Uncertainty and the Dynamics of R&D

By NICK BLOOM*

Uncertainty about future productivity and demand conditions varies strongly over time, rising by 50 percent to 100 percent during recessions and by 100 percent to 200 percent after major political and economic shocks.[1] These fluctuations in uncertainty appear to generate fluctuations in investment, hiring, and productivity, because higher uncertainty generates a temporary slowdown as firms postpone activity and wait for uncertainty to resolve (Bloom 2006).

Research and development (R&D), which has become a focus of recent business cycle models (Diego Comin and Mark Gertler, 2006), is omitted from this analysis. R&D may respond differently to uncertainty because of different adjustment costs. Investment in the capital stock typically incurs *stock* adjustment costs from changing the capital stock, while investment in the knowledge stock typically incurs *flow* adjustment costs from changing the flow rate of new knowledge from R&D (see Section I). I show that these different adjustment costs lead to different predicted dynamics under uncertainty, including making R&D rates much less responsive to business conditions and more persistent over time at higher uncertainty.

These adjustment costs and uncertainty effects can help explain the high persistence of R&D across time, which at the firm level is about three times more autocorrelated than investment. They may also help explain why, across business cycles, R&D is highly persistent and responds to recessions with a lag. The higher uncertainty

in downturns will reduce the responsiveness of R&D, delaying its response to worsening business conditions. Finally, the results imply firms will be much less responsive to technology policies during periods of high uncertainty, for example, during recessions.

I. Time Varying Uncertainty with Stock and Flow Adjustment Costs

The traditional real options models assumed time constant uncertainty in order to derive analytical solutions (for example, Avinash K. Dixit and Robert S. Pindyck 1994 or Andrew B. Abel and Janice C. Eberly 1996). They assumed some driving process, for example, price (P), evolved as a Geometric Brownian motion with a constant drift μ and constant volatility σ:

$$(1) \qquad dP_t = P_t(\mu + \sigma dW_t),$$

where $dW_t \sim \mathcal{N}(0, 1)$.

Since volatility is fixed, investigating the impact of time varying fluctuations in uncertainty is not possible in these models.

A small literature has tried to extend these models to incorporate time varying uncertainty (σ_t). It finds *temporary* increases in uncertainty cause a drop and rebound in investment, employment, and productivity growth due to a "delay effect" which can be summarized as $dI_t/d\sigma_t < 0$. At high levels of uncertainty, firms postpone making decisions so aggregate investment and employment activity slows down. Productivity growth also slows down as reallocation of factors of production from low to high productivity firms slows.[2] Higher uncertainty also induces a "caution effect," whereby firms are less responsive to any given shock because higher uncertainty increases the chances of making a costly mistake, so responsiveness is lower (Bloom,

[1] William G. Schwert (1989) shows that uncertainty over future industrial production, stock, and bond prices fluctuate over the business cycle, increasing by 50 percent to 100 percent in recessions. Bloom (2006) shows stock market volatility jumps 100 percent to 200 percent after economic and political shocks like the Cuban Missile Crisis, the assassination of President John F. Kennedy, and the 9/11 terrorist attacks.

[2] See Ben S. Bernanke (1983) and John A. Hassler (1996) for a single agent and factor model, and Bloom (2006) for a micro to macro multifactor model and empirical evidence.

Stephen R. Bond, and John Van Reenen 2007), which can be summarized as $\partial^2 I_t/\partial P_t \partial \sigma_t < 0$.

These extensions, however, have yet to examine the impact of time varying uncertainty on R&D and the knowledge stock.

In the productivity and innovation literature, the knowledge stock (G_t) is usually modeled as the accumulation of R&D expenditures (R_t) over time, in a similar way that capital stocks (K_t) are modelled as the accumulation of investment expenditures (I_t) over time:

$$(2) \qquad K_{t+1} = (1 - \delta_K)K_t + I_t,$$

$$(3) \qquad G_{t+1} = (1 - \delta_G)G_t + R_t.$$

Although uncertainty and real options are not modeled, one could speculate that R&D will be affected in the same way by uncertainty as investment. But, this turns out not to be true due to the different adjustment costs for capital and knowledge stocks.

