The Productivity J-Curve: How Intangibles Complement General Purpose Technologies

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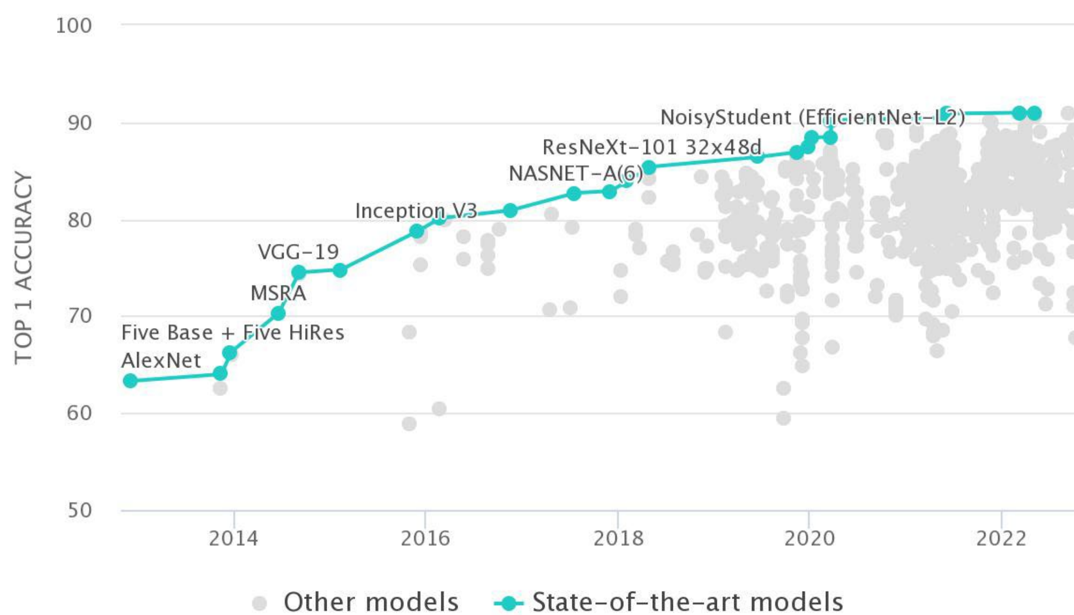
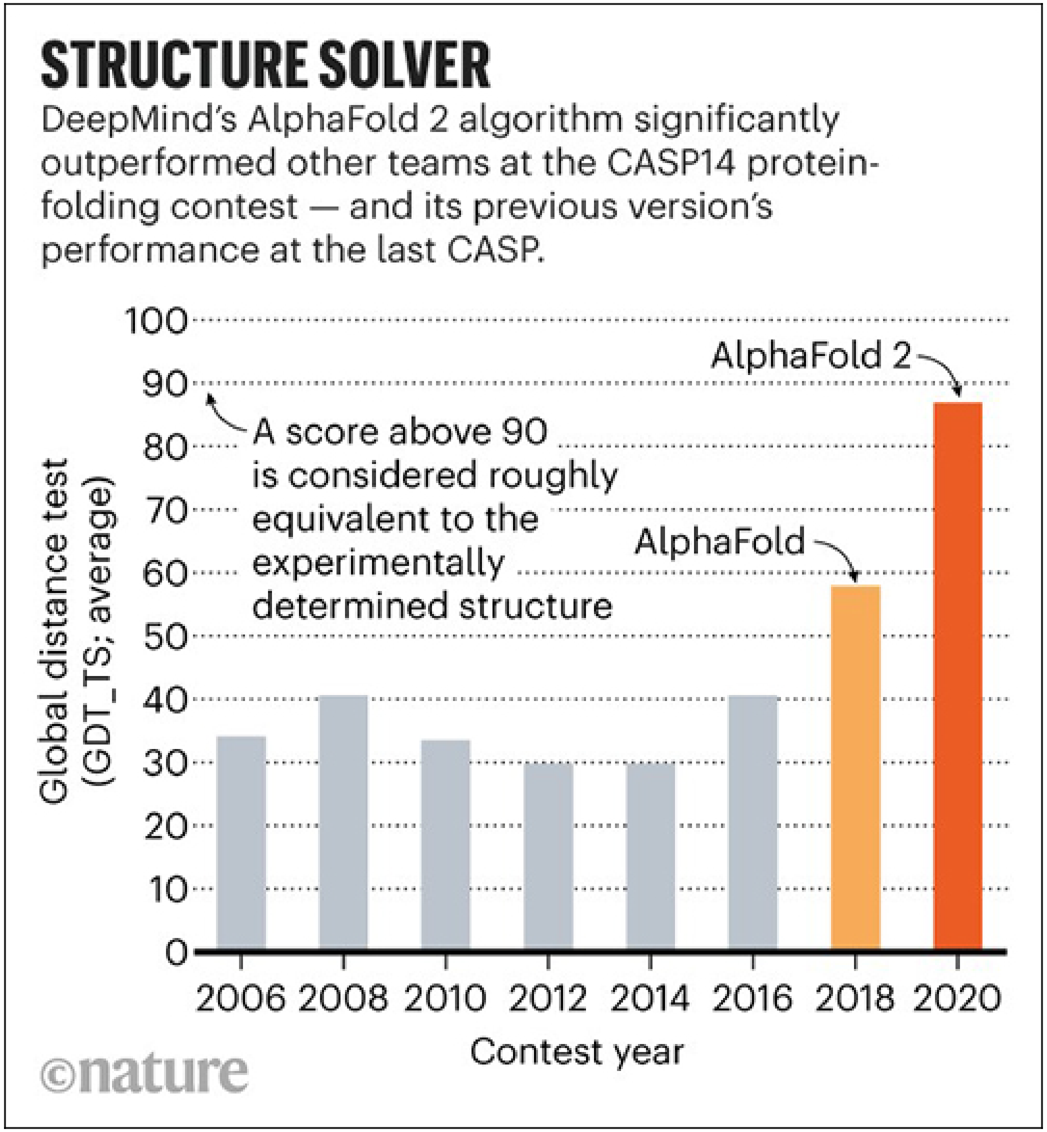
Based on joint work with Erik Brynjolfsson and Daniel Rock

Technological Progress: ML and Image Recognition

ImageNet Challenge Results



Technological Progress: ML and Protein Folding



The Disappointing Recent Reality

Juxtaposed with technological progress is slow productivity growth, everywhere

- We are 15+ years into a slowdown among OECD countries
  - Australia, labor productivity (GDP/hr) growth:
    - 1995-2004: 2.2% per year
    - 2005-2021: 1.2% per year
  - OECD: 27 of 32 countries saw slowdowns after 2004, average slowdown of 0.9% per year
- Major emerging markets slowdown later, around 2010

A Potential Explanation for the Paradox

Our earlier work: Implementation and restructuring lags

- Technology is real, but benefits take time to emerge
  - Must accumulate enough new general purpose technology (GPT) capital to observe effects in aggregates
  - Full benefits require complementary investments to be invented and installed

If this is correct, the paradox is not a contradiction

- A period with simultaneous recognition of technology's potential and poor productivity performance is natural

What Is a GPT?

