Cross-Country Technology Diffusion: The Case of Computers

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It has long been recognized that increases in technical efficiency play a critical role in long-term growth. For high-income countries, this has led researchers to focus attention on the R&D process. For low-income countries, which are presumed to operate inside the technological frontier, an additional source of efficiency gains is to be found in the adoption of technologies already developed in technologically advanced countries.[1] Yet not much is known empirically about the determinants of technology adoption. This paper presents a case study of the diffusion of computer technology around the world. In particular, it tries to identify variables that predict adoption of computers in a panel of countries.

Computers provide an ideal case study of technology diffusion. First, they have been introduced recently (i.e., after or in conjunction with the inception of the relevant data collection processes). This allows us to catch the process from its very beginning. Second, computers constitute a clear case of embodied technology: a country cannot adopt computer technology without physically installing computers. Hence, a measure of the computing capacity installed is a direct measure of technology adoption. In contrast, it is very hard to measure the diffusion of technologies that are disembodied.

Of course direct measures of investment in computing equipment do not exist for a large enough number of countries or for a long enough time span.[2] However, we argue that measures of *imports* of computing equipment are likely to be adequate proxies of such investments. This is because most countries simply do not have a computer-making industry, and this was especially true at the beginning of the diffusion stage. For these countries, the capacity installed is the capacity imported. In other words, technology diffusion takes place through imports of the equipment embodying the technology.

We have detailed data on imports of computer equipment for virtually all countries in the world, starting in 1970. Hence, this paper will use panel data to seek to characterize the determinants of imports of computers across countries. Our strongest findings are that computer adoption is associated with high levels of human capital, and with manufacturing trade openness vis-à-vis the OECD. We also find considerable evidence that computer adoption is enhanced by good property-rights protection, high rates of investment per worker, and a small share of agriculture in GDP. There is also some evidence for a negative role of the size of government and a positive role of the share of manufacturing in GDP. After controlling for the above-mentioned variables, we do not find an independent role for the English- (or European-) language skills of the population. The quantitative importance of these findings, as well as their theoretical interpretation, is discussed in the concluding section.

I. Data on Computer Imports

The focus of our analysis is computer investment per worker. We measure aggregate

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[1] Macroeconomic evidence that poor countries operate inside the technology frontier can be found in (among others) Caselli et al. (1996), Peter Klenow and Andres Rodriguez-Clare (1997), Robert Hall and Charles Jones (1999), and Caselli and Coleman (2000).

[2] The United Nations Development Program (UNDP) has a data set with information on stocks of personal computers for the 1990's. Jong-Wha Lee (2001) has examined these data and, consistent with our results, has found a strong role for human capital.

computer investment by imports of computer equipment. Almost all countries report detailed information on their bilateral trade flows by very disaggregated product or commodity to the United Nations. These detailed trade-flow data have been made available by Robert Feenstra et al. (1997). This paper focuses on imports of "automatic data processing machines and units thereof; magnetic and optical readers, machines for transcribing data onto data media in coded form and machines for processing such data, n.e.s. [not elsewhere specified]." In practice, this variable measures imports of assembled computers, as well as imports of key components, such as central processing units, memory chips, storage devices, and peripherals.[3] We focus on the period 1970–1990, which essentially covers the beginning and the coming of age of the computer revolution. Information on computer imports is available for 155 countries, though the country coverage for most of our empirical work will shrink because of limitations in the covariates we use. We express the import data in per-worker terms by dividing aggregate computer imports by the labor force, as measured by the World Bank (1999).

We believe computer imports per worker to be an adequate measure of computer investment per worker for a large majority of the countries in the world. Simply put, the computer industry is well known to be highly concentrated internationally, with a handful of countries providing most of the world's computer output. For this reason, computer imports and computer investment are probably very closely associated. A check of this idea based on computer exports per worker gives a somewhat ambiguous response. The percentage of countries in the sample with no reported computer exports falls from 58 percent in 1970 to 13 percent in 1990. Hence, a sizeable fraction of the sample appear to be exporting some computers, perhaps suggesting the existence of a domestic computer industry after all, especially in the later period of coverage. However, inspection of the data reveals that most of the positives are trivial in amount, suggesting to us that these exports almost certainly reflect reexports or statistical anomalies.