Capital stock adjustment costs are typically assumed to arise from direct changes to their stocks, for example, from resale losses for capital goods. This can be written as

$$(4) \qquad C_K(I_t) \approx C_K(\Delta K_t).$$

Knowledge stocks, however, are intangible and typically cannot be bought or sold. Instead, knowledge stocks are adjusted (more slowly) by changing the level of R&D, which changes the growth rate of the knowledge stock. The adjustment costs for R&D, for example resale losses on R&D equipment or scientists' hiring/firing costs, are similar to the adjustment costs for capital in that they depend on the change in R&D levels. Given the law of motion for the knowledge stock (3), this implies

$$(5) \qquad C_G(\Delta R_t) = C_G(\Delta\Delta G_t - \delta_G\Delta G_t)$$

$$\approx C_G(\Delta\Delta G_t).$$

Comparing (4) to (5), the adjustment costs for the knowledge stock are one order of difference apart from the adjustment cost for the capital stock. This distinction arises because the costs of adjustment for capital arise directly from changing its stock. The costs of changing knowledge stocks arise not from changing its stock, but from changing the rate of change of its stock (R&D). Thus, adjustment costs arise in changing the *level* of the capital stock and changing the *flow* rate of the knowledge stock. This distinction plays a critical role in shaping the response of investment and R&D to uncertainty.

Interestingly, in the macro literature a number of recent papers (Lawrence J Christiano, Martin Eichenbaum, and Charles L. Evans 2005, for example) assume a *flow* cost for changing investment rates between periods, $C_K(\Delta I_t)$. Under these assumptions, my results for R&D would extend to capital in these models.

II. Simulation Results for R&D and Uncertainty

Firms are uncertain about future business conditions (X), which evolve as a geometric random walk with mean μ and stochastic volatility σ_t:

$$(6) \qquad dX_t = X_t(\mu + \sigma_t dZ_t),$$

where $dZ_t \sim \mathcal{N}(0,1)$.

The uncertainty process (σ_t) is modeled for simplicity as an AR(1) process, consistent with smooth business-cycle fluctuations, noting this could easily be generalized:

$$(7) \qquad \sigma_t = \sigma_{t-1} + \rho_\sigma(\sigma^* - \sigma_{t-1}) + \sigma_S S_t,$$

where $dS_t \sim \mathcal{N}(0,1)$.

There are adjustment costs for changing R&D. In the baseline model these are assumed to be linear, reflecting the hiring/firing costs for scientists and buying/selling costs for R&D equipment, $C(\Delta R_t) = \kappa|\Delta R_t|$, where $\kappa > 0$. I also present results for quadratic adjustment costs for comparison, $C(\Delta R_t) = \kappa_Q G_t(\Delta(R_t/G_t))^2$, where $\kappa_Q > 0$. In the model, I assume the adjustment costs for capital and labor are zero for analytical tractability, and focus on the implications of R&D adjustment costs. This should not change the stylized results for R&D because in a Cobb-Douglas production function with isoelastic demand, each factor responds most to its own adjustment costs, with limited cross-factor response.[3]

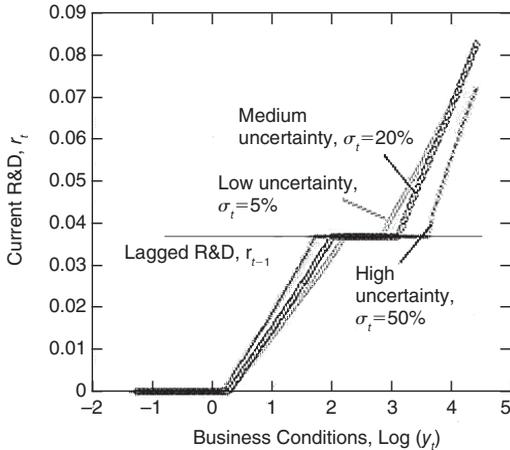[3] See the tables of results in Bloom (2006).

