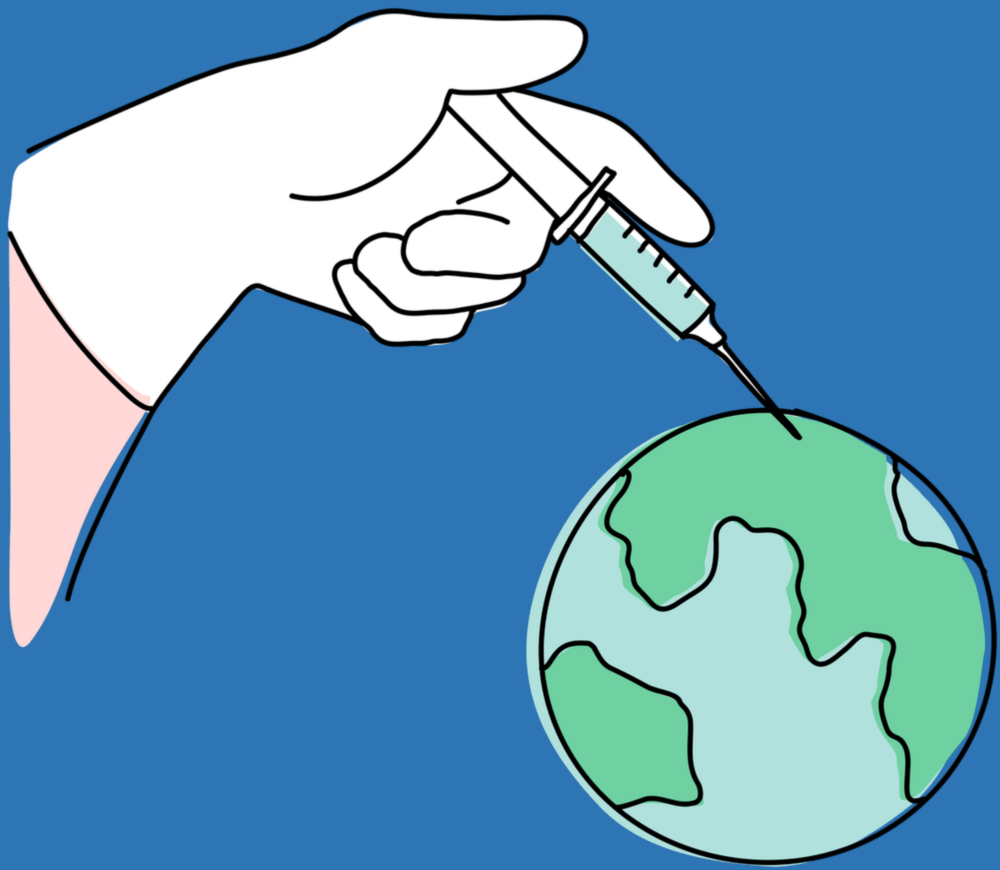
Vaccine Supply Chain Resilience and International Cooperation



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Introduction

- **Motivation**
  - Enormous global harm from Covid-19 pandemic each month
  - Social value from accelerating delivery of effective vaccines in pandemic
  - Scale of vaccine capacity
  - At-risk capacity investment
  - Public vs. private incentives
  - Sense that supply chains, international issues important, but little formal analysis

- **Background facts**
  - Extensive outsourcing of inputs but limiting offshoring
  - Widespread complaints about input shortages
  - Operation Warp Speed at-risk funding, Defense Production Act supply-chain contracts
  - Concerns about export restrictions (India vs. US, UK threat vs. EU)

- **Theoretical analysis**
  - Build simple, easily extensible model
  - Study optimal public incentives offered to pharma firms investing in vaccine capacity
  - See how answers change if vaccines and inputs offshored

- **Calibrations**
  - Determine which identified distortions are large, if any

Main Findings

- **Conditions for government subsidy of at-risk investment**
  - High disease harm relative to production cost
  - Long capacity lag
  - High likelihood of success
  - Low contractual frictions (social cost of public funds, variance of private information)

- **Offshoring exacerbates distortions**
  - Government internalizes less of foreign firm profit
  - Lower-power incentives to restrain information rents leaking to foreign suppliers
  - Export restriction threatens to hold up subsidy
  - Potentially enormous direct losses from vaccine supply being cut off

