R&D with Correlation and Learning

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September 19, 2019

Motivation

- Combating climate change requires long-term investment in a diverse set of technologies
- How should we allocate R&D resources over time and among technologies?
  - Policy interest: Mission Innovation ($30b), Breakthrough Energy Venture ($22b), DoE ($8b), etc.
- How have governments allocated R&D resources?
  - Lessons for climate R&D funding

This Paper

1. How do government R&D programs optimally allocate funding across projects and over time?
    - Theory: a simple model of dynamic decision making with 1) correlations in R&D outcomes among projects and 2) gradual resolution of the deployment benefit
2. How are we doing in practice?
    - Empirics: test how effectively DoE has allocated funding among nuclear energy R&D programs
        - Program-level R&D funding data from Abdulla et al. (2017)
        - To be combined with text data and contextual knowledge

Literature

- Theory:
  - Markowitz (1952), Gibbons, Ross & Shanken (1989)
  - Roberts & Weitzman (1981), Pindyck (2002)
  - This paper: a simple multi-stage R&D allocation model
- Empirics:
  - Effect of government R&D on energy patents or publication: Johnstone et al. (2010), Verdolini & Gaelotti (2011), Peters et al. (2012), Dechezleprêtre & Glachant (2014), Nesta et al. (2014), Costantini et al. (2015), Popp (2016)
  - Determinants of government R&D effectiveness: Wuchty et al. (2007), Costantini et al. (2015), Canter et al. (2016), Popp (2017), Fabrizi et al. (2018)
  - Simulation based on expert elicitation: Anadon et al. (2016), Verdolini et al. (2018)
  - This paper: testing allocative efficiency of government nuclear energy R&D based on program-level data

Outline

- Conceptual Model
    1. One technology
    2. Two technologies with correlations
    3. One technology with learning
- Data Source

One Technology

$t = 1$: invest $x \geq 0$ in R&D given R&D effectiveness $a > 0$
$t = 2$: R&D succeeds with probability $P(x, a) \in [0, 1]$

- If it succeeds: deploy technology at intensity $y \geq 0$, paying cost $C(y) \geq 0$ and receiving benefit $B(y) \geq 0$
- If it fails: do nothing, $C(0) = 0$, $B(0) = 0$

Social planner's problem:

$$\max_{x,y \geq 0} P(x, a)(B(y) - C(y)) + (1 - P(x, a)) \times 0 - x$$

Parametrization:

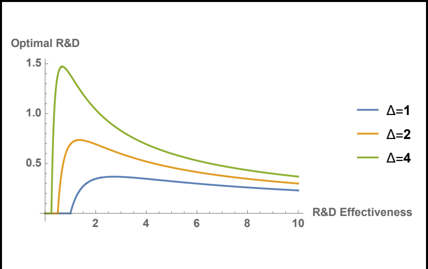
$$B(y) = \frac{y}{1+y}\gamma, \quad \gamma > 0$$
$$C(y) = ky, \quad k \in (0, \gamma]$$
$$P(x, a) = 1 - \exp(-ax)$$

$$\text{Optimal deployment: } y^* = \sqrt{\frac{\gamma}{k}} - 1$$

$$\text{Net deployment benefit: } \Delta \equiv (\sqrt{\gamma} - \sqrt{k})^2$$

$$\text{Optimal R\&D: } x^* = \frac{1}{a}\ln(a\Delta)$$

$$\text{Value of R\&D: } V = \Delta - \frac{1}{a} - x^*$$



Two Technologies

Parametrization:

$$B(y_1, y_2) = \frac{y_1 + y_2}{1 + y_1 + y_2}\gamma$$

$$C(y_1, y_2) = k_1 y_1 + k_2 y_2, \quad 0 < k_1 < k_2 \leq \gamma$$

$$\Pr(d_1 = 0, d_2 = 0 | x_1, x_2) = \mu$$

$$\Pr(d_1 = 1, d_2 = 0 | x_1, x_2) = 1 - p_2 - \mu$$

$$\Pr(d_1 = 0, d_2 = 1 | x_1, x_2) = 1 - p_1 - \mu$$

$$\Pr(d_1 = 1, d_2 = 1 | x_1, x_2) = p_1 + p_2 + \mu - 1$$

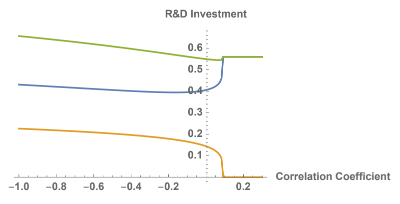
with

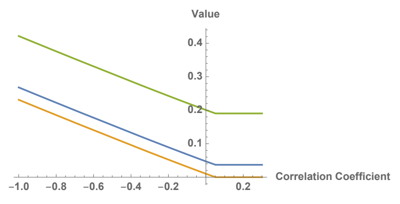
$$p_i \equiv P(x_i, a_i) = 1 - \exp(-a_i x_i) \qquad i = 1, 2$$

