NSW Treasury

# Trends in productivity: What should we expect?

TRP23-07

Keaton Jenner and Angus Wheeler [1]

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The slowdown in productivity growth across advanced economies over recent decades has puzzled economists. A working paper by Philippon (2022) suggests that the 'puzzle' simply reflects overly optimistic expectations for constant growth in total factor productivity (TFP). He proposes a new 'additive' model of TFP, based on the idea that economies add to, rather than multiply, their stock of useful knowledge. The additive model predicts declining TFP growth and produces more accurate out-of-sample forecasts, potentially resolving the productivity slowdown puzzle. The additive model has several other important implications, including that we should expect slower long-term output and tax revenue growth, as well as smaller positive spillovers from R&D activity.

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## Acknowledgement of Country

We acknowledge that Aboriginal and Torres Strait Islander peoples are the First Peoples and Traditional Custodians of Australia, and the oldest continuing culture in human history. We pay respect to Elders past and present and commit to respecting the lands we walk on, and the communities we walk with.

Artwork:
*Regeneration* by Josie Rose

## Overview

Total factor productivity (TFP) growth, spurred by new ideas, inventions, and processes, has underpinned increases in Australia's real incomes over time (Figure 1).[2] In recent decades, however, growth in TFP has slowed significantly, weighing on economic growth across advanced economies (Figure 2).

Figure 1: Decomposition of Australian GDP

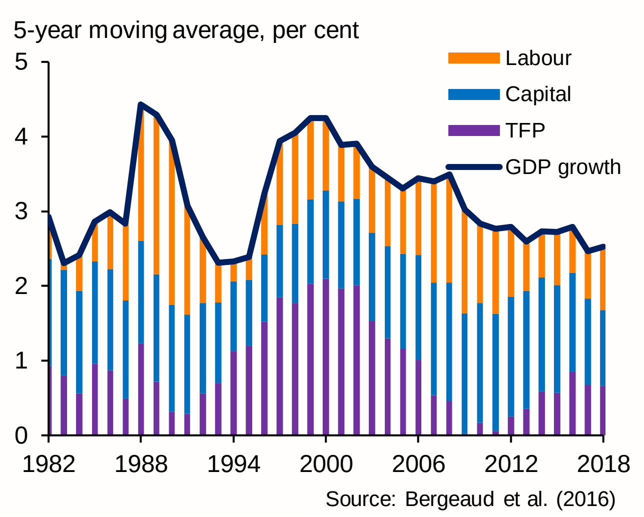
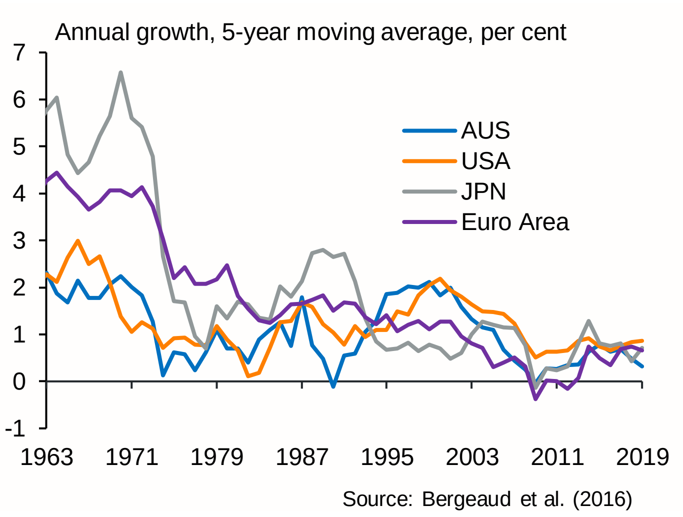



Figure 2: TFP growth has slowed since the mid-2000s




The slowdown in productivity has been of central concern to policymakers (e.g. see BOE 2017, Commonwealth Treasury 2022). This is because slow productivity growth has broader economic consequences, including muted real wages growth, weak business investment, and lower per capita output. An incomplete list of candidate explanations for the slowdown includes: mismeasurement, especially in intangibles (Byrne, Fernald & Reinsdorf 2016; Syverson 2016; Brynjolfsson et al. 2021; Goldin et al. 2021); increased market power, including its interaction with intangibles (Crouzet & Eberly 2021; Hambur 2020; Andrews et al. 2016); a reduction in allocative efficiency (Goldin et al. 2021); crisis related scarring (Oulton & Sebastia Barriel 2017); and decreased spillovers from intangible capital (Goldin et al. 2021).

## A simple alternative – additive growth

Philippon (2022) puts forward a simple alternative explanation: productivity growth should slow over time. To understand why, we start with the Cobb Douglas production function, which sits at the core of the standard growth model:

$$Y_t = A_t K_t^{\alpha} L_t^{1-\alpha} \qquad (1)$$

- $\boldsymbol{Y}$ is output
- $\boldsymbol{L}$ are labour inputs (e.g. hours worked)
- $\boldsymbol{K}$ is the capital stock (e.g. plant & equipment)

[2] TFP can also be boosted, at least temporarily, by declining misallocation. See Hsieh, Hurst, Klenow & Jones (2019) for an example. Capital deepening – that is, increasing the capital stock per worker – can boost GDP growth by increasing labour productivity.

- $\boldsymbol{A}$ is total factor productivity (TFP), which captures growth in output not attributable to changes in labour or capital inputs (i.e. it is a residual)
- $\boldsymbol{\alpha}$ is the elasticity, or factor share, of capital in production, with $0 \leq \alpha \leq 1$
- $t$ indexes the time period.

Economists typically assume that $\boldsymbol{A}$ follows a geometric process, with constant growth rate $\boldsymbol{g}$:

$$\mathrm{A}_{t+\tau} = \mathrm{A}_t(1+\mathrm{g})^{\tau} \qquad (2)$$

Where:

- $g$ is a constant growth rate
- $\tau$ indexes the number of years into the future.