Figure 1. Higher Uncertainty Makes R&D Less Responsive to Current Business Conditions and More Persistent over Time

Notes: Figures plot the numerical solution to the firm's optimization problem. The control variable, current R&D (r_t), is a function of the three state variables: lagged R&D (r_t), current business conditions (y_t), and the uncertainty over future business conditions (σ_t).

Analytical results can show that a unique solution to the firm's optimization problem exists, with numerical methods used to solve for exact values.[4]

Figure 1 plots the optimal rates of R&D as a function of current business conditions for low uncertainty ($\sigma_t = 5$ percent), medium uncertainty ($\sigma_t = 20$ percent), and high uncertainty ($\sigma_t = 50$ percent). There are two key results from the simulation.

First, the adjustment costs for changing R&D generate a zone of inaction in the response of R&D to changes in business (demand and productivity) conditions. Given the costs of changing R&D rates, firms incur this only when the gap between the actual and desired R&D rate is above a certain threshold, generating a central region of inaction. This creates a dynamic link between current and past R&D rates, consistent with the empirical evidence that R&D rates change slowly over time, and are more persistent

than sales growth, employment growth, or investment rates.[5]

Second, the zone of inaction is larger for higher values of uncertainty, and the response is more muted when it does occur. This is the "caution effect" of uncertainty on R&D behavior. When uncertainty is high, the probability of business conditions changing is greater, and, since it is costly to change R&D rates, the option value of waiting is greater.

Figure 2 plots the optimal rates of R&D expenditures at low, medium, and high uncertainty for low prior values of R&D and high prior values of R&D.[6] The key result is that the direct impact of uncertainty depends on the difference between optimal R&D and lagged R&D. If optimal R&D is higher than lagged R&D (the right side of A and B), so that firms want to raise R&D, then higher uncertainty reduces R&D, producing a negative delay effect. If optimal R&D is below lagged R&D (the left side of A and B), so the firms want to cut R&D, then higher uncertainty increases R&D, producing a positive delay effect. Thus, the impact of the delay effect depends on the relationship between desired R&D and lagged R&D.

Of course, if R&D depreciates over time (due to scientists quitting and equipment wearing out), then temporary increases in uncertainty will reduce R&D at the steady state. This is because the inherited level of R&D will have depreciated below the optimal level. This is similar to the reasoning behind the negative steady state delay effect of uncertainty on investment and hiring, which arises because depreciation, attrition, and growth mean inherited capital and labor are always below their optimal levels.

Figure 3 plots the optimal rates of R&D expenditure for low, medium, and high uncertainty assuming only quadratic adjustment costs

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[4] The full model and code are available on http://www.stanford.edu/~nbloom.

[5] For example, in Compustat data (1990 to 1999, manufacturing), the correlation between current and two-year lagged sales growth rates is 0.082, compared to 0.095 between current and two-year labor growth rates, 0.274 between current and two-year investment rates, and 0.690 between current and two-year R&D rates. The aggregate figures show a similar pattern (Diego Comin and Mark Gertler 2006).