Bresnahan and Trajtenberg's Criteria:

1. Pervasive

2. Able to be improved upon over time

3. Able to spawn complementary innovations

Slowdowns and GPTs in History

Prior general purpose technologies (GPTs) associated with implementation lags

- “Engels’ pause” during early industrial revolution
  - Wage growth stagnant even as output rose quickly
- Over half of U.S. manufacturing establishments unelectrified in 1919
  - 30 years after AC systems standardized
- Computer capital in U.S. topped off at about 5% of total nonresidential equipment capital by late 1980s
  - 25+ years after invention of integrated circuit
  - Only half that level 10 years earlier

GPT-Tied Intangibles & Productivity Measures

The productivity J-curve is a (mis-)measurement phenomenon that can happen when a new technology requires complementary intangible investments

We theoretically characterize this potential using standard growth accounting

Empirically estimate effects from past GPTs (computer software and hardware) and, more speculatively, AI

Intangibles and Productivity Measurement

How do intangibles affect productivity measurement?

$$Productivity = \frac{Output}{Input}$$

- Intangible capital would be an unmeasured input
  - As such, this will tend to cause productivity to be overstated
- However, intangible capital is also an output (measured as investment flow)
  - This will cause productivity to be understated
- Net effect on productivity measurement depends on relative timing of input vs. output mismeasurement

Intangible Growth Accounting

Standard production function: $Y = AF(K, L)$

Standard Solow residual TFP: $g_A = g_Y - \left(\frac{rK}{Y}\right) g_K - \left(\frac{wL}{Y}\right) g_L$

Intangible (U)-augmented production: $Y + \phi I_U = A^* F^*(K, U, L)$

Intangible-augmented TFP growth:

$$g_{A^*} = \left(\frac{Y}{Y + \phi I_U}\right)\left(g_Y - \left(\frac{rK}{Y}\right) g_K - \left(\frac{wL}{Y}\right) g_L - \left(\frac{r_U U}{Y}\right) g_U\right) + \left(\frac{\phi I_U}{Y + \phi I_U}\right) g_{I_U}$$

Intangible Growth Accounting

Define total output $Y^* \equiv Y + \phi I_U$ and intangible investment's share of total output η_t, so $Y_t = (1 - \eta_t) Y_t^*$

Difference between standard Solow residual and true TFP is:

$$= \underbrace{-\eta_t \left(\left(\frac{rK}{Y} \right) g_K + \left(\frac{wL}{Y} \right) g_L \right)}_{\substack{Intangible\ Capital\ Investment\ Produced \\ by\ Tangible\ Capital\ Inputs\ and\ Labor}} + \overbrace{(1 - \eta_t) \left(\frac{r_U U}{Y} \right) g_U}^{\substack{Contribution\ to\ Measured\ Output \\ of\ Intangible\ Capital\ Stock}}$$

$$+ \underbrace{g_{(1-\eta_t)}}_{\substack{Growth\ in\ the \\ Measured\ Share\ of\ Output}}$$

Intangible Growth Accounting

If (as is often done) capital's share is measured as 1 – labor's share, payments to intangibles will be relabeled as tangible capital income

Accounting for this additional mismeasurement, as well as assuming $g_U = g_K$ (as in our empirical approach), yields a simple expression relating true TFP and the standard Solow residual:

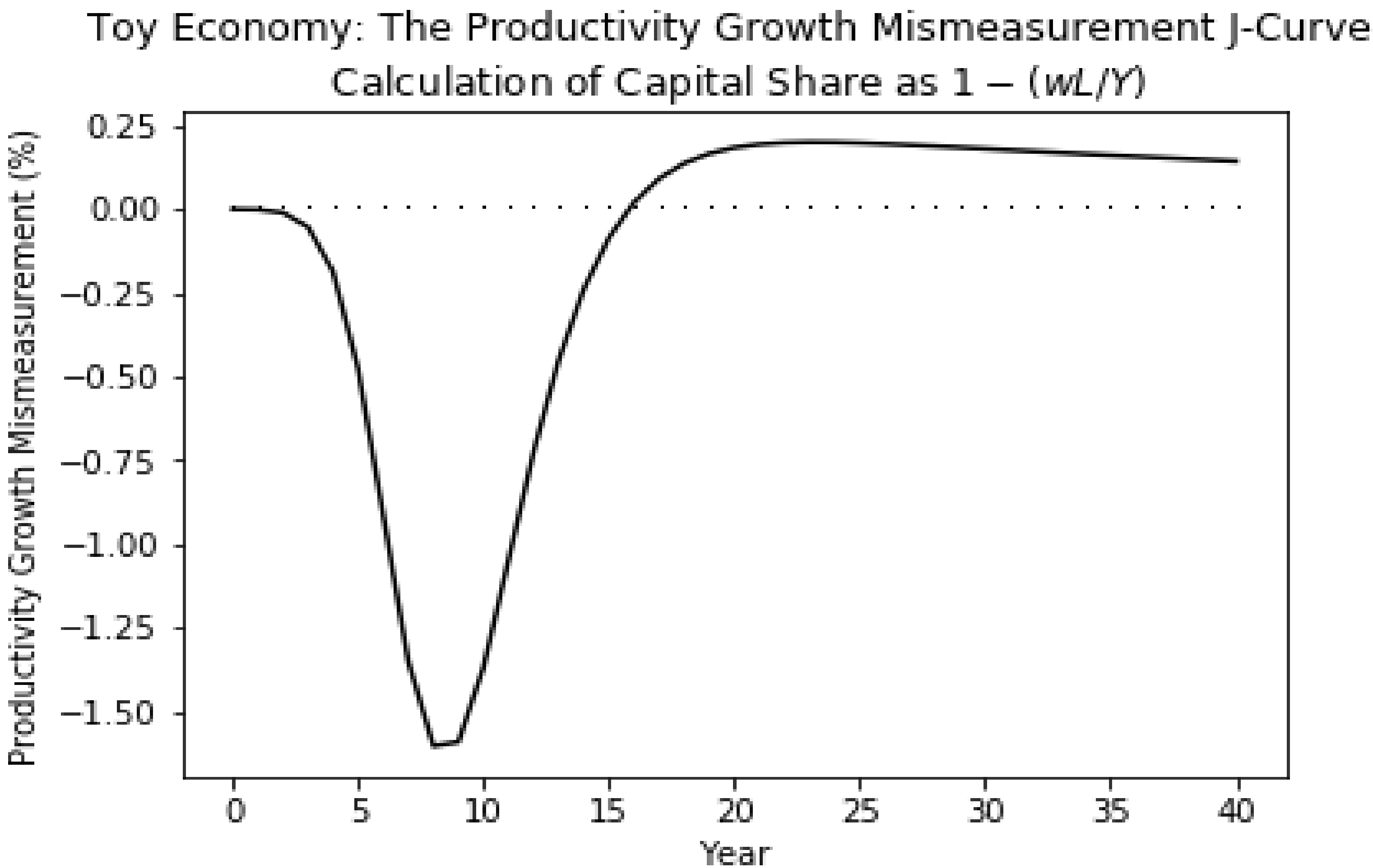
$$g_{A^*} = (1 - \eta_t) g_A + \eta_t \left(g_{I_U} - g_K \right)$$

The J-Curve

How might we expect this mismeasurement to evolve?

- Early in a GPT diffusion process, intangible investment growth g_{I_U} likely larger than growth in capital input stock g_K
  - Logic: Have to build intangibles before use as an input
- Hence new intangible diffusion will initially make true productivity higher than the Solow residual
- But later output growth will slow, causing Solow residual to overstate true productivity growth
- Eventually, in steady state, intangible investment output and capital inputs grow at similar rates—mismeasurement stabilizes

The J-Curve



Toy Economy: The Productivity Growth Mismeasurement J-Curve
Calculation of Capital Share as 1 − (wL/Y)
Productivity Growth Mismeasurement (%)
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
0
5
10
15
20
25
30
35
40
Year

Empirical Strategy

- Use firm value regressions to infer intangibles associated with measureable investments
  - Regressing firm market value on types of capital show how $1 of capital type X is valued by the market
  - A weight above 1 implies capital type is valued at an amount greater than investment & implies the presence of complementary intangibles
- Use estimates to construct implied productivity mismeasurement
- Integrate to find implied difference in TFP levels