- **International cooperation**
  - Ban export restrictions
  - Encourage capacity subsidies internalizing externality on foreign firms
  - Distortions may be bad enough to deter otherwise efficient offshoring, hiding distortions because domestic subsidies are conditionally efficient
  - As model sets aside issues of cross-border transmission of disease to focus on international pecuniary externalities, this is a job for the WTO, not the WHO

Model: Players

- **Domestic consumers**
  - Continuum, mass normalized to 1
  - Suffer harm from viral outbreak

- **Firm**
  - Monopoly vaccine producer
  - Upstream establishment U produces vaccine input
  - Downstream establishment D produces final vaccine

- **Domestic government**
  - Procures vaccine from D on behalf of citizens
  - Internalizes surplus of domestic, not foreign, consumers and producers
  - Faces frictions: social cost of public funds, asymmetric information

- **Foreign country**
  - May house U and/or D in variants of model with offshoring
  - May implement export restrictions to keep key supplies for own consumers

Model: Processes

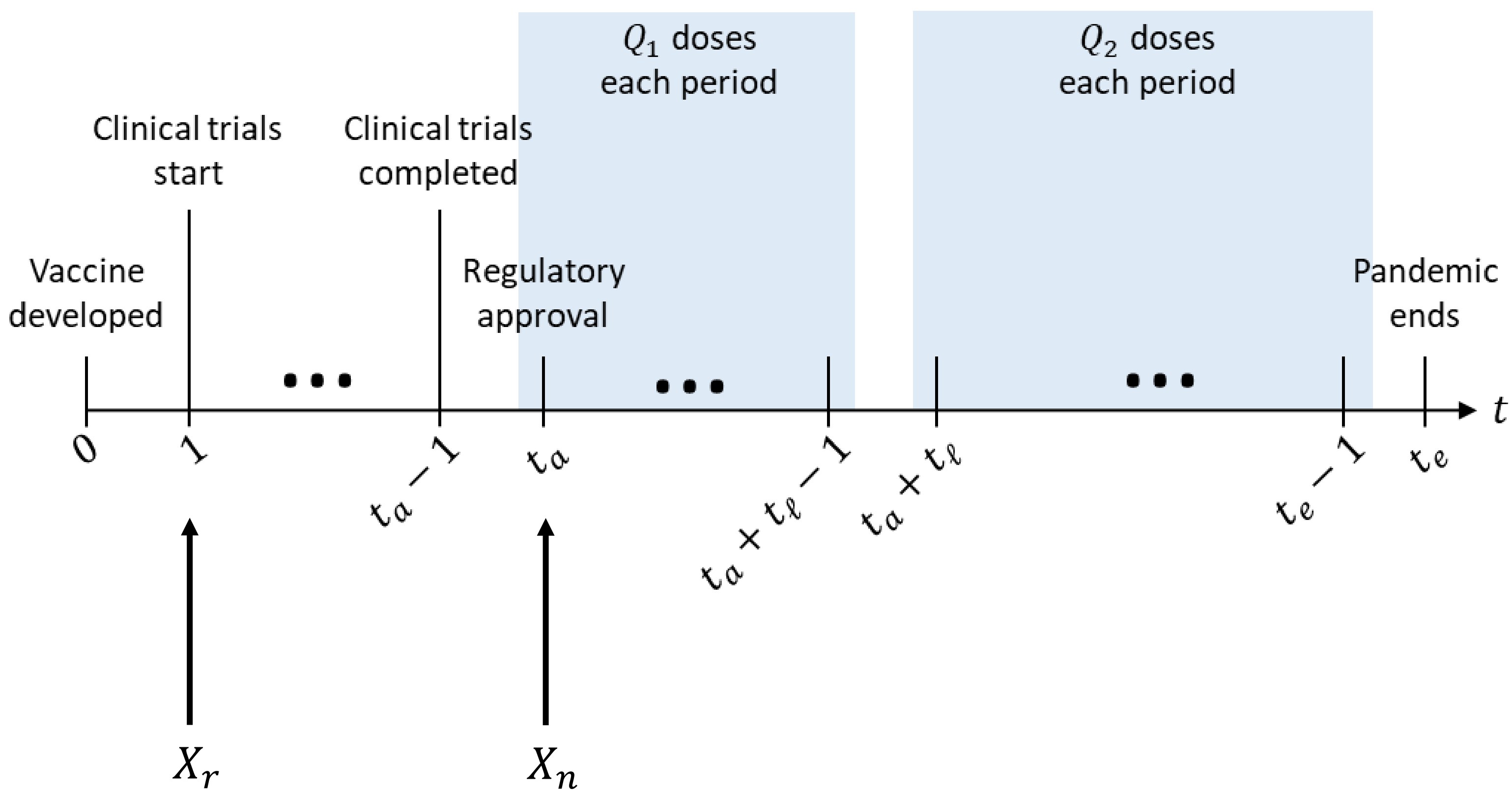
- **Disease epidemiology**
  - Absent vaccine, consumers infected each period with probability β
  - Recover by end of period
  - Social harm h from individual's infection that period
  - Outbreak starts in period 1 and ends by period t_e

