This draft: January 15, 2010

How Do You Measure a "Technological Revolution"? *

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How Do You Measure a "Technological Revolution"?
Carol A. Corrado and Charles R. Hulten[*]

It is hardly news that we are in the midst of rapid economic change. The advances in information and communication technology (ICT), in the life and other sciences and their profusion of innovative products from the newest electronic devices to the latest drugs and treatments are ample evidence. Equally pervasive are new business models in services (big box retail, online banking, on-demand media) and the explosion in social networking and new business practices ushered in by the Internet (telework, virtual meetings, job boards). Given the magnitude of the changes brought on by these innovations, it is useful to step back and ask: What does economic analysis have to say about the sources and mechanisms of these shifts and revolutions, and what economic metrics are available to measure their overall size and impact?

The received theory of economic growth is the natural candidate for this job. It came of age in the 1950s and 1960s with the neoclassical models and emergence of aggregate growth accounting. The latter has become the work horse of empirical macroeconomic growth analysis and the basis for official productivity statistics put out by the Bureau of Labor Statistics (BLS) since 1983. A technological revolution appears, in this framework, as an increase in the fruits of innovation, as measured by the shift in an aggregate production function (termed multifactor productivity or MFP), and possibly as an increase in the aggregate saving rate, as reflected in an increased rate of capital formation. MFP is an exogenous phenomenon in the growth accounting framework, and the subsequent development of endogenous and "Schumpeterian" models of

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economic growth have attempted to endogenize this variable (see Charles R. Hulten 2009b for a review).

The common feature of the received theory is a reliance on the production function as the organizing framework of the analysis. But companies are moving away from the making of things in the United States and focusing increasingly on services or product development, design, and marketing. Theories of growth based on standard inputs and even the endogenous growth approaches based on the production of ideas by scientists and engineers thereby become less compelling as frameworks for analyzing productivity and economic change.

A new strand of the empirical growth literature has emerged over the last decade aimed at addressing this problem by updating the way that business activity is depicted in macroeconomic data and analysis. It builds on diverse literatures, including the microeconomic work on R&D and ICT that established linkages between these investments, their co-investments, and increases in productivity at the firm level; the related literature that established similar linkages for workplace practices; and the business literature that documents actual innovation processes (for references to micro-productivity studies, see Carol A. Corrado, Hulten, and Daniel Sichel 2005, 2009, hereafter CHS; for innovation process examples see Corrado 2009).

The main features of the new approach are (1) that a company's expenditures on product design, marketing and customer support, and human capital and organizational development are essential inputs to innovation along with spending on R&D, broadly defined, and (2) that these innovation-related expenditures (collectively termed "intangibles") are investments that are produced within the business sector and need to be included in GDP as business investment.

The stock of scientific R&D appeared in the production function literature very early on, but only as an input. This approach focused on the consequences of privately performed R&D

for the production of output, but not on R&D as *a final output* of the economic system (that is, as an investment that adds to GDP). Moreover, innovation encompasses but is more than the advances in science and engineering captured in U.S. R&D data. New ideas, whether the result of perspiration or spontaneous inspiration, are only the starting point for successful innovation. They define the possibilities but not the outcome, and history is littered with products and companies that failed the test of commercialization. Innovation involves linking products to unmet customer needs and preferences, and the simple truth is that most new products do not sell themselves without effort. Any attempt to measure innovation needs to acknowledge these facts, and this involves a broader view of the process than offered by simply putting the stock of R&D or ICT equipment into a production function.

The following pages of this paper review the some of the key ideas about intangibles in the existing literature, and present new sources-of-growth estimates for the U.S. nonfarm business sector. The latter significantly expand the time horizon of our previous study with Sichel (by almost thirty years). The extended time perspective shows that the recent technological revolution, in its various manifestations, is associated with a dramatic shift in the *composition* of investment spending and in the factors driving the growth of output per worker hour. This is the main result of this paper.

II. Intangibles: Scope, Characteristics, and Measurement

Expenditures for R&D, product design, marketing, and organizational development are treated as current costs under conventional financial accounting practice, as well in the National Income and Product Accounts (although R&D investment has recently been incorporated as a satellite account and is scheduled to be included in headline GDP in 2013). Perhaps the first question that needs to be answered is: "Why should expenditures on these intangibles be

reclassified and treated as capital?" The answer given in CHS is that saving occurs when resources are use to provide for future rather than current consumption, and, from the producers' standpoint, investment is the commitment of current resources to gain future profits. Business fixed investment satisfies these criteria, but so does much spending on intangibles. A look at the biotechnology sector shows that R&D projects can take more than a decade to before producing revenue, and then require large co-investments in marketing. Other product development cycles may be shorter and involve little or no science, but are clearly aimed at future production and profit rather than to current production and profit. The same can be said of investments in brand equity and organizational capability.

There is a body of econometric evidence, reviewed in CHS, which shows a positive correlation between various types of intangible capital and firm market value. Capitalizing intangibles is also helpful in explaining the so-called market-to-value puzzles noted by Baruch Lev (2001) and others. The puzzle arises because the market price of corporate equities consistently exceeds the book value of the shares reported on company financial statements. Hulten and Janet X. Hao (2008) find that the book value of equity explained only 31 percent of the market capitalization of a sample of 617 companies drawn from the COMPUSTAT data base for the year 2006; when estimates of the capitalized cost of the stock of intangibles were added to the balance sheets of these companies, the fraction of the market capitalization explained by the augmented measure of book equity rose to 75 percent.