Firm Value Regressions: R&D

Table 1: Market Value Regressions on R&D and SG&A Stocks

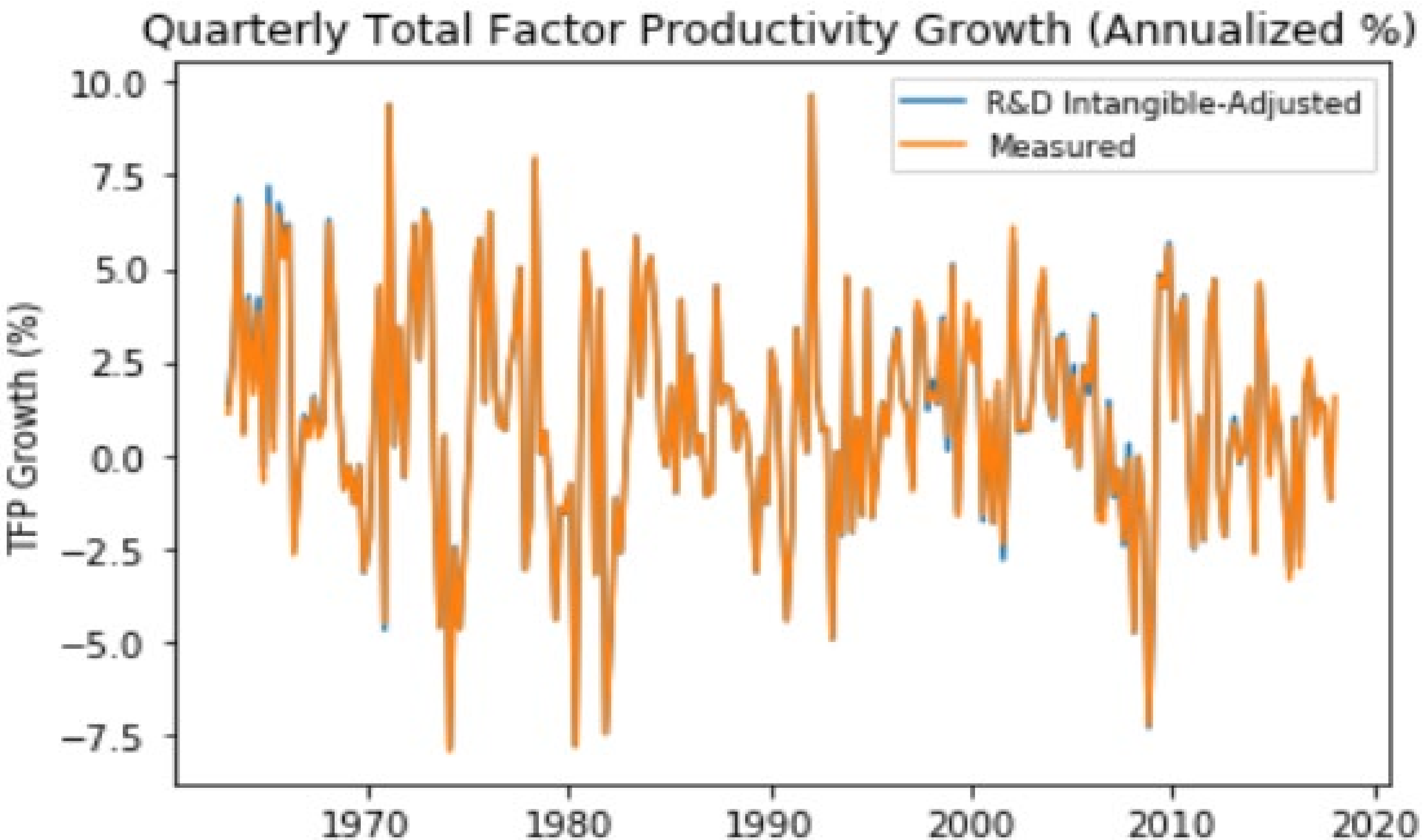
Market Value Regressions (1962-2017)	(1) Basic R&D	(2) Basic R&D and SG&A	(3) Industry-Year Fixed Effects: R&D	(4) Industry-Year Fixed Effects: R&D and SG&A	(5) Firm and Year Fixed Effects: R&D	(6) Firm and Year Fixed Effects: R&D and SG&A
Total Assets	1.016	0.998	1.015	0.999	1.013	0.997
	(0.00179)	(0.00232)	(0.00853)	(0.0107)	(0.00725)	(0.0110)
R&D Stock	2.730	1.753	2.841	1.953	2.161	1.509
	(0.105)	(0.0970)	(0.479)	(0.399)	(0.297)	(0.278)
SG&A Stock		1.755		1.657		1.453
		(0.102)		(0.399)		(0.374)
Constant	656.8	458.7				
	(14.32)	(18.06)				
Firm-Year Observations	268,687	268,687	266,795	266,795	267,683	267,683
R-squared	0.987	0.988	0.989	0.989	0.993	0.993
Industry-Year FE	No	No	Yes	Yes	No	No
Firm and Year FE	No	No	No	No	Yes	Yes

Robust standard errors in parentheses

Firm Value Regressions: R&D

- Tangible “standard” capital in Total Assets appears to be valued dollar-for-dollar, both across companies and within companies over time
- OTOH, $1 of R&D appears to be associated with $2 of shadow value, so perhaps $1 dollar of intangibles
- SG&A proxy for intangibles captures some of this, but also seems to be correlated with shadow value above $1

Measured and Adjusted TFP Growth: R&D



Adjusted TFP: R&D

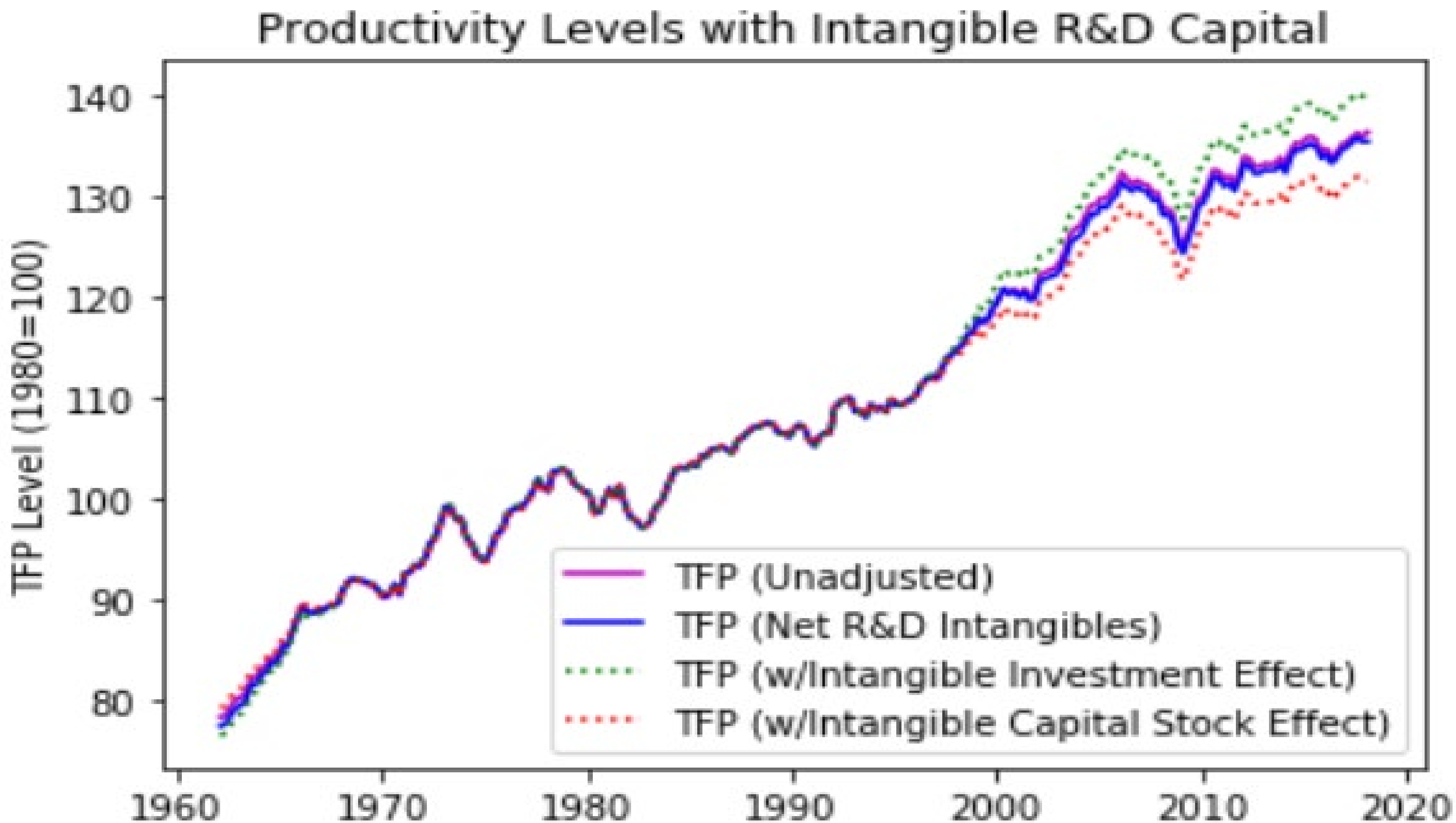
Why is mismeasurement so small if for every dollar of R&D there is an implied additional $1 of intangible capital?