[6] These values are 1.875 percent and 7.5 percent, chosen as half and twice the steady-state rate of R&D expenditure, $r_t = R_t/G_t$, given the 15 percent depreciation in G_t and quarterly periodicity.
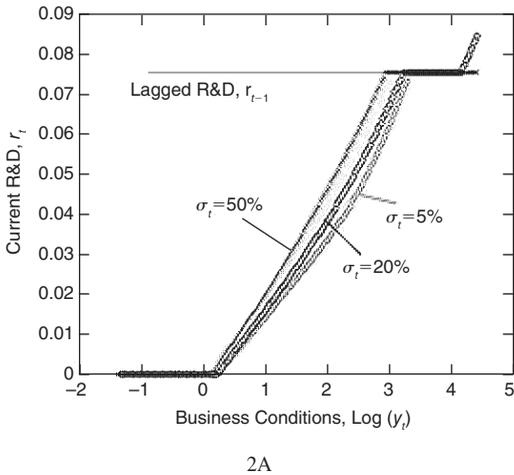
2A
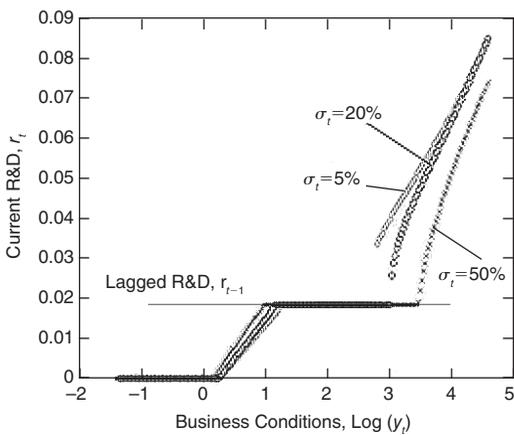
2B

FIGURE 2. THE EFFECT OF UNCERTAINTY ON R&D IS NEGATIVE IF R&D IS INCREASING, AND POSITIVE IF R&D IS FALLING

Notes: Figures plot the numerical solution to the firm's optimization problem. The control variable, current R&D (r_t), is a function of the three state variables: lagged R&D (r_t), current business conditions (y_t), and the uncertainty over future business conditions (σ_t).

for R&D. The effects of uncertainty almost completely disappear. With quadratic adjustment costs, no real options effects arise, and the assumed homogeneity on revenue function in demand conditions and knowledge stocks minimizes any Jensen's effects from a concave/convex marginal revenue product of R&D in demand conditions. Hence, the impact of uncertainty on R&D depends critically on the

adjustment costs for R&D, for which empirical evidence is very limited.

III. Implications of Uncertainty for Micro and Macro R&D

At the micro level the "caution effect" of uncertainty on R&D implies much lower responsiveness of firms in periods of high uncertainty. This could explain why, for example, US firms have been so slow to respond to the R&D tax credit, a policy beset by continued uncertainty over its survival (Bloom, Rachel Griffith, and Van Reenen 2002). This could be investigated by estimating (with appropriate instrumentation) the following type of regression:[7]

$$(8) \quad r_{i,t} = \alpha_0 + \beta_1 r_{i,t-1} + \beta_2 \Delta y_{i,t} + \beta_3 s_{i,t}$$

$$+ \beta_4 r_{i,t-1} \sigma_{i,t} + \beta_5 \Delta y_{i,t} \sigma_{i,t}$$

$$+ X_{i,t} + \varepsilon_{i,t},$$

where $r_{i,t}$ is firm i year t (R&D/sales), $y_{i,t}$ is firm i year t log (sales), and $X_{i,t}$ are a full set of controls including fixed effects and year dummies. The empirical implication from Section II is that higher uncertainty should reduce the responsiveness of firms to sales growth ($\beta_5 < 0$) and increase the responsiveness to lagged R&D expenditure ($\beta_4 > 0$).

At the macro level the delay effect of uncertainty on R&D is highlighted in Table 1, with uncertainty effects on investment in Table 2 for comparison. The two columns in Table 1 reflect the result that higher uncertainty increases R&D if the current period R&D is a downward adjustment ($R_t < R_{t-1}$), and reduces R&D if the current period R&D is an upward adjustment ($R_t > R_{t-1}$).