One of the first steps in developing a measurement framework for intangibles is the need for a classification system. Lev (2001) offers one system based on the structural characteristics of the intangibles themselves: innovation-related, human resource, and organizational. The business models of several leading technology companies are shown to be anchored these

categories. Other researchers have developed strategies for measuring the value of the implicit net income stream associated with intangible assets. But neither approach yields the kind of comprehensive measure needed for national accounting or sources-of-growth analysis.

This consideration has lead to the development of estimates of business investment in intangibles based on their cost of production. The approach was first taken by the OECD in 1998 (see www.oecd.org) and Leonard Nakamura (2001) and then by CHS (2005). The approach has the virtue of using the same cost-based accounting that is used for tangible assets, where arbitrage is assumed to bring the cost of acquiring the marginal asset into equality with the discounted present value of future income. CHS (2005) offered a broad scheme for categorizing business intangible investment (computerized information, innovative property, and economic competencies) and listed specific assets for inclusion in each category.

CHS (2009) took additional steps and estimated corresponding capital stocks by translating the investments to real terms and accumulating them using the perpetual inventory method. A depreciation rate is needed to implement the perpetual inventory method, and an output-based price index is needed to deflate intangible investment. The concept of depreciation applicable to privately-owned, knowledge-based assets is the rate of decay of appropriable revenues. For further discussion, see Ariel Pakes and Mark Schankerman (1984).

III. Trends in Intangible Investment

We update our previous estimates for the U.S. nonfarm business sector to 2007, and carry them backward in time to 1948. These estimates imply a total investment in intangibles of $1.6 trillion in 2007, or 11.3 percent of GDP in 2007 but just $1.3 trillion above the Bureau of Economic (BEA) estimates because two important intangible assets (software and mineral exploration) are already capitalized in the U.S. national accounts. When time series of these

investments are accumulated into the corresponding capital stocks, the result is an additional

$4.1 trillion in wealth beyond the conventional U.S. fixed asset measures for 2007.

Table 1 shows the average rate of investment in tangible and intangible capital for the

three subperiods between 1948 and 2007 (the three periods shown in the table correspond to the

high-growth period after World War II, the productivity slowdown from 1973 to the mid-1990s,

and the resumption of growth thereafter). This table highlights the shifts in the composition of

business investment that have occurred.

Table 1. Investment Rates and Shares of Capital Input, Nonfarm Business Sector

	1948-2007	1948-1972	1973-1994	1995-2007
Investment rate[1]				
1. Tangible	11.4	11.2	12.3	10.4
1a. ICT equipment	1.3	.6	1.6	2.0
2. Intangible	8.6	5.9	9.2	12.8
Share of capital input[2]				
3. Tangible	76.2	82.6	74.8	66.1
3a. ICT equipment	4.5	2.2	5.8	6.6
4. Intangible	23.8	17.4	25.2	33.9

Note--All figures are averages for period shown. Source--Author calculations.
1. Gross business fixed investment as a percent of output adjusted to include intangibles.
2. Value of component as a percent of the aggregate value. Capital input includes land
and inventories in addition to fixed assets.

When viewed from the perspective of total tangible capital formation (line 1), the rate of

business investment appears about flat. A closer look at its composition, however, reveals a shift

toward ICT equipment (line 1a), an important correlate of intangible asset creation (Erik

Brynjolfsson, Loren M. Hitt, and ShinkyuYang 2002). An even bigger change in perspective

occurs when the picture is enlarged to include the investment in intangible assets (line 2). The

average rate of investment in intangible capital formation *more than doubles* over the three

subperiods shown in Table 1, and when considered with ICT equipment, the dramatic increase in

these rates imply that very strong compositional effects within business investment have been at

work during the past 60 years. Although less dramatic because shorter time periods are used,

similar results have been obtained for other countries (Bart van Ark *et al.* 2009).

The last two lines of Table 1 show the compositional shift in tangible and intangible

capital inputs associated with the investment flows. The compositional shift is less evident here

because capital input shifts more slowly than the investment flows and the average rate of

depreciation is much higher for intangibles (21.5 percent) than for tangibles (5.3 percent).

Nevertheless, the main story of business capital formation in the postwar period is a story about

the growth of intangible capital. For further compositional detail, see the paper's supplementary

tables and figures.

IV. The Sources of Growth Model with Intangible Capital

In the CHS model, the conventional Solow-Jorgenson-Griliches sources-of-growth

framework is expanded to include intangible investments in output and the corresponding stocks

in capital input. In implementing the model, a term used by the BLS to account for the shift in

the composition of total hours worked to workers with higher wage rates (usually interpreted as a

shift to more highly educated workers) is included, and capital is estimated in sufficient detail to

capture corresponding shifts in the composition of total capital input to assets with higher rental

prices. The results for the period from 1948 to 2007 (including subperiods) are shown in table 2.

A look at table 2 shows that the growth rate of output per hour is virtually the same in the

1948-1973 and 1995-2007 periods (columns 2 and 4). By itself, this appears to be a reprise of

Robert Solow's famous quip that "you see the computer age everywhere except in the

productivity data." But one does see the computer age in the compositional shift toward

contributions of ICT equipment (line 2a) and every type of intangible capital deepening (see

Table 2. Sources of Growth in Output per Hour, Nonfarm Business Sector

	1948-2007 (1)	1948-1973 (2)	1973-1995 (3)	1995-2007 (4)
1. Output per hour	2.41	2.99	1.56	2.76
percentage point contribution:				
2. Tangible capital	.65	.76	.52	.64
a. ICT equipment	.23	.11	.28	.36
b. Other capital[1]	.42	.65	.24	.27
3. Intangible capital	.42	.30	.39	.74
a. Computerized information[2]	.06	.01	.07	.15
b. Innovative property[3]	.19	.15	.16	.32
c. Economic competencies[4]	.17	.14	.15	.27
4. Labor composition	.20	.15	.26	.20
5. MFP	1.14	1.78	.39	1.20

Note--Annual percent change for periods shown calculated from log differences.