Under the constant growth rate assumption in Equation (2), the *level* of TFP ($\boldsymbol{A}$) rises exponentially. Philippon's insight is to recast long-run productivity growth within a linear, rather than exponential (or constant growth rate), model. The intuition is that, in practice, we add to our stock of knowledge, rather than grow it. Or put another way: ideas and inventions are not generated in proportion to the existing stock of knowledge, but instead occur in fixed increments. More precisely, productivity increases by a constant increment $\boldsymbol{b}$ in each period:

$$\mathrm{A}_{t+\tau} = \mathrm{A}_t + b\tau \qquad (3)$$

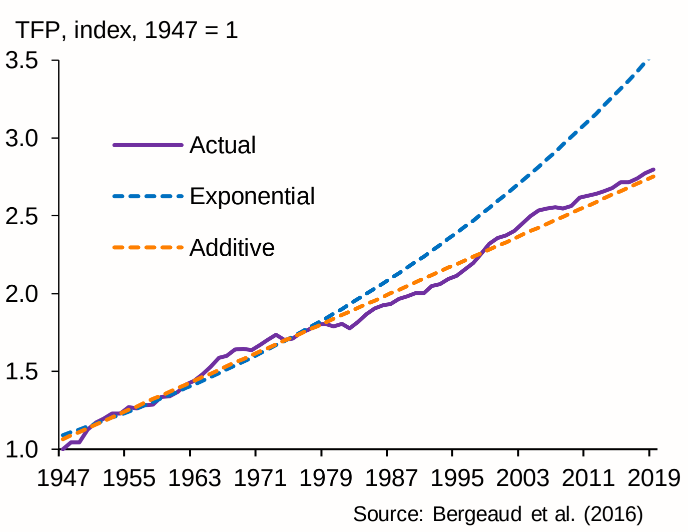
where $b$ represents a constant TFP increment.

Under the constant increment assumption in Equation (3), the level of TFP increases linearly and its growth rate declines over time. This is because as the existing stock of ideas, $A$, expands over time, the fixed increment, $b$, represents an increasingly small proportional increase.

## The additive model produces more accurate TFP forecasts

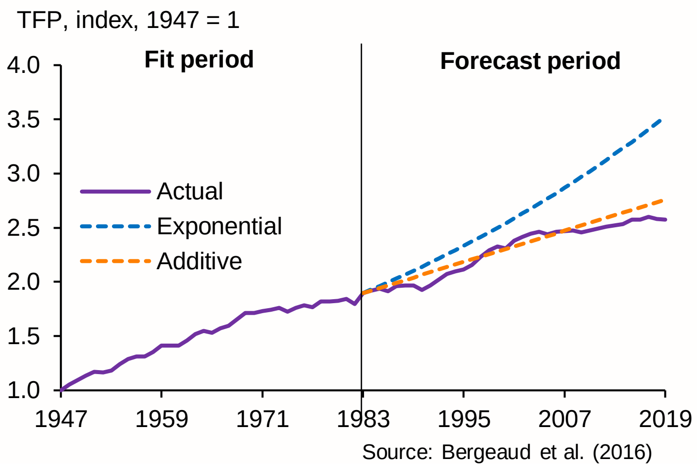
Philippon tests the performance of the additive model via a simple out of sample forecasting exercise. Specifically, he estimates both the additive and exponential models on historic TFP data for the US post War II period (1947-1983). These estimates are then used to generate a single long-range forecast for the 1984-2019 period. Philippon finds that the additive growth model forecasts are much more accurate (Figure 3). Moreover, there is no longer a TFP slowdown 'puzzle' under additive growth. We also test for the alternative hypothesis that TFP does grow exponentially, but that there was a 'structural break' in the growth rate sometime in the past half century. However, we find that this model also performs worse than 'additive growth' out of sample (see Appendix A.2).

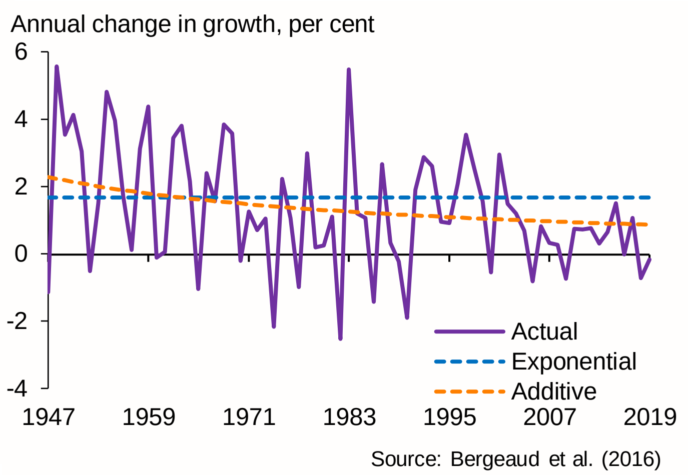
Figure 3: Additive v. exponential forecasts for U.S. TFP



We repeat Philippon's forecasting exercise for Australia, with similar results.[3] The standard exponential model implies a forecast with an annual TFP growth rate of 1.7 per cent, which we extend forward. The exponential model forecast significantly overshoots actual TFP (Figure 4a, blue line). The additive model implies that TFP increases in increments of 0.024 points per year, with a growth rate that tapers down from 1.25 per cent in 1984 to 0.9 per cent in 2019 (Figure 4b). The additive model yields a much more accurate, *albeit* still slightly optimistic, forecast (Figure 4a, orange line).[4]

Figures 4a and b: Additive model produces more accurate forecasts for Australian TFP