In order to deal with the ambiguous message from the export data, in our empirical work we work with three data sets of computer adoption. The first data set proxies computer adoption with computer imports and uses the full sample. The second data set uses the same adoption variable but limits the sample to those countries with no reported computer exports. This is clearly overkill, as it excludes some countries that cannot plausibly be deemed to produce their computers domestically. But any alternative cutoff criteria would be arbitrary, and this stringent criterion allows us to check the robustness of the results from the full sample. The third data set uses production data from United Nations Industrial Development Organization [UNIDO] (2000) to construct an adoption variable based on the formula: adoption = production + imports − exports. One shortcoming of this (otherwise ideal) adoption variable is that the production data pertain to a somewhat broader category of equipment, namely, office, computing, and accounting machinery (OCAM), so its identification with computer adoption is not as tight.[4] More distressingly, the country coverage is quite limited. Furthermore, time coverage for these data for a reasonable number of countries only starts in the 1980's. The important point, however, is that some key results are fairly similar in the three samples, as will be shown.

Throughout the paper we use the current U.S.-dollar value of computer imports to

[3] The computer-import variable is category 752 in the UN data set. It includes the following subcategories (for which separate data are available): analogue and hybrid (analogue/digital) data-processing machines (7521); complete digital data-processing machines, comprising in the same housing the central processing unit and at least one input unit and one output unit (7522); complete digital central-processing units; digital processors consisting of arithmetical, logical, and control elements (7523); digital central (main) storage units, separately consigned (7524); peripheral units, including control and adapting units (connected directly or indirectly to the central unit) (7525); and off-line data-processing equipment, n.e.s. (7528).

[4] The OCAM production variable is category 3825 in the UNIDO (2000) data set, which adopts an ISIC (international standard industrial classification) standard. Information provided by UNIDO itself allows us to determine that concordance with the trade data requires aggregation of categories 751 (office machines), 752 (our computer variable), and 759 (parts for 751 and 752) in the latter.

compare computer adoption across countries at a given point in time. Hence, we are implicitly assuming that computer prices obey purchasing-power parity. Given the absolute absence of computer-price indexes for all but a few countries, we frankly admit that we have no way of backing up this assumption. Even for the United States, the existing deflators are surrounded by considerable controversy, and different deflators behave wildly differently. For these reasons, in this paper we eschew intertemporal comparisons: all our empirical work will handle intertemporal variation through time dummies which (assuming again that the law of one price holds) should absorb changes in the dollar price of computing power. We leave the study of intertemporal patterns of computer adoption to future work.

II. The Determinants of Diffusion

Our strategy to investigate the determinants of differences in computer-technology adoption is to look at a variety of regression results using specifications of the form

$$(1) \quad \log(I_{\mathrm{c}}^{it}) = \alpha + \boldsymbol{\delta}^{t}\boldsymbol{\beta} + \mathbf{X}^{it}\boldsymbol{\gamma} + \eta^{i} + u^{it}$$

where I_{c}^{it} is computer imports per worker (in current U.S. dollars) in country i and year t, $\mathbf{X}^{it}$ is a set of explanatory variables, $\boldsymbol{\delta}^{t}$ is a set of year dummies, η^{i} is a country effect, and u^{it} is independently and identically distributed among countries and years. All the variables we will include in the vector $\mathbf{X}$ are available at annual frequency, except for our measure of human capital, which is only available at five-year intervals. Since this variable turns out to be a key determinant of computer adoption, our regressions are based on data for the years 1970, 1975, 1980, 1985, and 1990. Depending on the sample, the country coverage varies roughly between 40 and 90.[5]

In cross-country studies of this kind there is considerable controversy regarding the appropriate estimation technique, and in particular regarding the treatment of the country-specific term, η^{i}. The basic choice is between random effects (RE) and fixed effects (FE). The RE estimator is the most efficient but is consistent only under the most stringent assumptions (i.e., that η^{i} is uncorrelated with the vector $\mathbf{X}^{it}$). The FE estimator does not require this stringent assumption, but the country dummies absorb a lot of the variation in the data, making the estimator relatively inefficient. Our compromise solution in this "efficiency-consistency" trade-off is to do a bit of both: we include a full set of regional dummies (fixed region effects) and treat the residual country effect as random (random country effects). In other words, we do assume that η^{i} is uncorrelated with $\mathbf{X}^{it}$, but we include in the latter a full set of regional dummies. This technique is consistent if the part of the country effect that is orthogonal to the region effect is also orthogonal to the remaining elements of $\mathbf{X}^{it}$. The advantage is that it is more efficient than the "fixed country effect" estimator. It is important to acknowledge, however, that when we apply the fixed-country-effect technique to the specification below we can identify virtually no significant explanatory variables.[6]