Components are independently rounded.

Source--Author's calculations.

1. Non-ICT business equipment, structures, land, and inventories.

2. Mainly software. Excludes R&D double-count (see Robbins and Moylan 2007).

3. R&D (including finance and insurance and other social science R&D not included in

NSF/BEA figures); mineral and other geophysical rights; and other industrial design and

artistic assets.

4. Marketing, branding, and other strategic firm resources.

detail under line 3). When combined, these sources contributed less than one-half percentage

point to the growth rate of output per hour in the first sub period, but this rose to more than

2 percentage points in the last. The shift came at the expense of MFP and non-ICT capital

growth, which went from contributing about 2-1/2 to 1-1/2 percentage points to top-line growth in the two sub periods. By the end, intangibles had overtaken tangibles to become the largest systematic (that is, non-MFP) source of growth.

The dramatic changes seen in table 2 provide support for the idea that innovation-related intangible inputs are an increasingly important driver of U.S. economic growth. Moreover, the omission of these inputs gives a biased picture of the sources of growth. A parallel set of estimates without intangibles would overstate the contribution of MFP to growth since 1995, from the 43 percent of table 2 (column 4) to 62 percent absent all intangibles (supplementary table A2.2). The results of table 2 may thus suggest an answer to the question "How do you measure a technological revolution?": You must include a broad range of intangible investments in the analysis, as both inputs and outputs, because they are an essential part of the innovation process and they loom increasingly large in accounting for economic growth.

While intangibles provide an answer to question posed in this paper, they are only a partial answer. Innovations in product quality are an important aspect of economic (technological or other) change, providing both better consumer and capital goods (and, indeed, better intangibles). Whether the price indexes that determine real output and capital inputs and affect the MFP estimates in table 2 actually reflect the actual improvements in product quality and design is an open question, however (William D. Nordhaus 1997).

The magnitude of the product quality problem is illustrated by two recent studies. In a study of the Microsoft Corporation's sources of growth by Hulten (2009a), MFP is growth measured as per our table 2 and shown to be composed of two components: a product quality effect that accounts for 77 percent of the measured MFP residual, and pure factor productivity accounting for the rest. Absent the quality adjustment, the growth of Microsoft's output and

MFP would be significantly understated. David M. Byrne and Corrado (2009) looked at whether recent advances in communications technology (wireless, VoIP, etc) are being fully captured in prices for the equipment and systems that power modern communications networks and concluded existing measures for 1995 to 2007 understate these advances in the neighborhood of 7-1/2 percentage points per year .

Getting a better grip on the quality change aspect of innovation is a priority for improving both the output and the capital input side of the sources-of-growth analysis. As with the identification, classification, and price-deflation of intangibles, difficult measurement problems must be overcome, but these problems are not insurmountable, and progress in these areas is essential for a more accurate analysis of the factors shaping modern economic growth. Advances will undoubtedly require measurement systems that look deeply into the operations of the companies where much of the innovation originates (Corrado and Julia Lane 2009).

V. Conclusion

A major shift in the *composition* of investment and capital formation toward intangibles has occurred over the last 60 years. We have argued that this shift is of critical importance for the analysis of growth over this period, and, in particular, for understanding how the recent wave of innovation has shaped the U.S. economy. The message is clear: the innovation that has shaped recent economic growth is not an autonomous event that falls like Manna from Heaven. Nor is it a result of R&D and ICT investments, alone. Instead, a surge of new ideas (technological or otherwise) is linked to output growth through a complex process of investments in technological expertise, product design, market development, and organizational capability. This process affects all sources of growth to one extent or another, but is most clearly detected in the growing contribution of intangible capital.

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This draft: January 8, 2010

**Supplementary Tables and Figures for:**

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Table A1.1 Nonfarm Business Fixed Investment rates[1]

	1948-2007 (1)	1948-1972 (2)	1973-1994 (3)	1995-2007 (4)
1. Tangible	11.4	11.2	12.3	10.4
1a. ICT equipment	1.3	.6	1.6	2.0
1b. Non-ICT equipment	5.9	5.9	6.2	5.4
1c. Nonresidential structures[2]	3.2	3.2	3.5	2.6
1d. Residential capital	1.1	1.3	1.1	.8
2. Intangible	8.6	5.9	9.2	12.8
2a. Computerized information[3]	.6	.1	.6	1.6
2b. Innovative property	3.2	1.9	3.7	4.8
(1) R&D (NSF/BEA)	1.4	.9	1.6	2.1
(2) Other R&D, etc.[4]	1.2	.5	1.3	2.2
(3) Mineral exploration	.6	.5	.7	.5
2c. Economic competencies	4.8	3.9	4.9	6.4
(1) Brand equity	1.6	1.6	1.5	1.8
(2) Firm-specific resources	3.2	2.3	3.4	4.6

NOTE: All figures are averages for period shown.
SOURCE: Author calculations. Business intangible investments are as defined and estimated in Corrado, Hulten, and Sichel (2005). BEA's funder-based estimates are used for R&D.
1. Gross fixed investment as a percent of sector output adjusted to include new intangible investment.
2. Excludes mineral exploration.
3. Mainly software. Excludes the R&D double-count; see Robbins and Moylan (2007) for further details.
4. Finance and insurance and other social science R&D not included in NSF/BEA figures; other costs of creating new designs and artistic assets.
5. Marketing, branding, and other strategic investments in firms' organizational capital.

