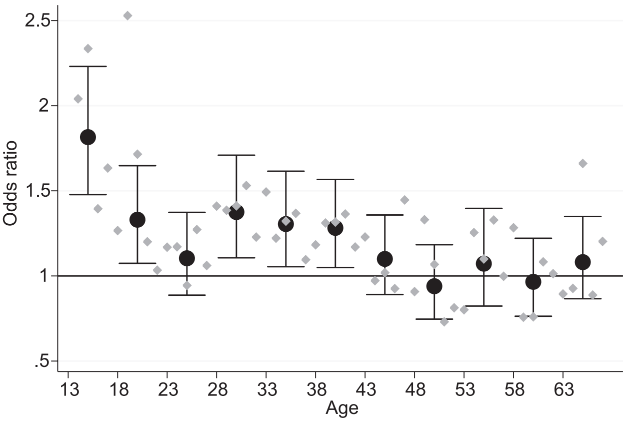

Fig. 2. Odds ratio of certificate-earning for participants with a college-educated parent compared with participants without one. Diamonds were estimated by means of a logistic regression model that includes sets of binary indicators for age, course, enrollment mode, and the interaction of each age indicator with a binary indicator for college-educated parent. Circles with error bars were estimated in an analogous specification where age group indicators (13 to 17 years, 18 to 22 years, etc.) replaced age indicators in the interaction. Error bars show ±1 SE. Each point on the plot represents the multiplicative difference in the odds of certification among students of the same age whose parents had a bachelor's degree compared with those whose parents did not.

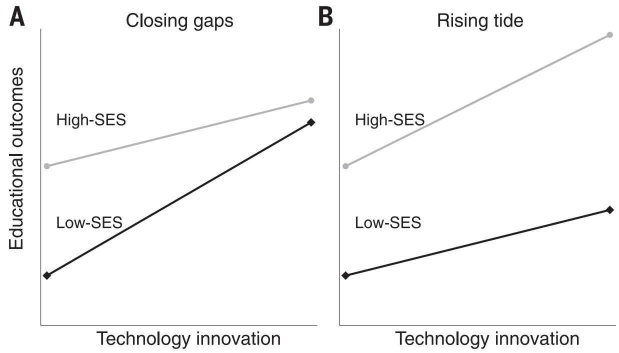

Fig. 3. Two stylized representations of the hypothesized effects of a technological innovation on educational outcomes for students from high-SES and low-SES backgrounds. We compare benefits from emerging technologies and gaps in educational outcomes.

additional year of neighborhood-average educational attainment increased the odds of participation by 69%. Among adolescents, the relationship between neighborhood SES and MOOC participation was even stronger (*24*).

Turning to the digital divide of usage, we found analogous patterns when we examined the relations between our measures and certificate attainment. Neighborhood- and individual-level SES measures were associated with higher rates of course completion, with larger magnitudes for younger participants. After examining the full age range of participants from 13 to 69, we interpreted the coefficients from Table 1 as modest in magnitude. Among the individuals who took the initiative to enroll and participate in a HarvardX course, neighborhood SES—like one's own educational attainment (*17*)—was a statistically significant but not substantively strong predictor of course completion on average (Fig. 2). These relatively modest overall differences, however, masked important differences in attainment by SES for young people. For an adolescent participant whose most educated parent has a bachelor's degree, the odds of certification were ~1.75 times those of an otherwise similar adolescent in the same course whose most educated parent has less than a bachelor's. Students from all backgrounds earned certificates in Harvard and MIT MOOCs, but especially among the young, high-SES students were more likely to earn a certificate.

Overall, individuals living in high-SES neighborhoods in the United States were substantially more likely to participate in Harvard's and MIT's MOOCs, and, conditional on participation, high-SES students earned certificates at higher rates. These patterns were particularly strong among adolescents, precisely the age at which we hope that students from low-income backgrounds can use education as a gateway to the middle class.

The rhetoric of democratizing education implies broad social benefits without precisely articulating how those benefits might be distributed. In Fig. 3, we present two stylized representations of the effects of a technological innovation, such as MOOCs, on educational outcomes from students from different backgrounds. In the scenario that we call "closing gaps" (Fig. 3A), expanding access simultaneously benefits all students and ameliorates inequality. In the "rising tide" scenario (Fig, 3B), all groups benefit from emerging technologies, but gaps in educational outcomes widen.

Whether particular gaps will widen or close, for whom, and under what circumstances, are all questions worthy of further study as MOOCs and other new learning opportunities expand. The findings from this observational study appeared more consistent with the rising tides than closing gaps scenario, but additional research will be necessary to identify causal effects on SES-education gaps. Despite early research that socially advantaged children watched more *Sesame Street* and learned at least as much from watching (*25*), later research found that it narrowed an SES-related gap in school readiness (*26*).