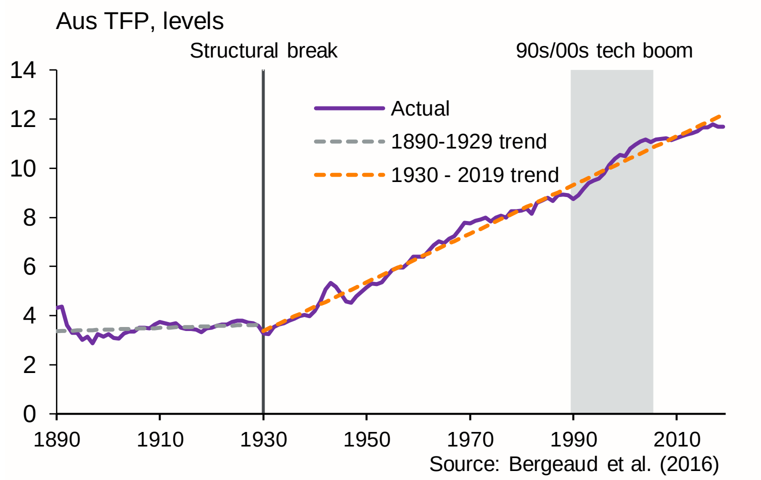



## Changes in the rate of additive growth correspond with known technological progress

Philippon (2022) finds that TFP grows linearly within broad historical periods. At least for the United Kingdom, these periods correspond to 1650-1700 to 1830, 1830 to 1930, and 1930 until today. Convincingly, these breaks correspond with known shifts in technological progress, such as the industrial revolution and the electrification of advanced economies.[5,6] Bergeaud et al. (2016) similarly identify a major acceleration

Figure 5: There is a structural break in Australian TFP growth around 1930

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[3] We focus on Australia, rather than NSW, for this exercise reflecting better data availability. However, the implications are likely to be the same at the subnational level.

[4] To check that this result is not an artefact of timing choices, we repeat the exercise using different initial data periods (rolling from 1937-1973 through to 1957-1993). The results are summarised in Appendix A.1. We find that the forecast errors for the additive model are much smaller, on average, using the additive model.

[5] This piecewise linear structure can give the appearance of a series that grows exponentially, or at least has some convexity, over long time periods.

[6] Philippon identifies a single structural break in the additive model in 1933 for the United States. We find a similarly timed break in the Australian data.

in productivity associated with the second technological revolution (e.g. use of electricity, the internal combustion engine, chemical production) in the 1930s and 1940s. They document a smaller acceleration around the 1990s, which is attributed to productivity gains from the Information & Communication Technology revolution (see shaded region in Figure 5). We identify a single structural break for Australia in 1930, consistent with Philippon's results (Figure 5).

## The additive model predicts (very) modestly increasing increments in living standards

At face value, the additive model appears to imply stagnation in living standards. Absent any new general-purpose technologies (e.g. electricity), the model predicts that TFP growth will tend toward zero. Closer inspection reveals that the additive model is consistent with ongoing increases in living standards. To understand why, consider that in the long-run GDP is equal to the product of labour productivity and the size of the labour force:

$$GDP = \text{Labour productivity} \times \text{population} \times \text{participation rate} \qquad (4)$$

Equation 4 makes it clear that it is primarily labour productivity that drives increases per capita living standards, assuming a constant participation rate. To investigate further, we decompose labour productivity as the product of TFP and capital per worker ($k$), scaled by the capital share ($\alpha$):

$$Labour\ productivity_t = \text{TFP}_t \times \text{k}_t^{\alpha} \qquad (5)$$

This motivates a comparison of forecasts for labour productivity under both the exponential and additive growth models (see Appendix A.4 for details). Once again, the additive model generates much more accurate forecasts (Figure 6). Importantly, labour productivity is not linear under the additive model; rather, it is (very slightly) convex. This means that labour productivity grows at increasingly large increments, but not exponentially (Figure 7). This yields indefinite increases in living standards but with a growth rate that tends toward zero over time.

Figure 6: The additive growth model produces better forecasts for labour productivity

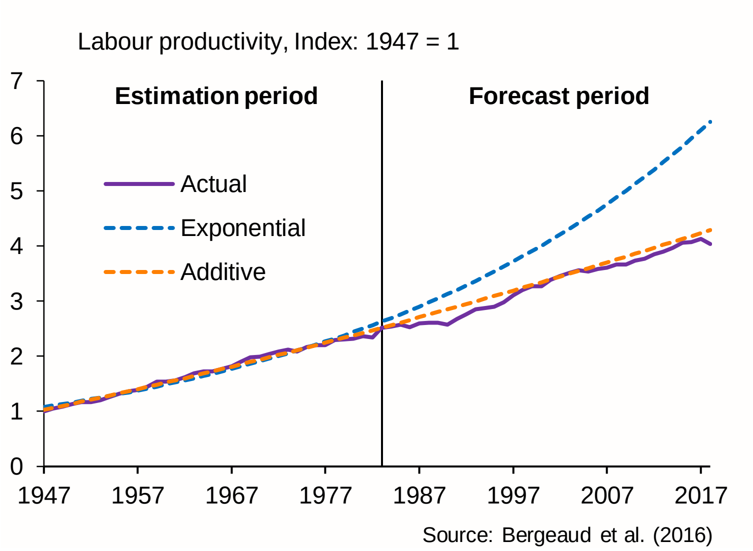
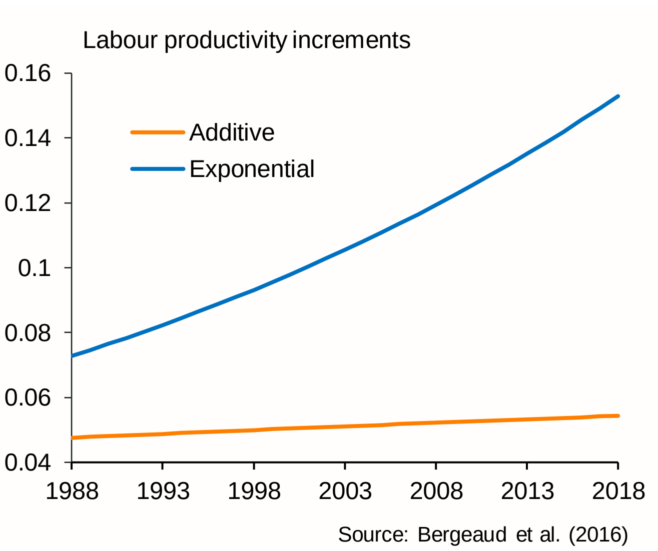