Table A1.2 Shares of Nonfarm Business Capital Input[1]

	1948-2007 (1)	1948-1972 (2)	1973-1994 (3)	1995-2007 (4)
1. Tangible	76.2	82.6	74.8	66.1
1a. ICT equipment	4.5	2.2	5.8	6.6
1b. Non-ICT equipment	24.3	25.3	24.9	21.1
1c. Nonresidential structures[2]	26.5	28.4	26.3	23.1
1d. Residential capital	8.7	9.8	8.4	7.1
1e. Inventories and land	13.0	16.9	10.5	9.8
2. Intangible	23.8	17.4	25.2	33.9
2a. Computerized information	1.4	0.2	1.5	3.9
2b. Innovative property	9.6	6.4	10.7	14.0
(1) R&D (NSF/BEA)	4.1	2.6	4.8	6.0
(2) Other R&D/design	4.2	2.2	4.6	7.1
(3) Mineral exploration	1.3	1.5	1.4	1.0
2c. Economic competencies	12.8	10.9	13.0	15.9
(1) Brand equity	3.8	3.9	3.6	3.9
(2) Firm-specific resources	9.0	7.0	9.5	12.1

NOTE: All figures are averages for period shown.
SOURCE: Author calculations. Business intangible capital estimates are as developed in Corrado, Hulten, and Sichel (2009). BEA's output-based deflator for R&D is used to obtain real R&D investment and capital.
1. Percent of total nonfarm business sector capital input adjusted to include intangible assets
2. Excludes mineral exploration.

Table A2.1 Sources of Growth in Output per Hour (including intangibles)[1]

	1948-2007 (1)	1948-1973 (2)	1973-1995 (3)	1995-2007 (4)
1. Output per hour	2.41	2.99	1.56	2.76
percentage point contribution:				
2. Tangible capital	.65	.76	.52	.64
2a. ICT equipment	.23	.11	.28	.36
2b. Non-ICT equipment and nonresidential structures[2]	.32	.47	.20	.21
2c. Other capital[3]	.10	.18	.04	.06
3. Intangible capital	.42	.30	.39	.73
3a. Computerized information	.06	.01	.07	.15
3b. Innovative property	.19	.15	.16	.32
(1) R&D (NSF/BEA)	.10	.08	.07	.18
(2) Other R&D/design	.09	.07	.09	.14
(3) Mineral exploration	.03	.05	.01	.00
3c. Economic competencies	.17	.14	.15	.27
(1) Brand equity	.04	.04	.03	.05
(2) Firm-specific resources	.13	.10	.12	.21
4. Labor composition	.20	.15	.26	.20
5. MFP	1.14	1.78	.39	1.20

NOTE: Annual percent change for periods shown calculated from log differences. Components are independently rounded.
SOURCE: Author calculations.
1. Nonfarm business sector, with output and capital input adjusted to include business intangible investment.
2. Excludes mineral exploration.
3. Residential capital owned by business, land, and inventories.

Table A2.2 Sources of Growth in Output per Hour (excluding intangibles)[1]

	1948-2007 (1)	1948-1973 (2)	1973-1995 (3)	1995-2007 (4)
1. <u>Output per hour</u>	2.28	2.90	1.39	2.61
percentage point contribution:				
2. <u>Capital deepening</u>	.72	.82	.58	.76
2a. ICT equipment	.25	.12	.31	.42
2b. Other capital	.47	.70	.27	.35
4. <u>Labor composition</u>	.22	.16	.29	.22
5. <u>MFP</u>	1.34	1.92	.53	1.63

NOTE: Annual percent change for periods shown calculated from log differences. Components are independently rounded.
SOURCE: Author calculations.
1. Nonfarm business sector, with output and capital input adjusted to exclude published intangible assets (software and mineral exploration).

Table A3. Difference in Sources of Growth Estimates (with and without intangibles)[1]