It's because R&D investment rates have been stable for many decades

Thus $g_{I_U} \approx g_K$

This can be seen in TFP level breakdown into missing output (investment) and input (stock) components

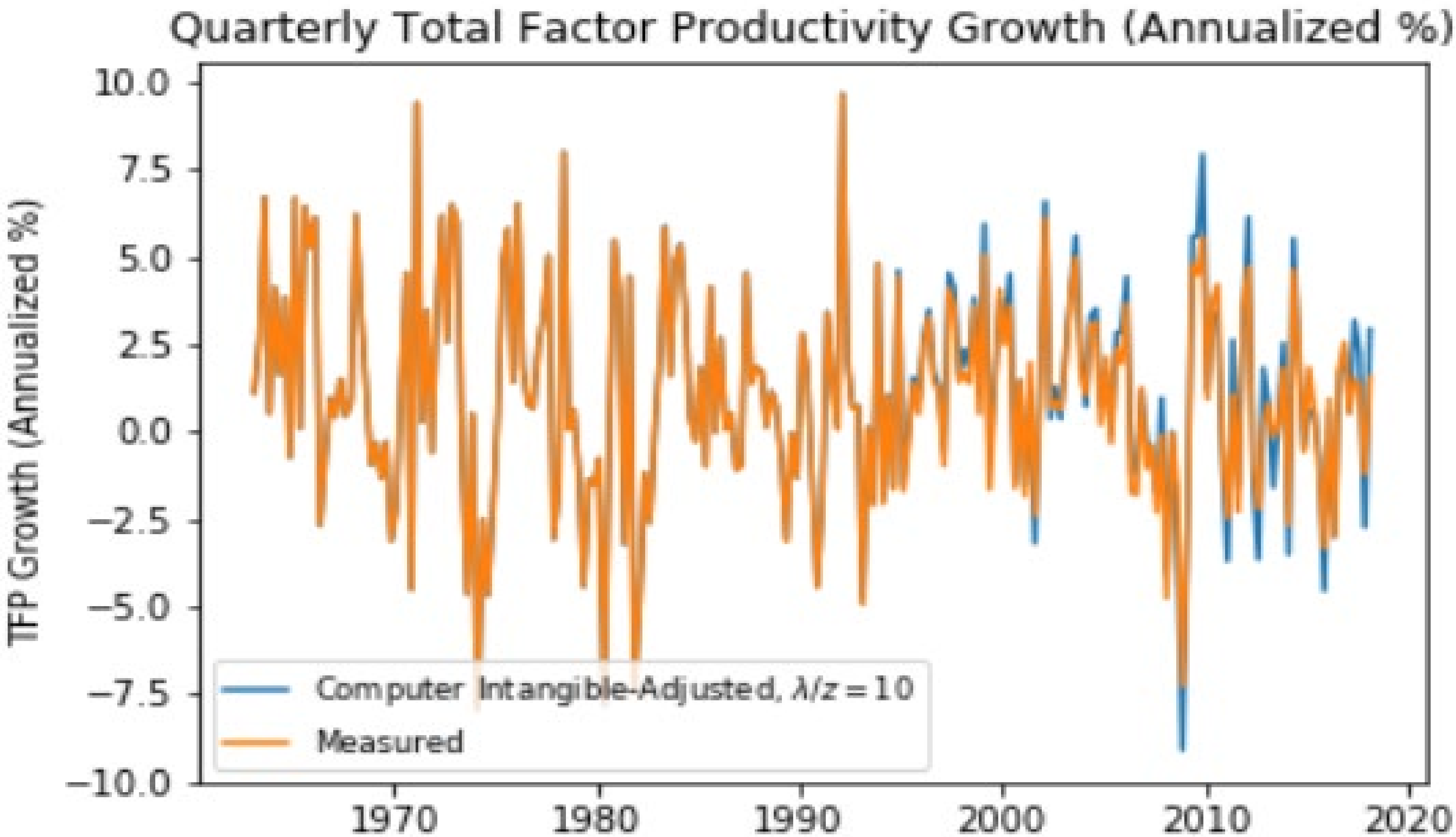
Measured and Adjusted TFP Levels: R&D



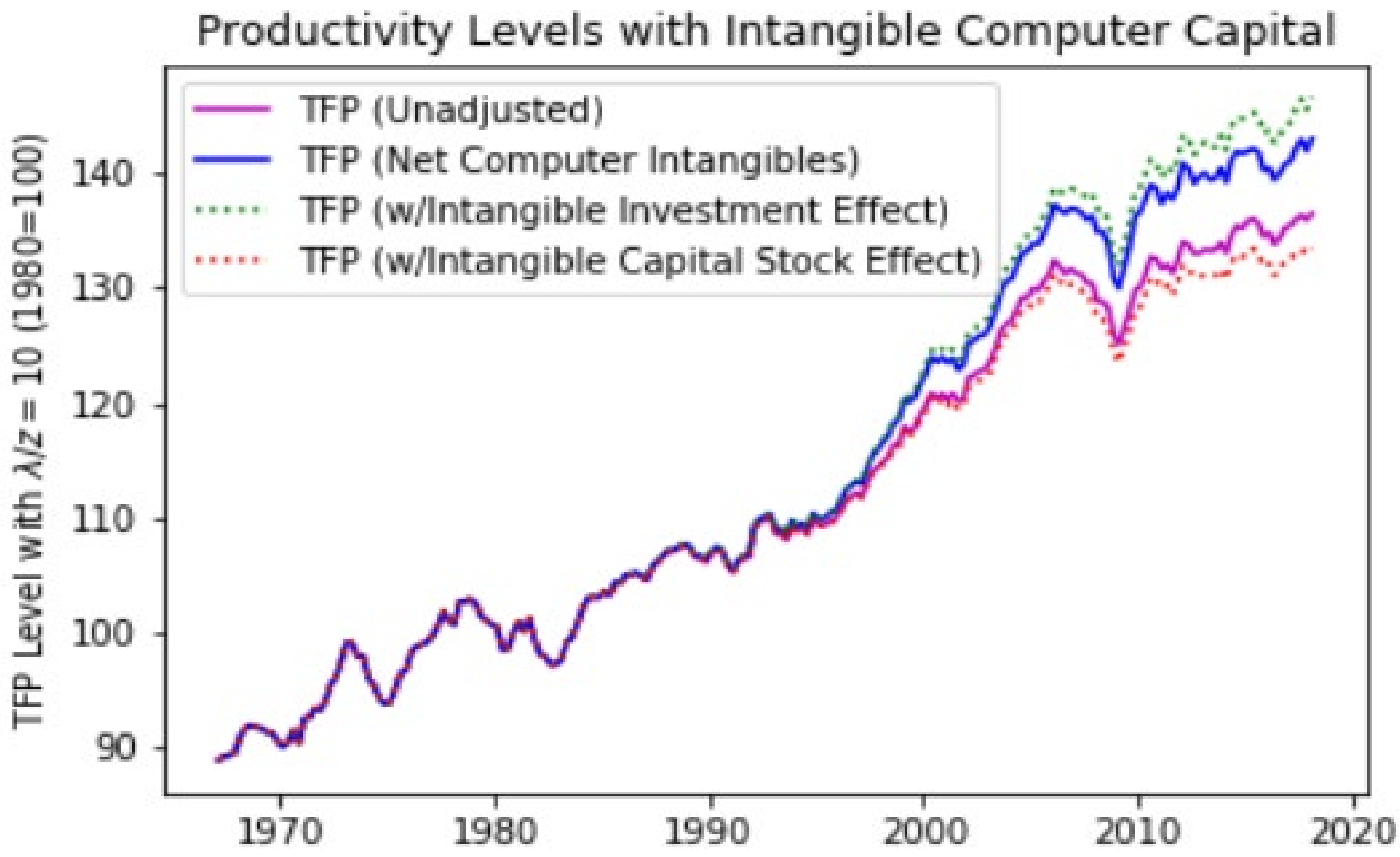
Firm Values: Hardware and Software

- We don't have firm-level IT capital data as we did for R&D
- We instead proceed by computing implied mismeasurement for different values of λ/z based on the literature
  - Brynjolfsson, Hitt, and Yang (2002) estimate $1 of computer hardware and software associated with about $12 (s.e. = $4) of market value
  - We use λ/z of $10, though also compute for $5, $3, and $2