MOOCs are one of many online learning opportunities, and our findings cannot be generalized to all open educational resources or education technologies. Nevertheless, our research on MOOCs—along with previous decades' research examining the access and usage patterns of emerging learning technologies—should provoke skepticism of lofty claims regarding democratization, level playing fields, and closing gaps that might accompany new genres of online learning, especially those targeted at younger learners. Freely available learning technologies can offer broad social benefits, but educators and policymakers should not assume that the underserved or disadvantaged will be the chief beneficiaries. Closing gaps with digital learning resources requires targeting innovation toward the students most in need of additional support and opportunity.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/350/6265/1245/suppl/DC1
Materials and Methods
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References (*27*–*31*)

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WATER RESOURCES

Local flow regulation and irrigation raise global human water consumption and footprint

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Flow regulation and irrigation alter local freshwater conditions, but their global effects are highly uncertain. We investigated these global effects from 1901 to 2008, using hydroclimatic observations in 100 large hydrological basins. Globally, we find consistent and dominant effects of increasing relative evapotranspiration from both activities, and decreasing temporal runoff variability from flow regulation. The evapotranspiration effect increases the long-term average human consumption of fresh water by 3563 ± 979 km^3/year from 1901–1954 to 1955–2008. This increase raises a recent estimate of the current global water footprint of humanity by around 18%, to 10,688 ± 979 km^3/year. The results highlight the global impact of local water-use activities and call for their relevant account in Earth system modeling.

Hydroclimatic changes on land determine the availability of freshwater resources required for human societies and ecosystems on Earth. However, the magnitude and key drivers of such changes historically (*1*, *2*) and in the future (*3*) are highly uncertain, especially regarding the global role of human drivers and the magnitude of their related freshwater consumption. Both changes in the atmospheric climate and in the landscape may drive freshwater change (*4*, *5*) (fig. S1). Among landscape changes, human-controlled flow regulation and irrigation (FRI) affect inter- and intra-annual freshwater conditions locally, but recent results indicate possible important effects on larger scales as well (*6*).

FRI developments over the past century have either moderately or strongly affected 59% of the world's largest river systems (*7*). They include around 45,000 large dams and many other smaller ones, spread over 140 countries around the world (*8*) and constructed mostly over the past century to store water for irrigation, flood control, urban water supply, hydropower, or a combination of such purposes. These developments are linked with approximately 12 to 16% of the current global food production and 19% of the world's electricity supply (*8*), even though they only cover 0.3% (*9*) and 2% (*10*) of the global land area, respectively. Regarding the environmental impacts of FRI, attention so far has focused on ecosystem effects of river fragmentation and diversion (*11*) and water storage (*12*). More recently, studies at local to regional scales have found an FRI-related enhancement of the ratio of actual evapotranspiration (AET) to precipitation (P); i.e., of AET/P (*6*, *13*, *14*). For flow regulation, a concurrent decrease is also found in the short-term (daily and monthly) variability of runoff (R) (*6*, *14*, *15*). A combination of these effects on AET and R can be then used to distinguish the impacts of FRI developments from those of other drivers of freshwater change (*6*). At a global scale, some studies have addressed at least one of these FRI-related effects in global-scale modeling (*16*–*21*) but have not provided observation-based evidence of the global importance of FRI as a driver of freshwater change.

To fill this key observation gap, we analyzed global hydroclimatic data from 1901 to 2008 for 100 large hydrological basins (Fig. 1). For these basins, we computed hydroclimatic changes (supplementary materials) between the 54-year periods 1901–1954 and 1955–2008 and compared them with previously categorized impact levels (*7*, *11*) and parameterized developments (*9*, *10*) of FRI (table S1). From the results, we further quantified the magnitude of the FRI-driven hydroclimatic changes in each basin and assessed their implications for global human consumption of fresh water.

Globally, the quantified hydroclimatic changes reveal consistent characteristic signals of increased AET/P and decreased relative intra-annual variability of monthly runoff (CV_R) with higher FRI impact level (Fig. 2 and fig. S3). Further study of the distribution of AET/P changes among basins shows large variability (Fig. 3A and fig. S4), but still a significant AET/P increase with increasing basin measures of FRI development (Fig. 3, B and C). The latter measures are quantified from previous basin parameterization of total reservoir storage capacity (*9*) relative to basin area, specifically its change between 1901–1954 and 1955–2008 (ΔRES), and area equipped for irrigation (*10*) relative to basin area (I_A).

We also tested the possibility of the AET/P changes being explained by geographic basin location or atmospheric climate change. Specifically, we checked the relationship of AET/P change with relative potential evapotranspiration (PET/P, expressing water-relevant climate conditions in each basin) and change in PET/P (expressing water-relevant climate change occurring in the basin) (*22*). We did not find these explanatory patterns between AET/P change and PET/P or PET/P change (Fig. 3, D and E). Regarding PET/P, the water-limited basins (PET/P > 1) should have less water available for AET/P increase than the basins with mostly energy-limited conditions (PET/P < 1) (*5*, *22*, *23*). Rather, the relatively large AET/P increases in water-limited basins are consistent with irrigation developments occurring preferentially in their arid and semiarid climates. Overall, changes in AET/P among the investigated basins are better explained by differences in the basin characteristics of reservoirs and irrigation than by differences in atmospheric climate conditions or their changes.

Changes in CV_R among the 100 basins are also variable (Fig. 4A), yet a dominant change pattern is seen as CV_R decreases with higher increase in

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