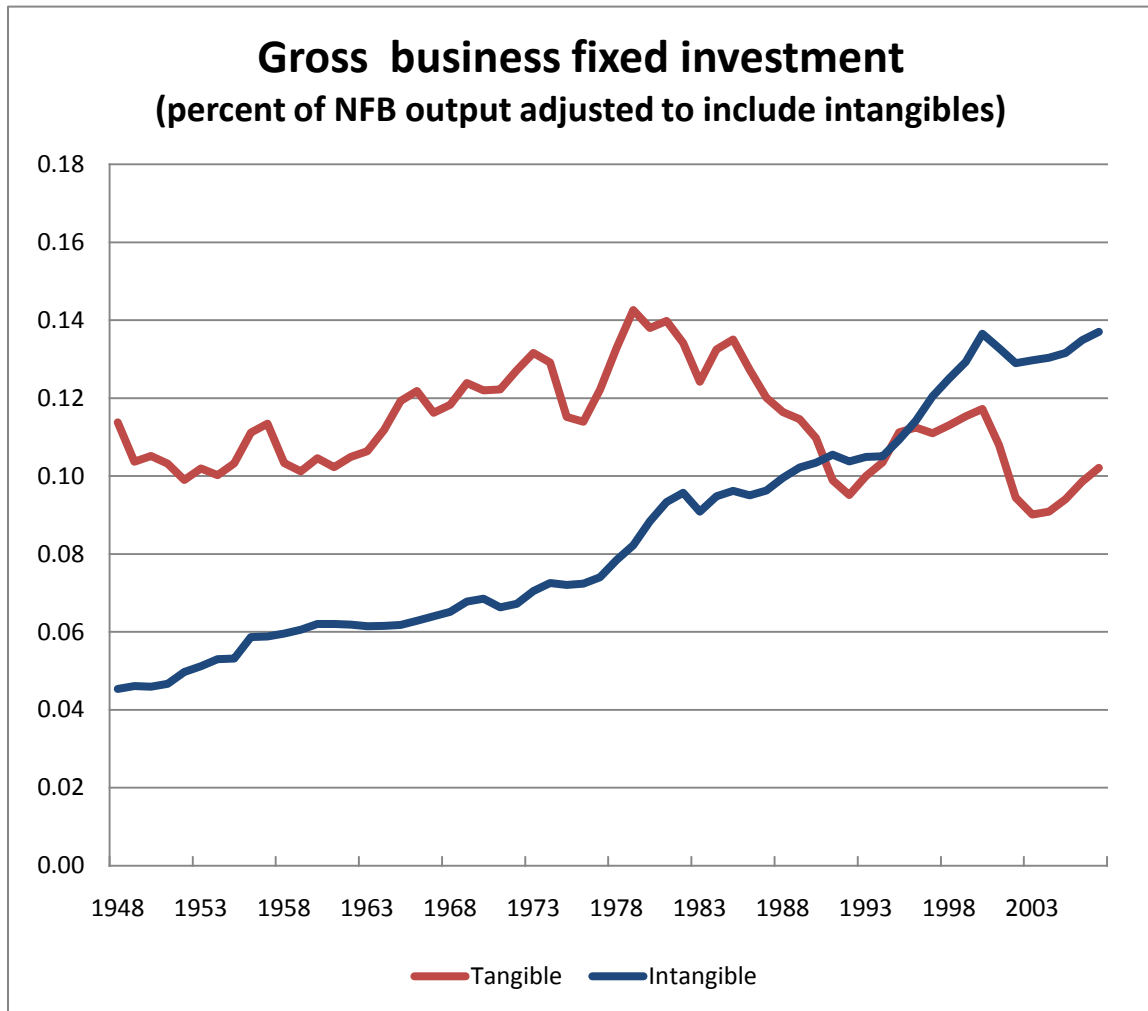|	1948-2007 (1)	1948-1973 (2)	1973-1995 (3)	1995-2007 (4)
1. <u>Output per hour</u>	.13	.09	.17	.15
percentage point contribution:				
2. <u>Capital deepening</u>	.35	.24	.33	.61
2a. ICT capital[2]	.04	.01	.04	.09
2b. Other published assets	-.01	-.01	-.01	-.03
(1) Mineral exploration	.03	.05	.01	.00
(2) Other capital	-.04	-.06	-.02	-.03
2c. New intangible assets	.32	.24	.29	.56
4. <u>Labor composition</u>	-.02	-.01	-.03	-.02
5. <u>MFP</u>	-.20	-.14	-.14	-.37

NOTE: Annual percent change for periods shown calculated from log differences. Components are independently rounded.
SOURCE: Tables A2.1 and A2.2
1. Output per hour (or contribution to output per hour) results for the nonfarm business sector including intangibles less corresponding results excluding published intangibles.
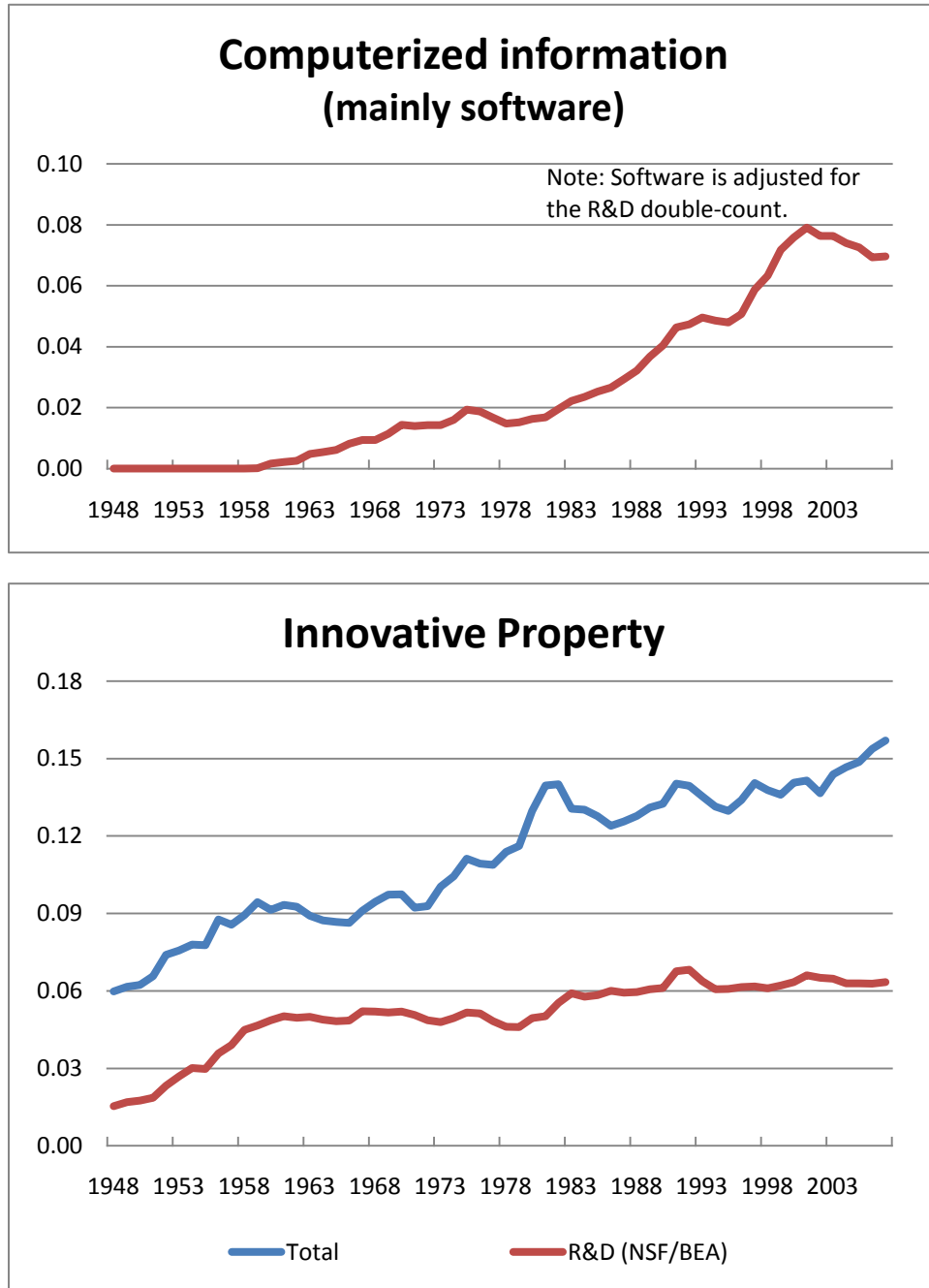2. Equipment and software.