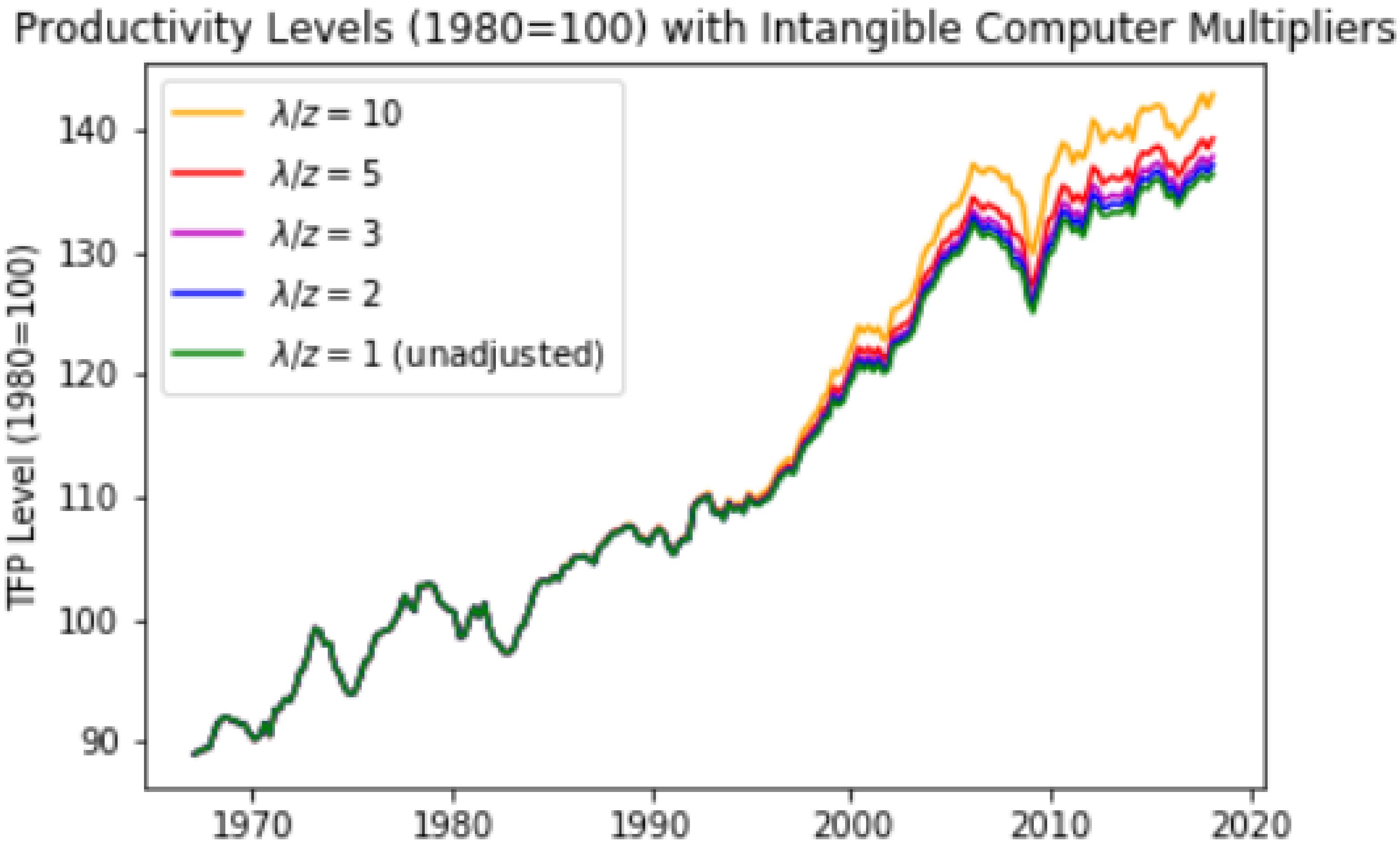
Adjusted TFP Growth: IT Hardware



Adjusted TFP Levels: IT Hardware



Adjusted TFP Levels: IT Hardware



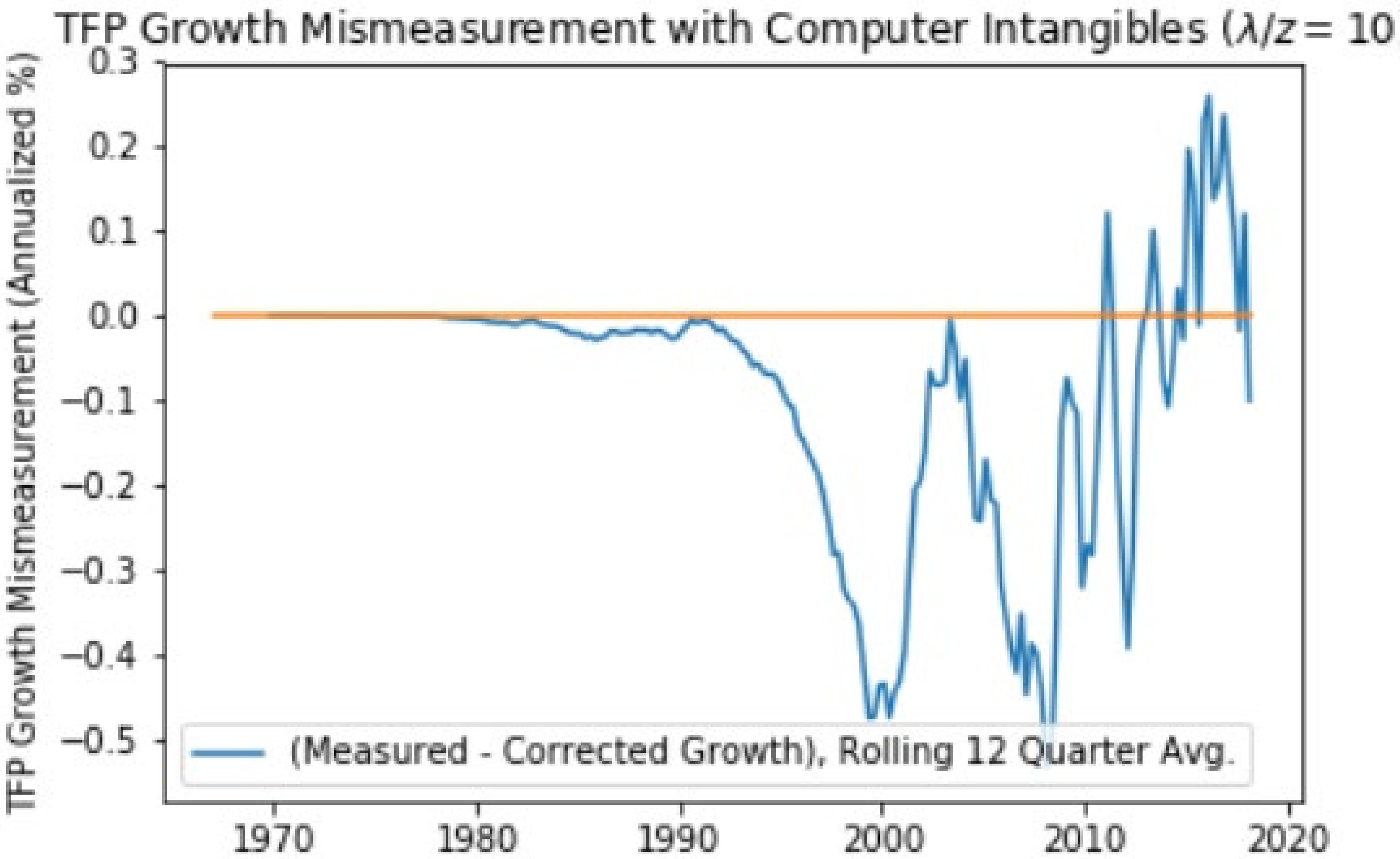
Adjusted TFP: IT Hardware

Adjusted TFP level is 3.7% higher in 2016 than measured

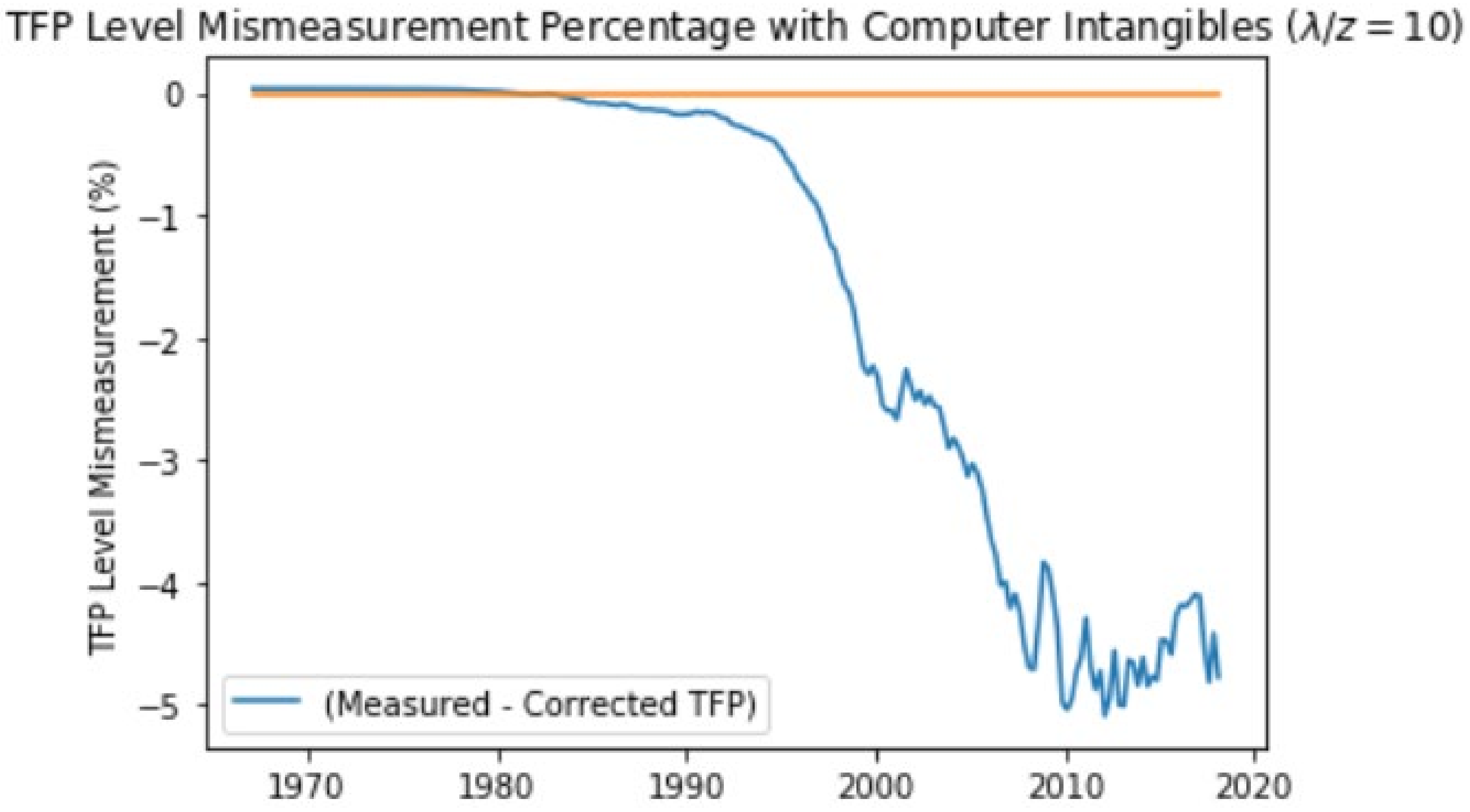
- Note this is the total growth measurement error accumulated over almost 50 years

- First half of *growth* J-curve has played out; hardware-related intangible accumulation has lately caused productivity growth overstatement (and brought levels back toward measured level)