Figure 7: Labour productivity continues to rise by increasing increments



## Implications

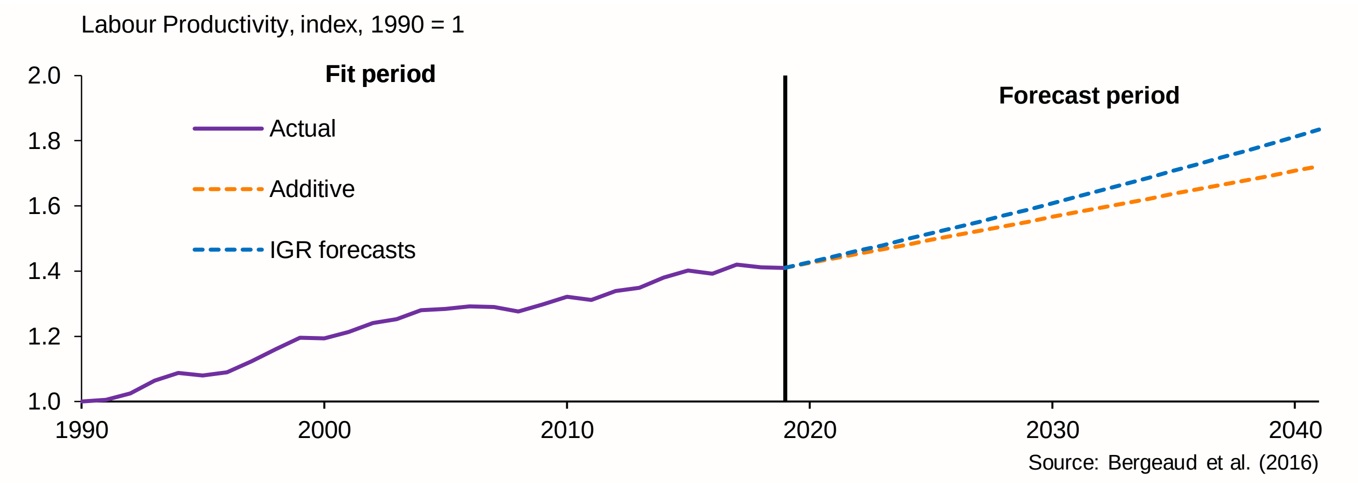
The apparent success of the additive growth model in fitting the data could have significant implications for policymakers. Productivity is a central 'anchor' variable that determines expectations for the long run GDP, along with labour force participation and population. The outlook for productivity growth also affects private and public investment incentives, as well as expectations for fiscal revenue.

### *Long-term growth forecasts*

Federal and State Treasuries typically forecast constant productivity growth in their macroeconomic projections (i.e. they use the exponential model described above). The NSW Intergenerational Report (IGR) most recently used a 30-year historical annual average growth rate of 1.2 per cent (NSW Treasury 2021). Combined with assumptions about population, labour force participation, and hours worked, this translated into a GSP forecast of 2.2 per cent growth per annum, on average, out to 2041.

The additive growth model produces lower TFP and labour productivity forecasts (Figure 8). Using the same 30-year baseline estimation period, the additive growth model predicts that labour productivity growth will decline from 1 per cent to 0.8 per cent over the forecast horizon. This works out to an average GSP growth rate of 1.9 per cent per annum, 0.3 percentage points lower than assumed in the IGR. The slower growth forecast implies that the NSW economy would be approximately 7 per cent smaller in 2041 than was projected in the IGR. If realised, this would have material implications for the government's revenue base and budget position, given no obvious reason to assume an offsetting reduction in government expenditure. Indeed, future governments could decide to undertake relatively more capital spending in an effort to boost labour productivity should this more pessimistic scenario eventuate.

Figure 8: Additive growth v. NSW IGR 30-year average growth rate assumption




**Note:** The IGR forecast is calculated as the 29-year constant average growth rate (CAGR) to 2019 While the additive growth forecast is the average increment over the 30 years to 2020. The forecasts are projected out over the 20 years to 2041.

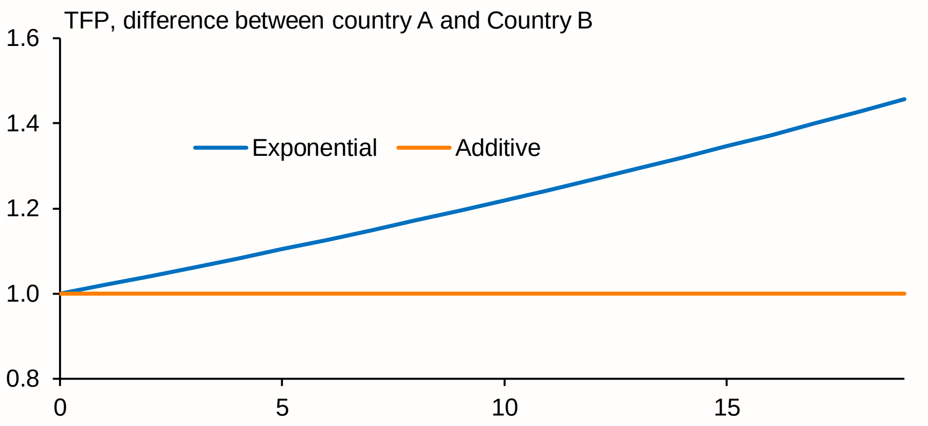
### *Smaller R&D spillovers and the link to the production of ideas*

Philippon (2022) argues that the slower expected productivity growth in his framework implies smaller 'intertemporal' spillovers from R&D spending. Here 'intertemporal spillovers' refers to the idea that technological breakthroughs and innovations today make future discoveries easier to obtain.