Figure 1.

Gross business fixed investment
(percent of NFB output adjusted to include intangibles)
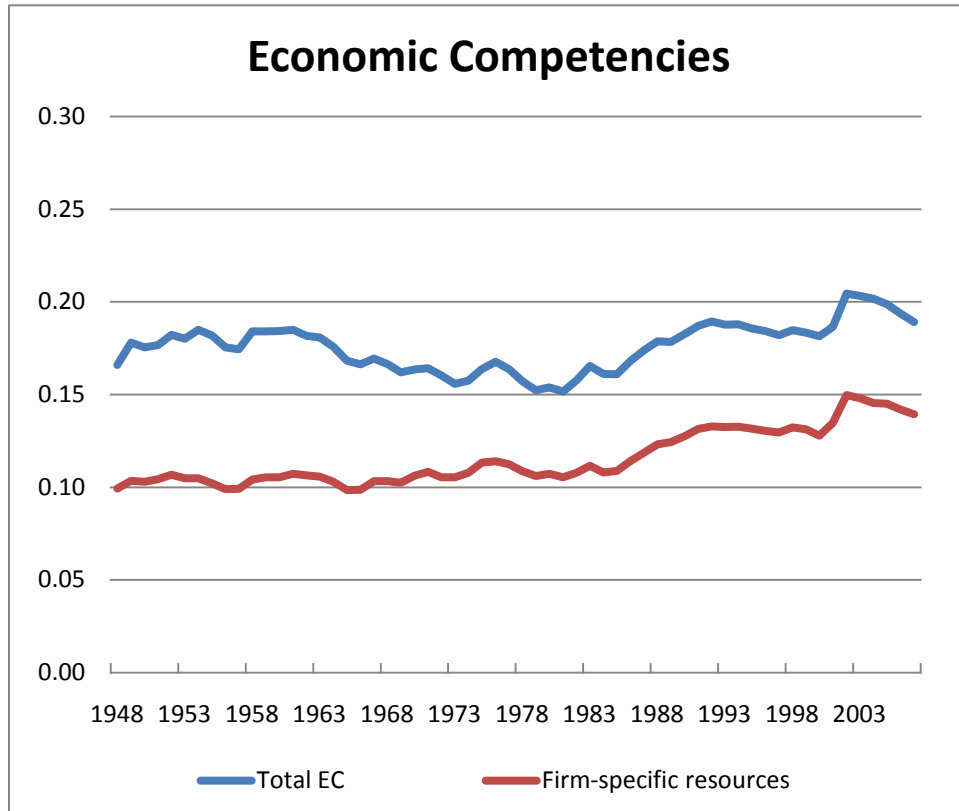

Note. Last point plotted is 2007.