We treat the vector $\mathbf{X}^{it}$ as exogenous for $\log(I^{it})$. Reverse causation is extremely unlikely to be a problem. For almost all countries in our samples, computer adoption is extremely limited between 1970 and 1990, and it is unlikely to have caused changes in any of the macroeconomic variables on the right-hand side. For example, it is highly unrealistic that computer adoption may have impacted the supply of human capital in countries other than the most advanced ones, and even there it is doubtful before 1990. Of course, that reverse causation is not a major concern does not rule out the possibility that we have induced bias in our

[5] In view of the fact that several countries report no imports of computers, the log specification may seem to generate sample selection. It turns out, however, that none of the country-year observations with zero computer imports has complete data on the set of explanatory variables we employ, so taking logs per se does not induce any additional censoring.

[6] The regional dummies are for sub-Saharan Africa, Latin America and Caribbean, Eastern Europe, Arab World, East Asia, and rest of Asia. In practice, the "omitted" region coincides almost perfectly with the OECD. See Caselli and Coleman (2001) for more details on country-year coverage and regional assignments.

TABLE 1—DETERMINANTS OF DIFFUSION

Independent variable	FS	NES	OCAM
Log income per worker	0.333†	−0.467	−0.075
	(0.190)	(0.444)	(0.358)
Log investment per worker	0.259*	0.666*	−0.038
	(0.123)	(0.299)	(0.238)
Agriculture share in GDP	−0.028**	−0.015	−0.078**
	(0.006)	(0.014)	(0.014)
Manufacturing share in GDP	0.005	−0.009	0.045**
	(0.005)	(0.020)	(0.011)
Government spending share in GDP	−0.012	0.011	−0.023†
	(0.008)	(0.018)	(0.013)
Property rights (1–10)	0.035	0.138	0.122*
	(0.030)	(0.090)	(0.059)
Fraction who speak English	−0.079	0.040	−0.035
	(0.214)	(1.134)	(0.299)
Human capital	0.012*	0.057**	0.012*
	(0.004)	(0.018)	(0.006)
Log Mfg. imports from OECD PW	0.588**	0.956**	0.425†
	(0.129)	(0.347)	(0.220)
Log non-Mfg. imports from OECD PW	0.079	−0.366	−0.052
	(0.131)	(0.384)	(0.246)
Log Mfg. imports from non-OECD PW	−0.033	−0.360†	0.159
	(0.076)	(0.199)	(0.142)
Log non-Mfg. imports from non-OECD PW	−0.078	−0.155	0.038
	(0.070)	(0.183)	(0.140)
R^2:	0.951	0.905	0.966
Number of countries:	89	44	45
Number of observations:	337	87	72

Notes: The dependent variable is the log of computer imports per worker in 1970, 1975, 1980, 1985, and 1990. FS is the full sample; NES is the non-exporting sample; OCAM is the OCAM sample. Year dummies and a set of regional dummies were included in each regression. The estimation technique is random effect (RE). Standard errors are reported in parenthesis. "Mfg." stands for "manufacturing," and "PW" stands for "per worker."

† Statistically significant at the 10-percent level.

* Statistically significant at the 5-percent level.

** Statistically significant at the 1-percent level.

estimates by omitting some important explanatory variable.

We report representative results in Table 1. The specification is the same in all three columns, but each column uses a different sample. The first column reports results for the full sample; the second column reports results for the non-exporting sample; and the rightmost column reports results for the OCAM sample. These regressions include the following set of explanatory variables: the log of real per capita income; the log of real investment per worker; the share of agriculture in GDP; the share of manufacturing in GDP; the share of government spending in GDP; the extent of property-rights protection, as measured by an index (taking values from 1 to 10) based on international surveys; the share of the population who speak English; human capital, as measured by the fraction of the labor force (over 15 years of age) with at least a completed primary education; and (log) imports per worker, broken down by nature (manufacturing vs. nonmanufacturing goods) and source (OECD vs. non-OECD).[7] Details on these variables and their sources can be found in Caselli and Coleman (2001), where we also present results from a broader set of specifications.[8] To conserve space, in Table 1 we do not report the coefficients on the five year dummies or on the regional dummies. About the former we note that they are highly significant, as expected, and growing very rapidly. On the latter we briefly report below.