To illustrate, suppose we observe two (almost) identical countries: A and B. The only difference is that country A starts with slightly more advanced technology (e.g. $TFP^{A}_{t=1} = 1.01$ while $TFP^{B}_{t=1} = 1.00$). To understand how spillovers are smaller under additive growth, we can examine how the different starting position of each country affect their long run outcomes under both the exponential and additive models.

The difference between countries under exponential growth is stark (Figure 9).[7] There is a linearly increasing gap between country A and B, with country A increasingly advantaged in absolute terms by its better starting position. This reflects that the standard growth model implicitly assumes that an additional discovery made today makes future discoveries exponentially easier to obtain. In contrast, these dynamics do not exist under additive growth, which maintains the base 0.01 point difference between the two countries.

Figure 9: Difference in TFP levels (x100): exponential vs additive growth




Applying this logic to actual productivity data, Philippon conducts the following thought experiment: what if the electrification of the economy had occurred in the 1910s instead of the 1930s? For Australia, this counter-factual scenario implies that the level of TFP would be 60 per cent higher today under exponential growth, compared with a 15 per cent difference under additive growth (Figure 10).[8]

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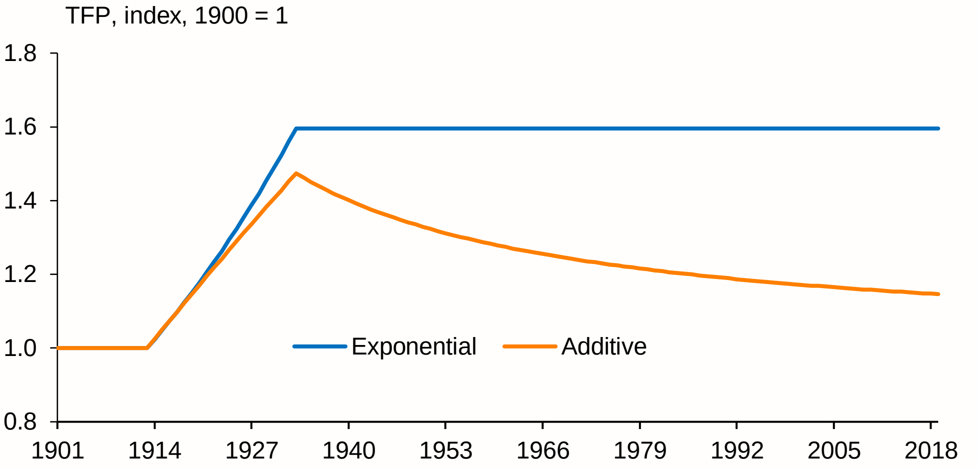
[7] We assume that under the exponential model growth is 2 per cent per annum in both countries, and that under the additive model TFP increases by a constant increment of 0.03 per annum.

[8] The difference under additive growth, 15 per cent, is calculated as the difference in the 'increments' (0.029 post-1933 vs ~ 0 during 1900-1932), multiplied by 20 years, divided by the 2019 fitted value for TFP under additive growth (~3.6). The difference under exponential growth treats the change in increments from ~0 to 0.029 as proportional to the level of TFP in 1933, compounded over a 20-year period.

Figure 10: Earlier electrification of the economy: exponential vs additive growth



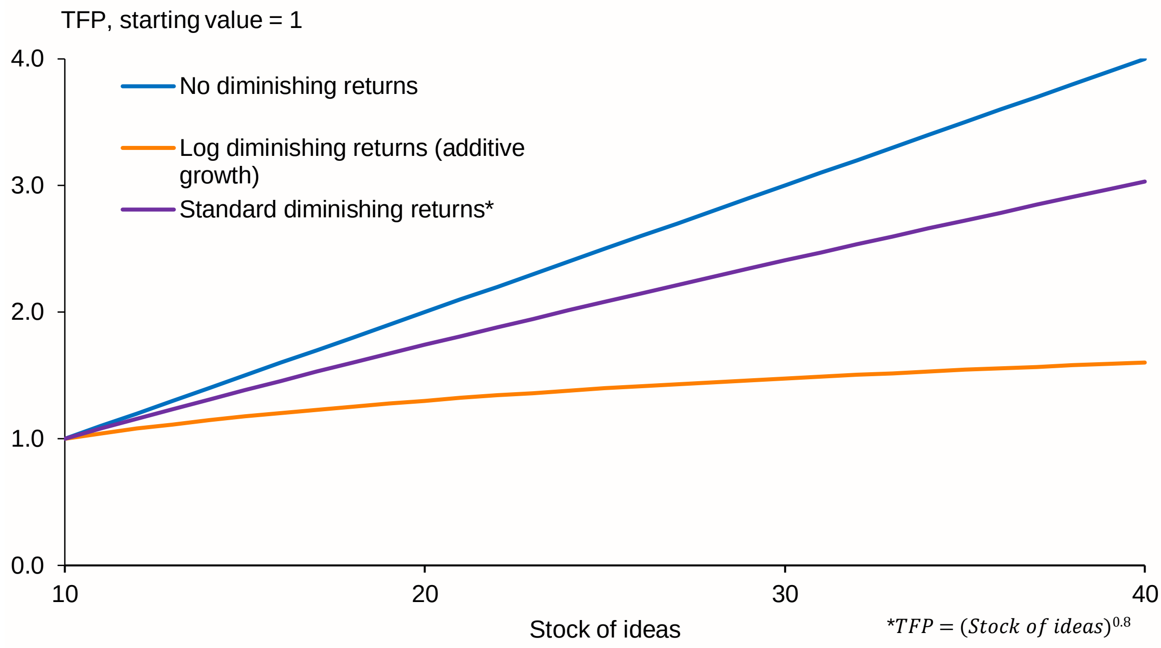

Source: Bergeaud et al. (2016)