In contrast, Table 2 shows that lagged investment plays no role in determining current investment. Instead, comparing across the two rows shows that uncertainty increases current investment if the capital stock is

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[7] Micro data are particularly suitable for testing the "caution effect" because of the large samples of impulses and responses in firm panel data. Macro data are particularly suitable for testing the "delay effect" because of the role of reallocation across firms in driving the productivity component of the "delay effect," which arises only under aggregation.
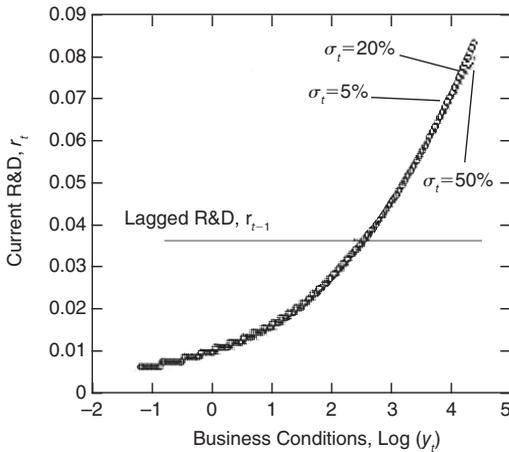
FIGURE 3. WITH ONLY QUADRATIC ADJUSTMENT COSTS THERE ARE NO REAL OPTIONS EFFECTS OF UNCERTAINTY ON R&D

Notes: Figures plot the numerical solution to the firm's optimization problem. The control variable, current R&D (r_t), is a function of the three state variables: lagged R&D (r_t), current business conditions (y_t), and the uncertainty over future business conditions (σ_t).

TABLE 1—THE MARGINAL IMPACT OF AN INCREASE IN UNCERTAINTY ON R&D

	R&D decreasing*	R&D increasing
Knowledge stock decreasing	+	−
Knowledge stock increasing	+	−

* If R&D rates depreciate at rate δ_R, the condition is $R_t < (1 - \delta_R)R_{t-1}$.

TABLE 2—THE MARGINAL IMPACT OF AN INCREASE IN UNCERTAINTY ON INVESTMENT

	Investment decreasing*	Investment increasing
Capital stock decreasing	+	+
Capital stock increasing	−	−

* After controlling for depreciation, $K_t < (1 - \delta_K)K_{t-1}$.

decreasing after controlling for depreciation ($K_t < (1 - \delta_K)K_{t-1}$), and reduces it if capital stock is increasing ($K_t > K_{t-1}$).

Thus, this implies uncertainty would reduce R&D when it is *increasing*, typically during the recovery from a recession and initial part of a boom. In comparison, it would reduce investment when capital is *above trend*, typically during a boom. In addition, higher uncertainty will tend to increase the persistence of R&D changing its *dynamics*, but reduce the responsiveness of investment changing its *amplitude*. Thus, uncertainty will have a differential impact on the levels and dynamics of R&D versus investment due to different *flow* versus *stock* adjustment costs.

IV. Conclusions

Uncertainty varies strongly over time, persistently rising by 50 percent to 100 percent during recessions, and temporarily rising by 100 percent to 200 percent after major political and economic shocks. The impact of these changes in uncertainty on investment and hiring appears to be twofold. First, higher uncertainty typically reduces aggregate investment, hiring, and pro-

ductivity growth due to a "delay effect." Second, higher uncertainty makes firms less responsive to any changes in their environment, a "caution effect." These effects have been shown to be analytically and empirically important in micro and macro investment and employment behavior.

This paper extends these results on time varying uncertainty to R&D by modeling the *flow* adjustment costs of knowledge stocks and contrasting this to the *stock* adjustment costs of capital and labor. I show that higher uncertainty reduces the responsiveness of R&D to changes in demand conditions and increases the persistence of R&D over time, the R&D equivalent to the "caution effect." I also show that if firms are increasing R&D, then the marginal effect of uncertainty on R&D will be negative, while if firms are reducing R&D, then the marginal effect of uncertainty on R&D will be positive. Thus, the R&D equivalent to the delay effect depends on the desired change in R&D. I then present micro and macro predictions, with the hope that future empirical research will make progress in testing these.

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