- **Vaccine benefits**
  - Prevents (serious) harm, not transmission
  - Effective for individual with probability θ
  - Protection wanes after one period, so need revaccination to continue protection

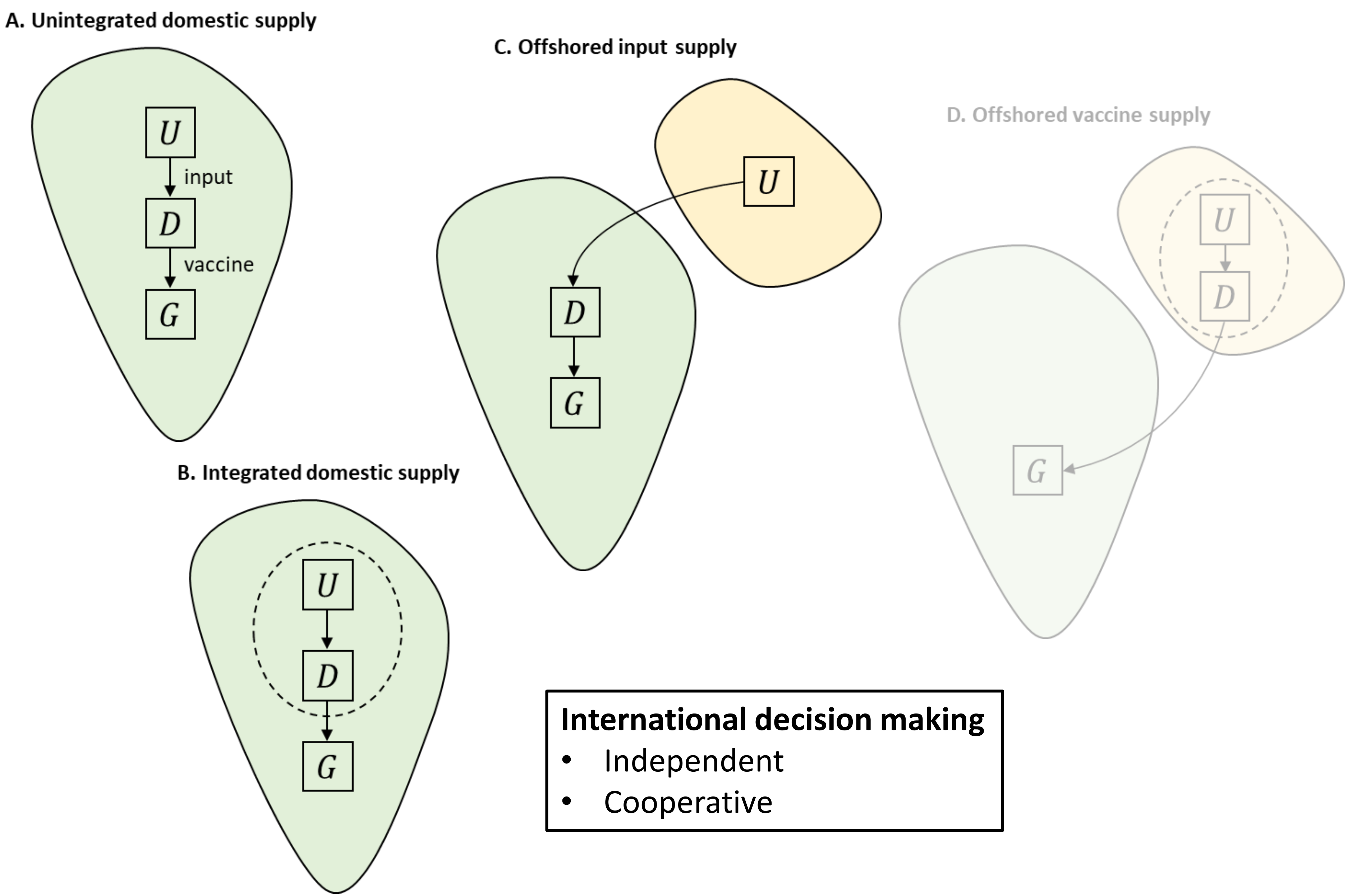
- **Regulatory approval**
  - Clinical trials and health agency decision take time, decision in period t_a
  - Probability of successful approval s