The discussion so far has pre-supposed a link between TFP and the stock of ideas or knowledge without making this connection precise. Indeed, others have sought to explain the apparent slowdown in TFP by examining whether it is becoming increasingly difficult to generate new ideas (Bloom, van Reenan, Jones & Webb 2020). Bloom et al. find that research productivity is declining sharply. For instance, they find that it is 18 times harder to maintain Moore's law – the doubling of computer chip density – today than in the early 1970s.

Although Philippon claims that the additive growth model does not resolve Bloom et al.'s question, it is not hard to see how the two explanations could be related. Ideas could be getting harder to find and research effort growing at exactly the rate required to produce additive TFP growth. Philippon (2022) and Vollrath (2022) offer a slightly different way to generate additive growth. They instead propose that within productivity regimes (e.g. 1930s-present), the link between ideas and TFP could suffer from sharply diminishing returns. Specifically, additive growth implies that TFP grows with the logarithm of ideas. This would represent a departure from standard growth models, which often assume TFP increases one for one with the stock of ideas (e.g. Jones 2022).

To illustrate, suppose that the initial stock of ideas is normalised to 10. In models without diminishing returns to ideas, quadrupling the stock of knowledge from 10 to 40 implies a proportional quadrupling of TFP. If TFP instead increases with the log of ideas, as is needed for additive growth, we only achieve an approximate 60 per cent increase in TFP (Figure 11). Standard diminishing returns, shown in the purple line, are not strong enough to generate linear TFP.

Figure 11: Relationship between TFP and ideas under alternative assumption




### *Why might this be the case?*

Vollrath (2022) conjectures that diminishing returns might arise because each new invention needs to interact with an increasing number of existing ideas. For instance, driverless cars would represent an immense technological breakthrough in a very simple road network; however, their (current) utility is limited by the need to interact with complex traffic signals, human-operated vehicles, buildings, pedestrians, and so on. Philippon notes forthcoming work by Jones (2022) shows that additive growth in productivity is possible when new ideas are generated by combining existing ideas, which generates explosive growth in the number of ideas, but that better ideas become more difficult to find at an offsetting rate.[9] It is worth noting, however, that most versions of Jones' combinatorial growth model are also consistent with exponential growth – this occurs when better ideas are still getting harder to find, but not so quickly that growth is linear. Clancy (2021) provides a slightly different summary that suggests Jones' model also produces slowing growth if real economic resources are required to sort through an expanding universe of available ideas.

The key implication for governments is that the 'social returns' or positive externalities from R&D spending within productivity 'regimes' are likely smaller than is typically understood. We caution that this does not necessarily imply that governments should reduce R&D subsidies. Rather, it might imply that more resources should be dedicated to basic research that is more likely to generate large breakthroughs, or possibly more importantly in Australia's case, facilitate their diffusion.

### Other implications

Philippon (2022) discusses several other implications of the additive model that we do not expand upon here. These include the existence of a balanced growth path, declining interest rates, asset valuations, the rate of convergence in living standards across countries, and the role of education in driving TFP.

[9] Specifically, when idea quality follows a Gompertz distribution, at least in the upper tail.

## Caveats

The purpose of this paper is not to argue that the ‘additive growth’ model is necessarily correct. Instead, we have tested the theory’s core claims using Australian data and explored some possible implications. To conclude our discussion, however, it is worth noting that there are potential caveats to the model.

First, we should take seriously the idea that alternative theories could also fit the data. For example, productivity growth could be more sporadic, with long waves of innovation and stagnation, rather than following a deterministic process like constant additive or exponential growth (Kelly et al. 2021; Aghion et al. 2013; Adao et al. 2022).

Second, we have assumed the TFP residual is entirely driven by the production of ideas or knowledge, excluding any role for changing misallocation. This is despite an extensive literature showing that economic growth can be, at least temporarily, affected by declining misallocation. For example, Hsieh et al. (2019) find that between 20-40 per cent of growth in the US is attributable to declining discrimination against women and African-Americans since 1960, up to 2010. At face value it does not seem clear to us whether changes in misallocation should be more consistent with additive or exponential growth. This is a potential area for future research.