Figure 2. Components of Business Intangible Investment

(share of component in total business fixed investment
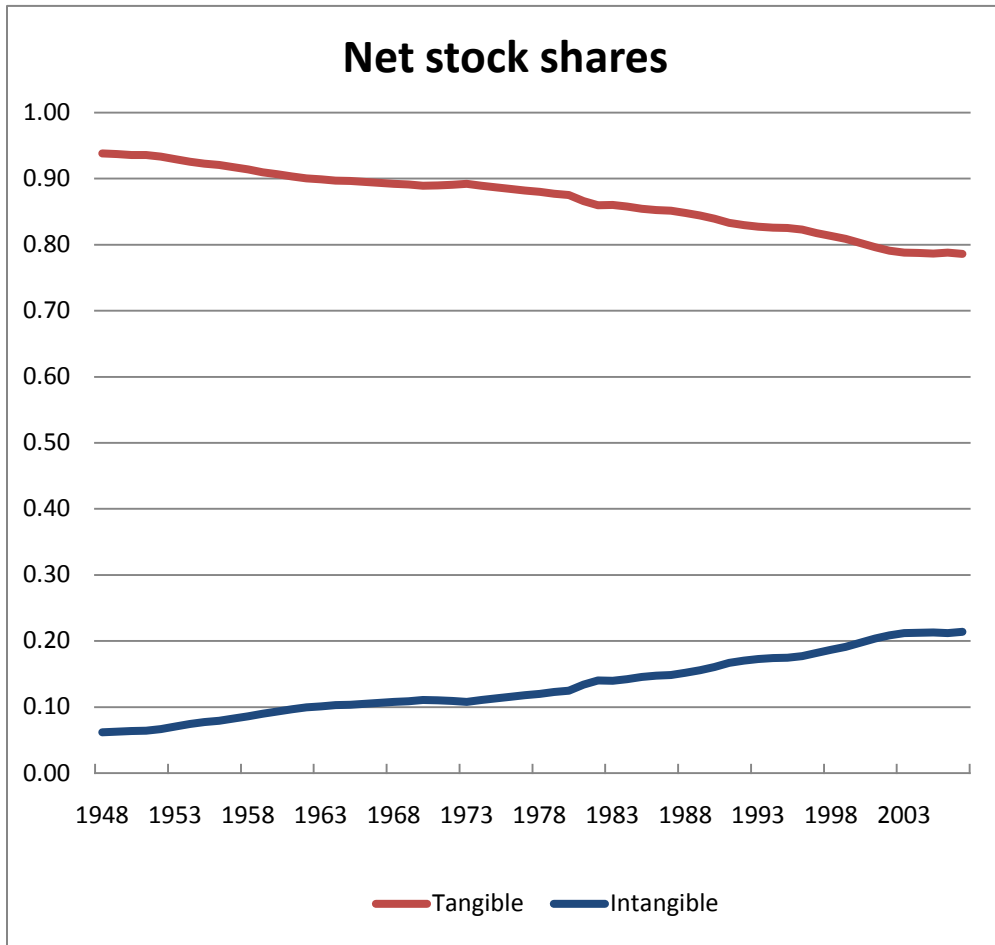adjusted to include new CHS intangibles)

Computerized information (mainly software)

Note: Software is adjusted for
the R&D double-count.

Innovative Property

Total   R&D (NSF/BEA)

Last point plotted is 2007.

Figure 2 (continued).

(share of component in total business fixed investment
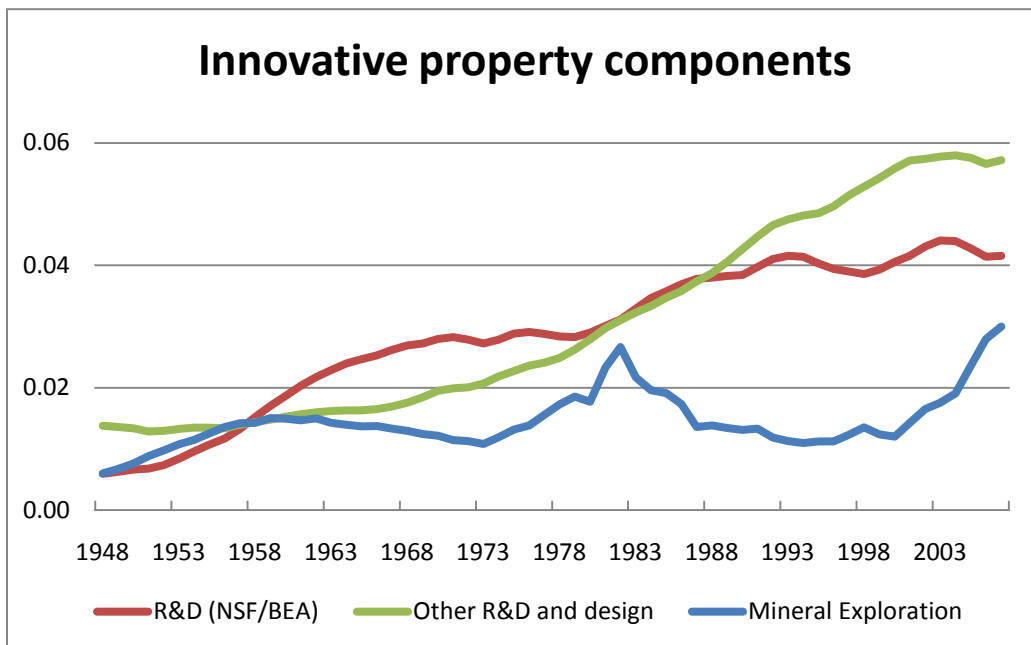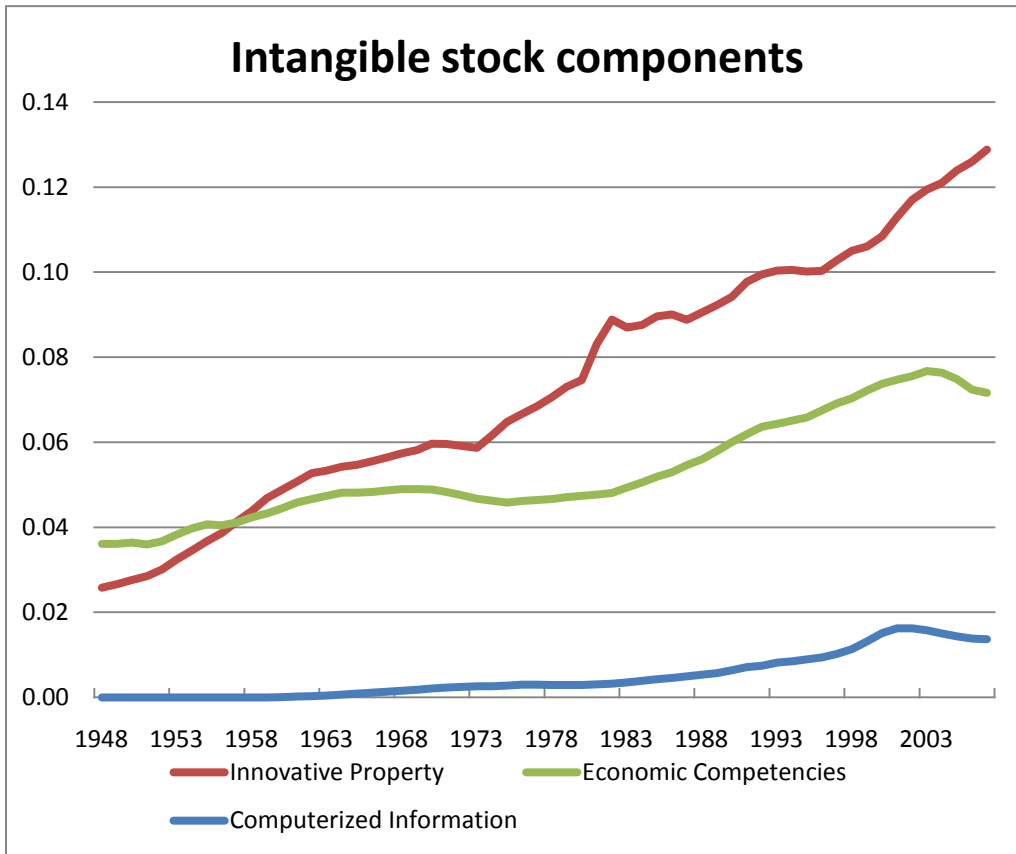adjusted to include new CHS intangibles)