III. Discussion

In all three samples, high levels of educational attainment are important determinants of computer-technology adoption, even after controlling for a variety of other macroeconomic variables, including per capita income. The effect is quantitatively substantial: in the full sample and in the OCAM sample a 1-percentage-point increase in the fraction of the labor force who have better than primary education leads to an increase in computer investment per worker of roughly 1 percent. In the non-exporting sample, the response exceeds 5 percent.

The finding of a robust and strong role for human capital in determining computer-technology adoption constitutes new confirmatory evidence that recent technological developments have had a skill-biased component. The presumption of a skill bias in information-technology adoption is at the center of several attempts to

[7] More accurately, we treat as OECD members those countries that were members as of 1990 (this excludes Korea, Mexico, and the Eastern European members). We further exclude Turkey and include Israel.

[8] In that paper the reader can also find a table of univariate regressions of the dependent variable on each of the explanatory variables used in this study, one at a time.

explain recent wage dynamics in the United States and in several other countries (see e.g., Alan Krueger, 1993; Oded Galor and Daniel Tsiddon, 1997; Jeremy Greenwood and Mehmet Yorukoglu, 1997; Daron Acemoglu, 1998; David Autor et al., 1998; Caselli, 1999). There exists some country-specific evidence of computer-skill complementarity in the United States, but in this paper we have shown that the complementarity is a worldwide phenomenon.[9] Unfortunately, this being a case study, we cannot say whether the key role played by human capital is specific to computers or extends to any new technology.[10,11]

The other result that is robust across all samples is that computer investment responds positively to a country's openness to manufacturing imports from the OECD. In the full sample, a 10-percent increase in manufacturing imports per worker from the OECD leads to roughly a 6-percent increase in computer investment per worker (10 percent in the non-exporting sample, 4 percent in the OCAM sample). The interpretation of this finding that is most consistent with the existing literature is that countries that import manufactures from the OECD benefit from a knowledge spillover. As people and products from the manufacturing industries of technologically advanced countries are the most likely to possess or reflect knowledge of computers, their uses and operations, exposure to such people and products allows other countries to learn about and, hence, adopt the new technology.[12] We should stress that imports of computers are always and everywhere a minuscule fraction of overall manufacturing imports from the OECD. Hence, it is emphatically not the case that the significance of manufacturing imports from the OECD is driven by computers being a component of such imports. The fact that in the non-exporting sample imports of manufactures originating outside of the OECD are associated (albeit weakly) with *lower* propensities to invest in computers is somewhat of a puzzle.

We have subjected this result to a battery of checks by including alternative openness-related variables, such as (bilateral-trade weighted) distance from the leading world exporters, measures of foreign direct investment (FDI) inflows, the black-market premium, and the Sachs-Warner openness measure. None of these entered significantly in our regressions nor did the inclusion of any of these variables affect the significance of other variables. We also investigated a separate role for exports, finding only weak results and no change in the coefficients on the import variables. The fact that other measures of openness, as well as the fact that only manufacturing imports from the OECD affect computer adoption, reinforces the "knowledge spillover" interpretation.

Both in the full sample and in the non-exporting sample, computer adoption is strongly associated with high overall investment rates (e.g., because of high saving rates). In the full sample, a 10-percent increase in investment per worker leads to an increase in computer invest-

[9] Mark Doms et al. (1997) show that manufacturing plants with relatively high skill intensity are more likely to adopt computers.

[10] In the literature, one can find two views of the relationship between skills and technology. One view emphasizes "skill in adoption" and holds that an educated (and hence flexible) workforce is always a critical factor in the adoption of new technology. Another view focuses on "skill in use" and argues that certain technologies are inherently skill-biased (i.e., complementary with educated workers). If the first view is correct, then adoption of *any* new technology depends on human capital; if the latter is correct, only adoption of skill-biased technologies depends on human capital. Furthermore, in the first view, the role of human capital becomes less important over time, while in the second it remains important throughout. By performing more case studies of new-technology diffusion on data with improved time-series comparability, it might be possible to exploit the above-mentioned differences in predictions to assess the relative importance of the two views.

[11] An alternative interpretation is that the complementarity between human capital and computers is in consumption (educated people derive utility from computers), rather than in production. As a partial check on this hypothesis we have rerun some of our specifications with an interaction term between the share of agriculture and the share of skilled labor. The coefficient is significantly ($P < 0.05$) negative. Hence, human capital is less conducive to computer adoption in countries with a relatively large share of agriculture. It seems to us that this supports a production interpretation over a consumption interpretation of the complementarity between human capital and computers.