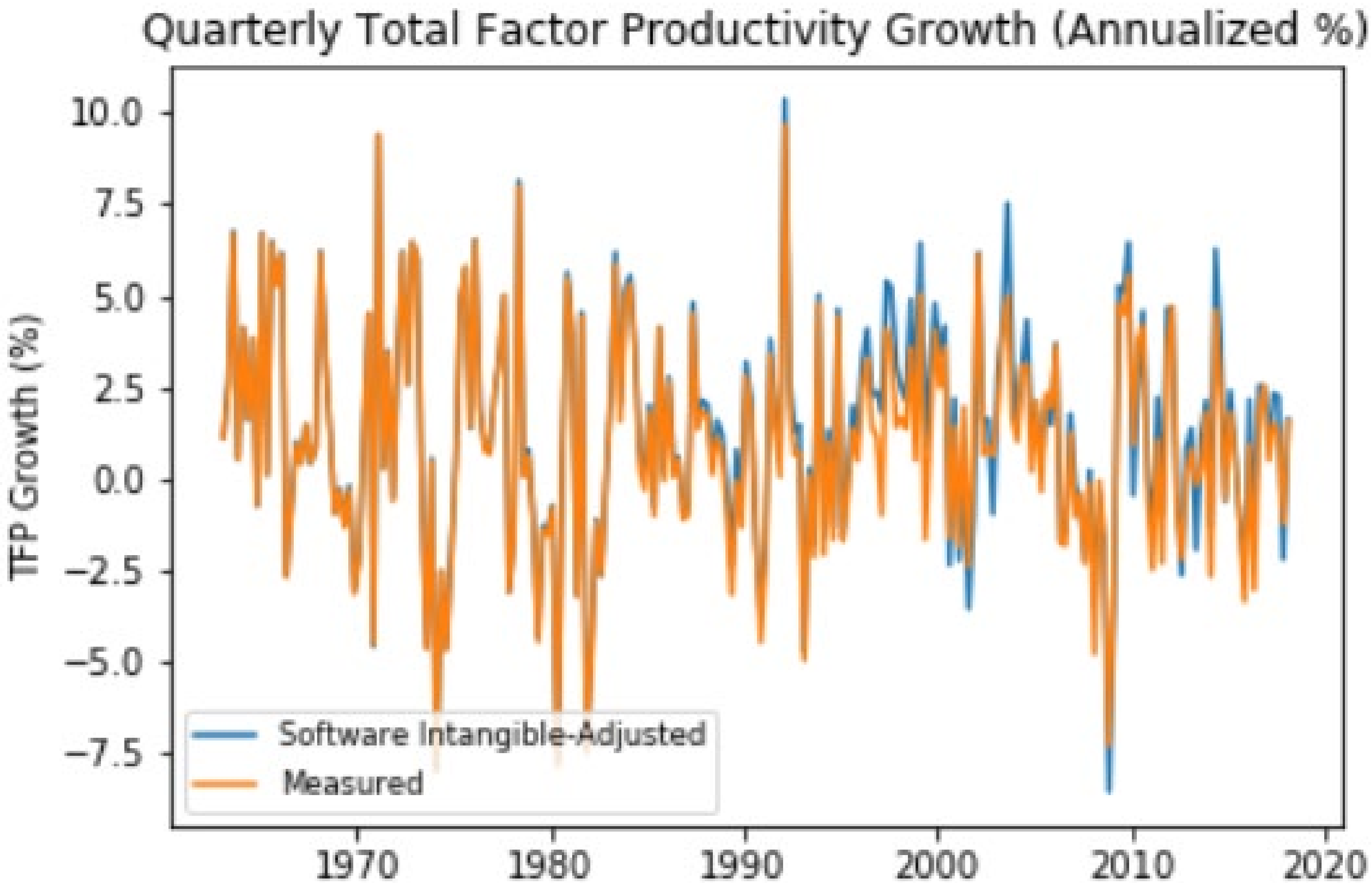
TFP Growth Mismeasurement by Year: IT Hardware



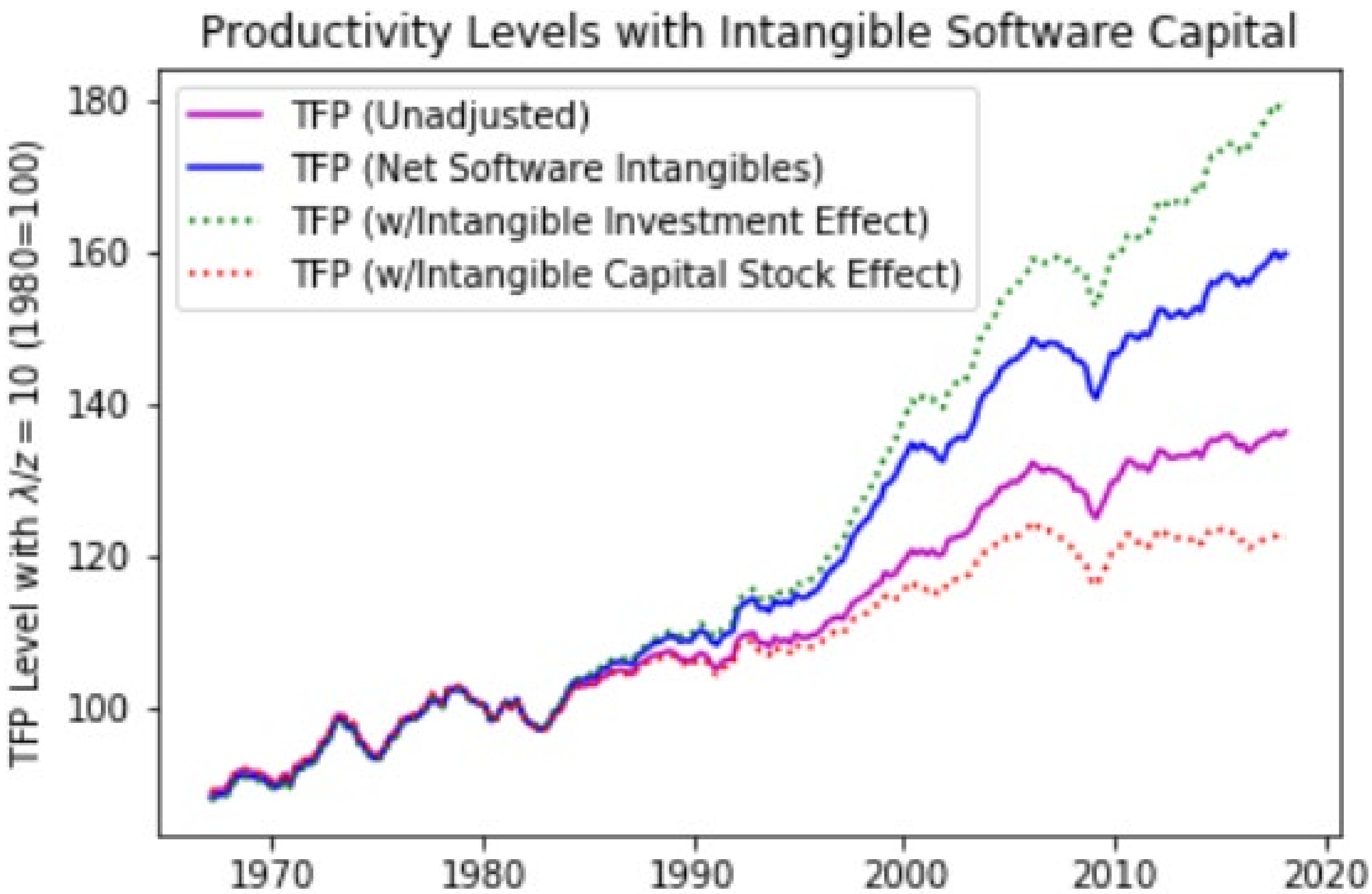
TFP Accumulated Level Mismeasurement: IT Hardware