$$\mu = (1 - p_1)(1 - p_2) + \rho\sqrt{p_1 p_2 (1 - p_1)(1 - p_2)}$$

where $\rho \in [-1, 1]$ is the correlation coefficient of the two technologies' R&D outcomes.

Two Technologies with Correlation





(Blue - cheap tech; Orange - expensive tech; Green - total)

One Technology with Learning

$t = 1$: invest $x_1 \geq 0$ in R&D while facing uncertain γ

$t = 2$: with probability $p \in [0, 1]$, $\gamma \geq k$; otherwise, $\gamma < k$

- if last-period R&D succeeds, do nothing this period
- if it fails, can invest again this period

$t = 3$: Deploy the technology if it is deployable

Social planner's problem:

$$P(a, x_1)p\Delta + (1 - P(a, x_1))p[P(a, x_2)\Delta - x_2] - x_1$$

Hence:

$$x_1^* = \frac{1}{a}\ln[p(1 + \ln(a\Delta))]$$

$$x_2^* = \frac{1}{a}\ln(a\Delta)$$

$$V = p\Delta - \frac{1}{a} - x_1^*$$

Compare with Dixit and Pindyck

Without R&D uncertainty:

- Dixit and Pindyck (1994): wait until the benefit uncertainty resolves
  - Suppose investment $I > 0$ will surely bring R&D success
  - If invest at $t = 2$, get larger expected value:

$$p[(\sqrt{\gamma} - \sqrt{k})^2 - I]$$

  - If invest at $t = 1$, get smaller expected value:

$$p(\sqrt{\gamma} - \sqrt{k})^2 - I$$

With R&D uncertainty:

- invest right away iff $p(1 + \ln(a\Delta)) > 1$

What Have We Learned from This Toy Model?

#1 Need to diversity the portfolio

#2 Cannot wait until we know the benefit better (under some conditions)

Empirical Exercise: Testing Allocative Efficiency of the DoE Nuclear Energy Programs

Abdulla et al. (2017):

- Obtained annual budget justification documents from DoE through a Freedom of Information Act and constructed a database that traced both funding levels and project names and designations from 1999-2015

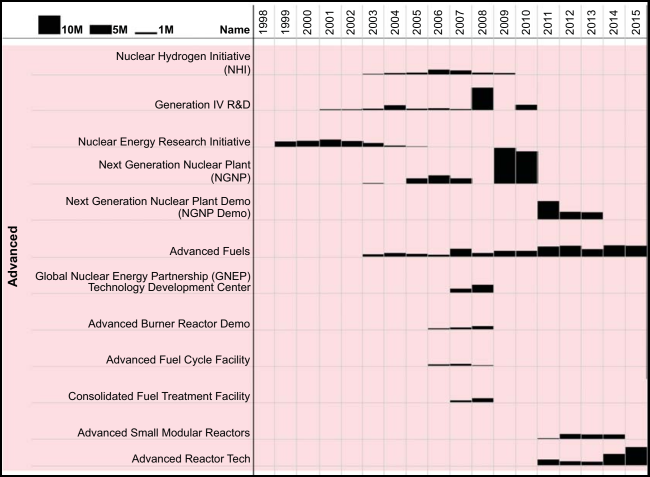


Figure 1: Part I of data from Abdulla et al. (2017)

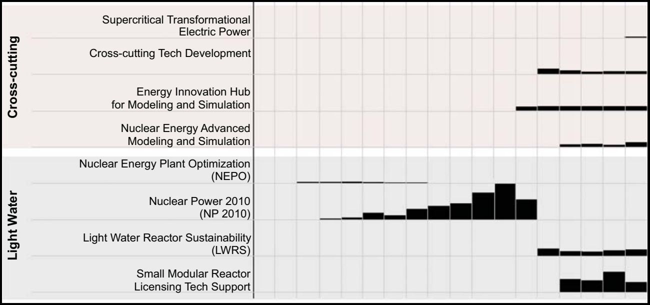


Figure 2: Part II of data from Abdulla et al. (2017)