# Appendix

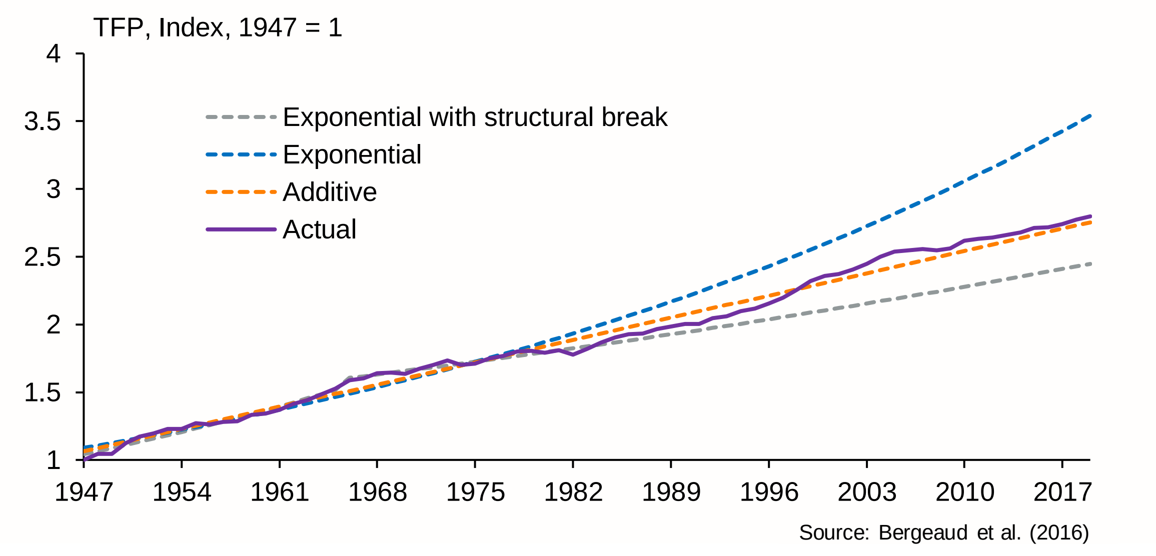
## A.1: Additive vs exponential model forecasts, root mean square error (RMSE)

### Estimation period begins 1937-1957, rolling out of sample forecasts

| Forecast horizon (years) | Exponential model RMSE | Additive model RMSE |
|---|---|---|
| 5 | 0.21 | 0.11 |
| 10 | 0.29 | 0.15 |
| 15 | 0.36 | 0.15 |
| 20 | 0.42 | 0.09 |
| 25 | 0.54 | 0.07 |

## A.2: Alternative specification of exponential model with structural break in 1969 – US TFP

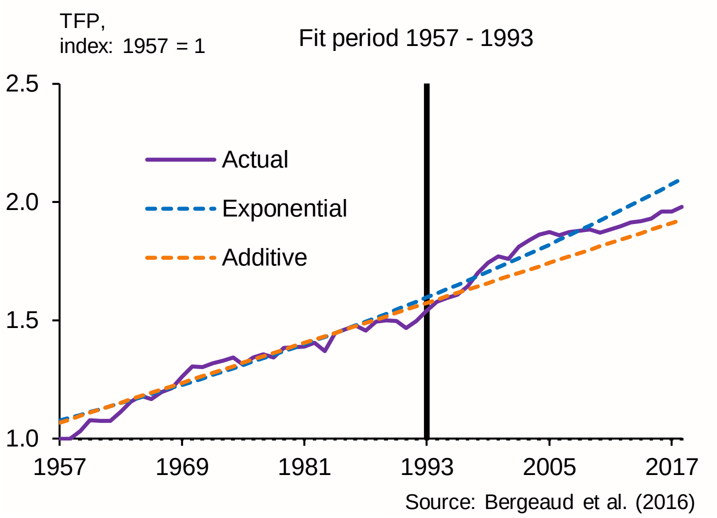
The exponential model for the US estimated over 1947-1983 overshoots TFP by 27 per cent in 2018/2019. The exponential model with a structural break in 1966 undershoots actual TFP by 13 per cent.[10] The additive model is within 2 per cent of actual TFP at the end of the sample.

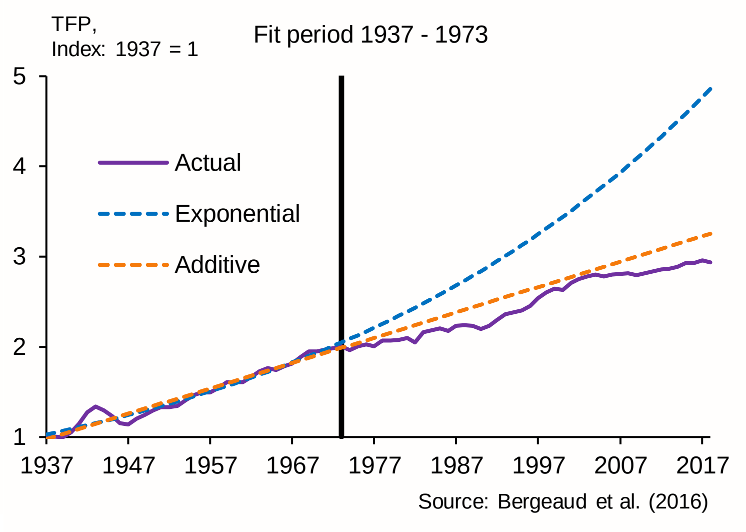



| Model | Additive | Exponential | Exponential with structural break |
|---|---|---|---|
| Root mean square error | 0.06 | 0.39 | 0.25 |

[10] We use the entire post-1947 time series to identify the structural break with a Bai-Perron test.

## A.3: Additive vs exponential model under different sample periods, TFP levels




## A.4: Forecasting labour productivity

We forecast labour productivity under the exponential model using Equation 2. For the additive model, we start with the standard production function:

$$Y = AK^{\alpha}L^{1-\alpha}$$

Re-write in intensive units, defining labour productivity as $\lambda_t$:

$$\lambda_t \equiv \frac{Y_t}{L_t} = \frac{A_t K_t^{\alpha} L_t^{1-\alpha}}{L_t} = A_t\left(\frac{K_t}{L_t}\right)^{\alpha} = A_t k_t^{\alpha}$$