Adjusted TFP Growth: IT Software



Adjusted TFP Levels: IT Software



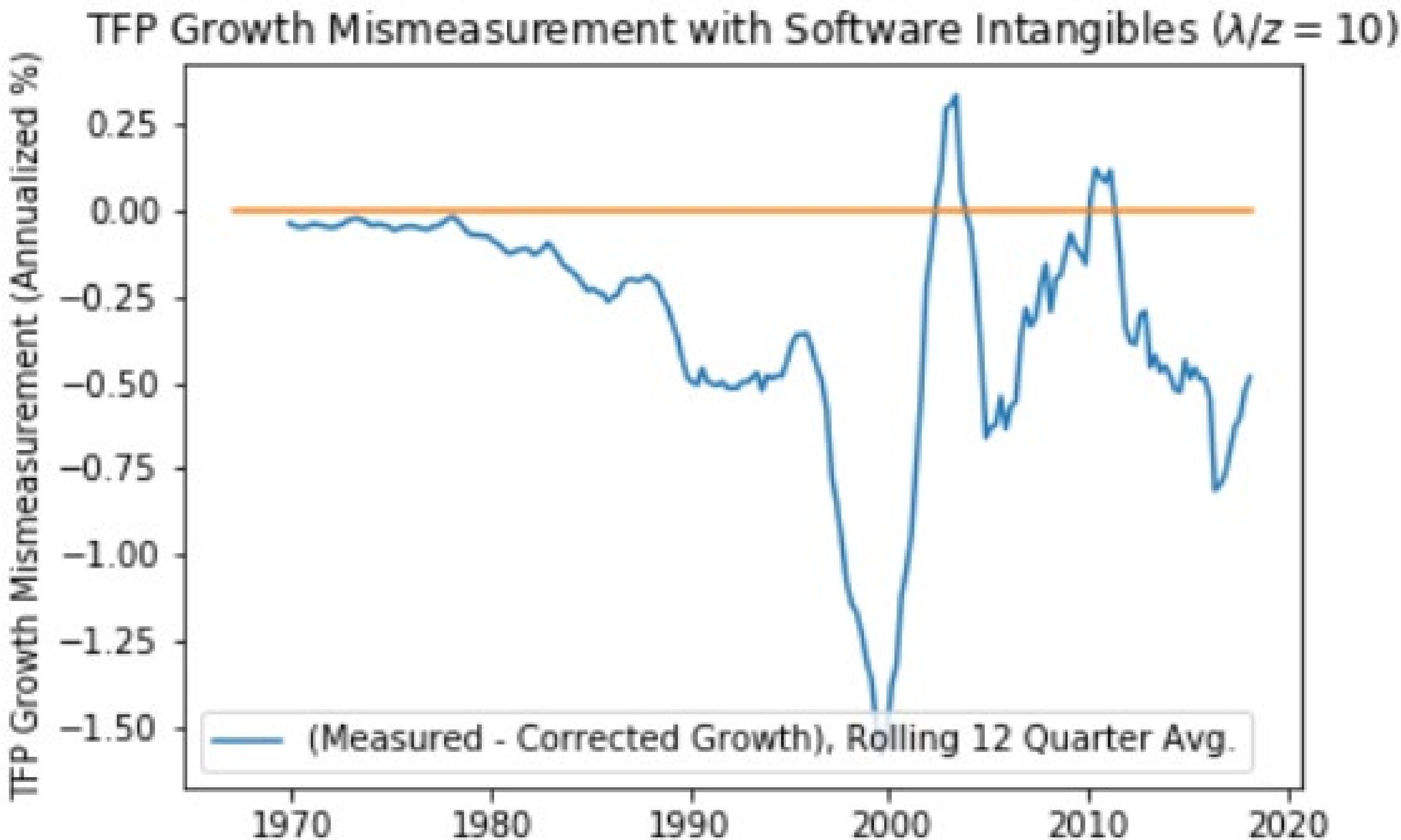
Adjusted TFP: IT Software

Implied mismeasurement due to software-related intangibles is much larger than for intangibles related to R&D or hardware

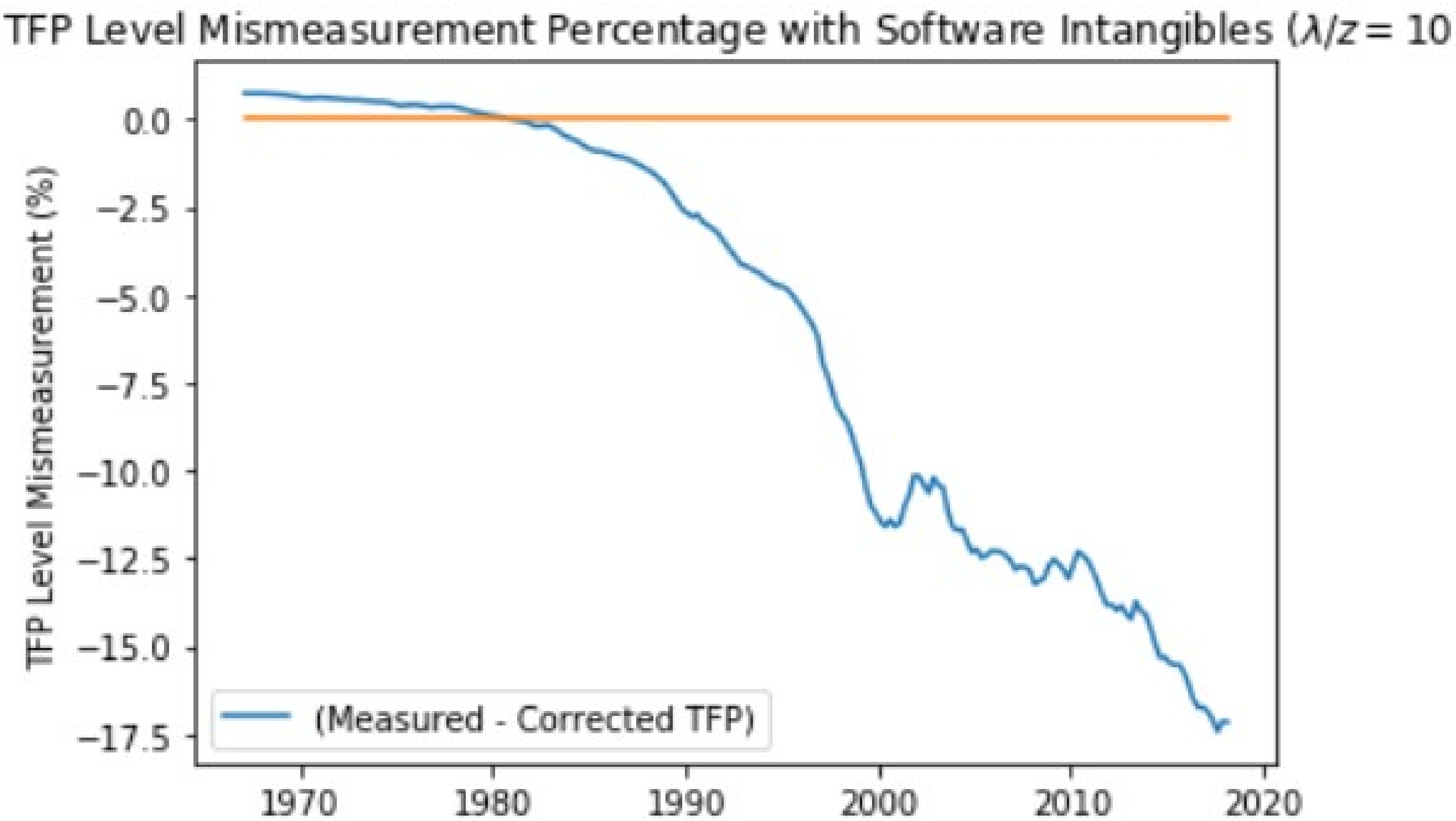
Adjusted TFP level is 12.4% higher in 2016 than measured

First half of growth J-curve might be played out, but less clear than for hardware

TFP Growth Mismeasurement by Year: IT Software



TFP Accumulated Level Mismeasurement: IT Software



Does This Explain the Post-2004 Productivity Slowdown?

No; implied slowdown actually larger, at least through 2018

A mismeasurement explanation for the slowdown doesn't just require mismeasurement. It requires:

- A *change* in mismeasurement
- In a particular direction
- Around 2004

Are AI-Related Intangibles Causing Mismeasurement Already?

- Still very early in AI adoption, but fast investment growth
- IDC estimates Australian AI investments of $1.9B in 2022
  - Expected annual growth of 24% going forward
- If each observed dollar of AI investments is correlated with about $5 in additional intangible investments, that implies current annual GDP is 0.4% (= $9.5/2300) higher than observed
  - Not implausible
  - However, pre-2020 AI investments probably too small to have had aggregate effects, so only recent part of story

Conclusion

- New technologies often require complementary intangible investments
- These intangibles can lead to productivity mismeasurement
  - First as missing output (productivity understatement)
  - Later as missing input (productivity overstatement)
- Recently, this dynamic appears to have largely played out for R&D- and hardware-related intangibles
- Still in play for software-related intangibles
- AI-related intangibles might just now be creating enough mismeasurement to matter for aggregates