Last point plotted is 2007.

Figure 3.

(share of component in total nonfarm business
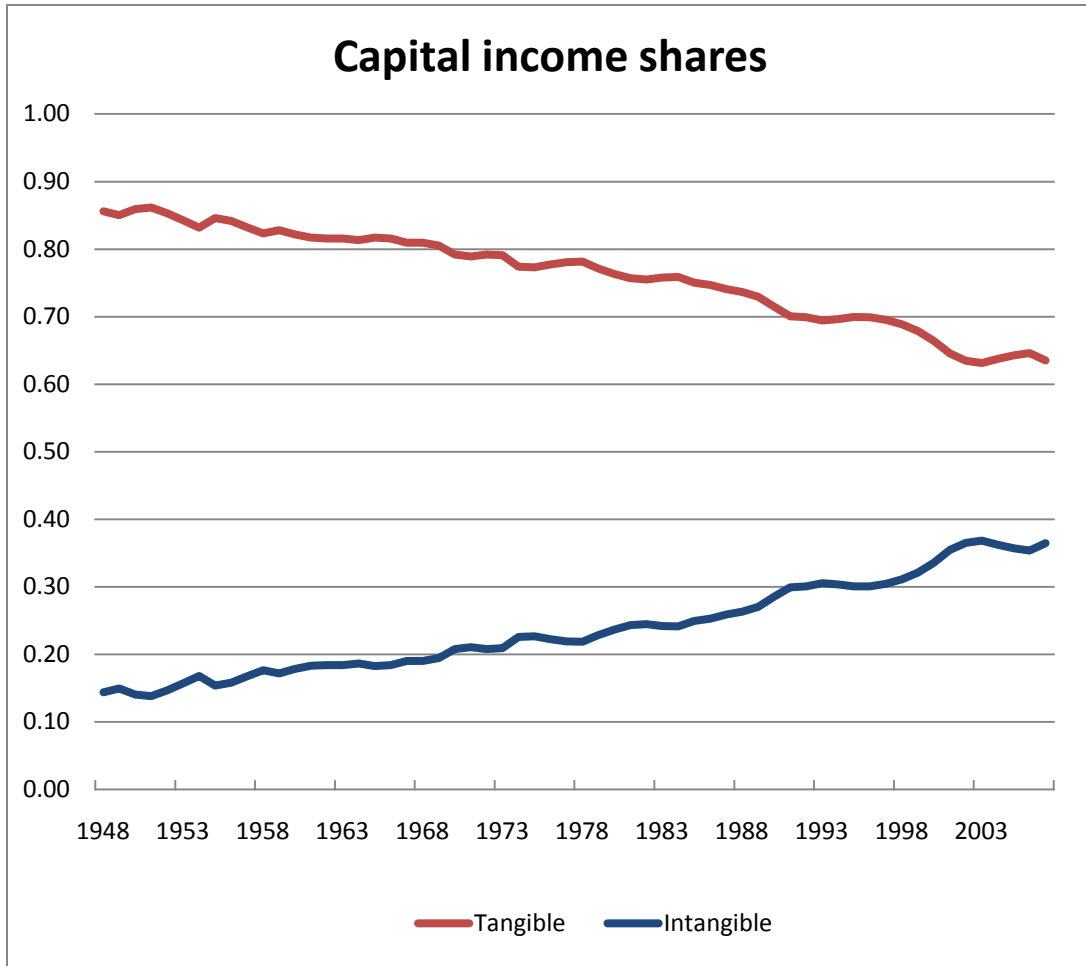net stocks including intangibles)

Net stock shares

Last point plotted is 2007.

Figure 3. Components of Intangible Net Stocks

(share of component in total net stock including intangibles)

Intangible stock components

Legend: Innovative Property — Economic Competencies — Computerized Information

Innovative property components

Legend: R&D (NSF/BEA) — Other R&D and design — Mineral Exploration

Last point plotted is 2007.

Figure 4.

(share of component in total value of nonfarm business
capital input including intangibles)

Capital income shares

Last point plotted is 2007.