[12] For models of trade and technology diffusion, see, for example, Gene Grossman and Elhanan Helpman (1991), Robert Barro and Xavier Sala-i-Martin (1995), and Philippe Aghion and Peter Howitt (1998). Also, see the related empirical work in David Coe and Helpman (1995), and Coe et al. (1997).

ment per worker of around 3 percent. In the non-exporting sample, the estimate is approximately 6. This result is perhaps not surprising, but it reminds us of an important lesson: when new technology is embodied in capital, high investment rates are a precondition to technology adoption.[13]

Both in the full sample and in the OCAM sample we find that a large share of agriculture in GDP is associated with lower adoption of computers. In the full sample, a 1-percentage-point increase in the share of agriculture leads to a 3-percent decline in computer investment per worker (8 percent in the OCAM sample). Unfortunately, the two samples disagree strongly on the question that is perhaps more interesting, that is, whether there are differential effects on the relative shares of manufacturing and services: no in the full sample; yes in the OCAM sample, where manufacturing appears to be more computer-friendly than services. The full-sample result is consistent with the view that computers are a general-purpose technology, with a broad scope of applicability both in manufacturing and services.[14] The OCAM result points to more sector-specificity (at least at this level of aggregation) with a bias toward manufacturing.

In the OCAM sample we find a role for the degree of property-rights protection. A role for property rights is also showed by some specifications for the non-exporting sample reported in Caselli and Coleman (2001). When significant, the effect of property-rights protection is large. The index is on a scale from 0 to 10, and a unit increase would lead to an increase in computer investment per worker in excess of 10 percent (in the OCAM sample). To make this more concrete, moving from the first quartile to the median of the distribution of the property-rights index requires a 2-point increase. It would be easy to rationalize a role for property rights in embodied technology adoption. Computers, for example, are relatively easy to confiscate, steal, or loot. Interestingly, however, the results suggest that property-rights protection is important even after controlling for general investment. This might indicate that property-rights protection has an impact on the composition of investment over and above its impact on the general level of investment.

In the OCAM sample we also find a strong negative effect on computer adoption from a large government share in GDP. A 1-percentage-point increase in government spending as a share of GDP is associated with an increase in computer investment per worker of 2–3 percent. The result that large governments are bad for technology adoption would make a lot of sense: public bureaucracies are notoriously conservative and generally lack the incentives to seize new efficiency-enhancing opportunities. A country in which a larger share of economic activity is dominated by this inertia will be slower at embracing new technologies.

In none of the three samples is there any evidence that particular foreign-language skills are important determinants of technology adoption.

To conserve space, we have not included in the table the coefficients on the regional dummy variables. Yet such coefficients are of some interest in themselves. In terms of regional adoption performance a surprising result is that the sub-Saharan Africa dummy is often significantly positive. Hence, relative to the OECD, sub-Saharan Africa tends to adopt computers to an extent that is greater than what would be predicted by its human capital, outward openness, investment rate, and so forth. All the other regional dummies tend to have negative coefficients (when significant) and are therefore conditional underperformers (vis-à-vis the OECD) without a clear ranking among themselves.

In including per capita income in our regressions we did not have in mind any specific causal mechanism. Rather, we thought of it as a control (admittedly rudimentary) for other possible determinants of technology adoption that data limitations (or limitations of imagination) prevented us from including. From this perspective, a fully successful case study of technology adoption should lead to specifications in which per capita income is *not* statistically significant, as its continued significance signals that those additional determinants for which per capita

[13] The literature on embodied technological progress is huge. Among recent contributions are Jeremy Greenwood et al. (1997) and Boyan Jovanovic and Rafael Rob (1998).

[14] See Helpman (1998) for a collection of contributions on general-purpose technologies.

income is a stand-in have not been fully identified. Since per capita income has some (if weak) significant predictive power in our full sample, our list of determinants of computer adoption is conceivably still incomplete.

Besides identifying additional determinants, future work will have to answer several questions left open by the present contribution. Is the complementarity between computer adoption and human capital a sign of a long-run technical complementarity, or is it driven by the fact that skills are especially useful during the early stages of a technological change? What exactly is the role of property rights in technology adoption? Are large governments bad for technology adoption? Also, we have been unable to seek evidence on the role for learning externalities in computer adoption.[15] We believe that additional case studies of other episodes of international technology diffusion along the lines of the present work could be invaluable in starting to answer these questions.

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