So how can we forecast labour productivity? Using ^ to denote a forecast:

$$\hat{\lambda}_t = \hat{A}_t \hat{k}_t^{\alpha}$$

The linear growth model gives us (from Equation 3):

$$\widehat{\lambda_t} = (\hat{a} + \hat{b}t)\,\hat{k}_t^{\alpha}$$

We need a way to forecast $\hat{k}_t$. The standard neoclassical model says that the user cost of capital ($\chi$) is equated with the marginal product of capital, i.e.:

$$\chi \equiv \frac{\partial Y}{\partial K}$$

$$\chi = \alpha A K^{\alpha-1}L^{1-\alpha}$$

$$\frac{1}{A}\frac{\chi}{\alpha} = \left(\frac{K}{L}\right)^{\alpha-1}$$

$$\frac{\alpha}{\chi}A_t = k_t^{1-\alpha}$$

This condition says that the inverse marginal product of capital (IMPK) grows proportionally with A. Therefore, under the additive model we have:

$$E[k_t^{1-\alpha}] = \hat{a}_{impk} + \hat{b}_{impk}t$$

It is straightforward to plug this back into our labour productivity forecast:

$$\hat{\lambda}_t = (\hat{a} + \hat{b}t)(\hat{a}_{impk} + \hat{b}_{impk}t)^{\frac{\alpha}{1-\alpha}}$$

## A.5: Spillovers from R&D spending

Philippon uses the semi-endogenous growth model of Jones (2021a) to make explore this implication. In this model people are employed either in production (L) or research (R). The labour resource constraint is therefore:

$$R + L = N$$

The simplified production function (ignoring capital) is:

$$Y = AL$$

Jones assumes an exogenous labour allocation between production and research, where $\kappa < 1$:

$$R = \kappa N$$

Therefore, output per capita can be defined as:

$$y = \frac{Y}{N} = \frac{AL}{N} = \frac{A(N-R)}{N} = \frac{AN - AR}{N} = A\left(1 - \frac{R}{N}\right) = A\left(1 - \frac{\kappa N}{N}\right) = (1-\kappa)A$$

This establishes the main result, which is that growth in per capita output ($y$) depends fundamentally on growth in A. We have two competing processes for A, Philippon's additive model, which implies:

$$\frac{dA}{dt} = \Gamma(R)$$

And the standard constant growth model, which instead implies:

$$\frac{dA}{dt} = \Gamma(R)A_t$$

The key difference is in the strength of inter-temporal spillovers. Consider a one-time deviation from a constant $\Gamma(R)$ so that research output increases by an arbitrarily small amount $\epsilon$ from $t_0$ to $t_0 + \Delta$. At any point $t > t_0 + \Delta TFP$ becomes:

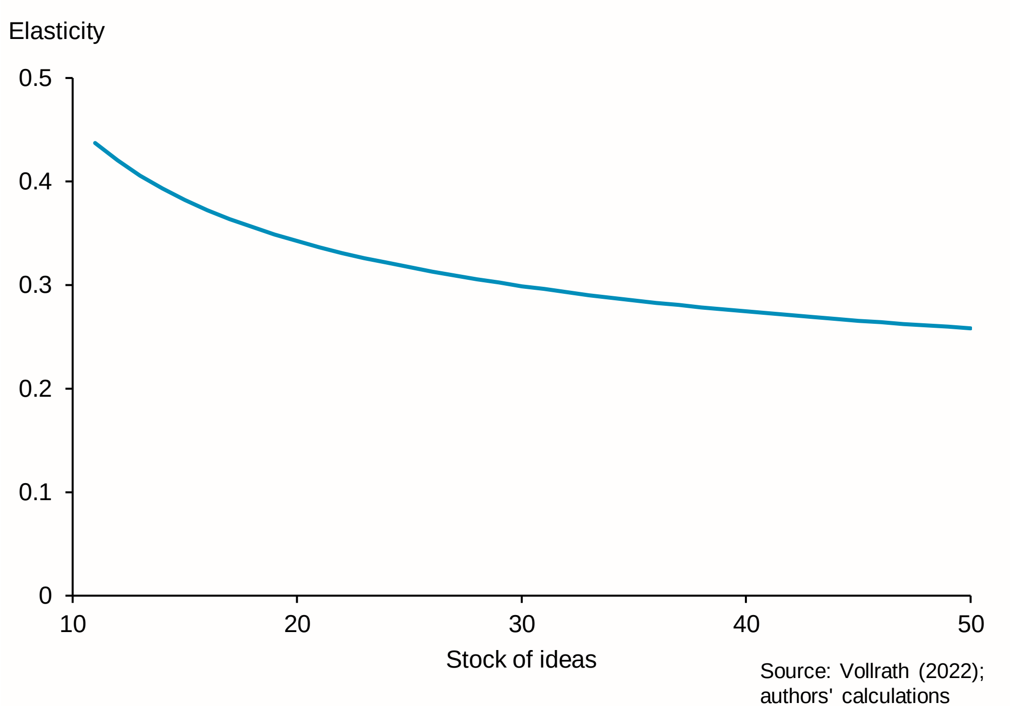
- $A_t = A_{t_0} + \Gamma(R)(t - t_0) + \epsilon\Delta$ under additive growth
- $A_t = A_{t_0}^{\Gamma(R)(t-t_0)+\epsilon\Delta}$ under exponential growth

In the exponential model, the impact on future productivity of a small change at $t_0$ becomes infinitely large as we extend the time horizon. In the paper, this is modelled as the 0.01 point starting difference in TFP levels between Country A and Country B.

Vollrath's (2022) explores the link between TFP and ideas in more mathematical detail. Here we reproduce a key result, which is that under logarithmic diminishing returns, the elasticity of TFP with respect to ideas is:

$$\frac{dA}{dI} \times \frac{I}{A} = \frac{1}{A}$$

Where $I$ is the stock of ideas. Normalising the initial stock of ideas to 10 and the starting level of A to 1, we can show visually how the elasticity falls as TFP rises:



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## Further information and contacts

52 Martin Place

Sydney NSW 2000

GPO Box 5469

Sydney NSW 2001

W: treasury.nsw.gov.au