- **Linear production technology**
  - U can produce vaccine input up to available capacity each period
  - Costs k for a unit of vaccine input capacity
  - Capacity installation takes lag of t_ℓ periods
  - Unit production cost c for vaccine input
  - D costlessly transforms input into final vaccine

Model: Timeline



Model: Alternative Structures



International decision making
- Independent
- Cooperative

First Best

- **Setup**
  - Government has full control over firms' operations
  - No social cost of public funds
  - Government has full information about k

- **Components of government surplus**
  - Expected harm avoided $s\beta h\theta Q_1 t_\ell + s\beta h\theta Q_2(t_e - t_a - t_\ell)$
  - Expected production costs $scQ_1 t_\ell + scQ_2(t_e - t_a - t_\ell)$
  - Expected capacity costs $kX_r + skX_n$

- **Optimization problem**

$$\max_{X_r, X_n, Q_1, Q_2 \geq 0} \{s(\theta\beta h - c)[Q_1 t_\ell + Q_2(t_e - t_a - t_\ell)] - kX_r - skX_n\}$$

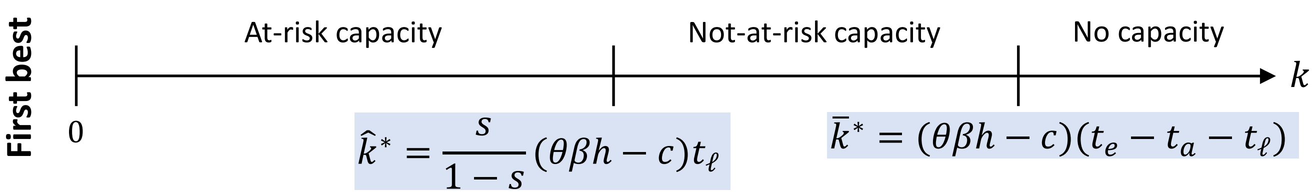
$$\text{s.t.} \quad \begin{aligned} Q_1, Q_2 &\leq 1 \\ Q_1 &\leq X_r \\ Q_2 &\leq X_r + X_n \end{aligned}$$

First Best

- **No excess capacity**
  - $Q_1 = X_r$
  - $Q_2 = X_r + X_n$

- **Corner solution in capacity**
  - Linear programs typically have corner solutions, true here
  - If serve any consumers, serve all
  - If invest in capacity, it is either all at risk or all not at risk

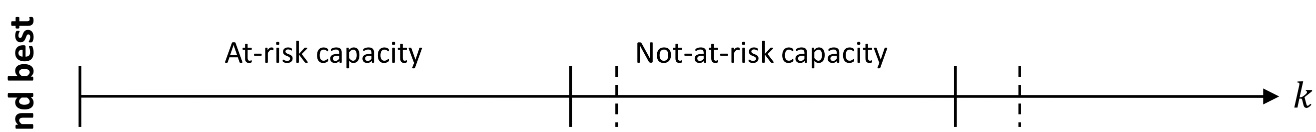
- **Threshold policy**
  - First best simply characterized by capacity-cost thresholds
  - Threshold for at-risk investment $\hat{k}^*$ and any investment $\bar{k}^*$



Second Best

- **Setup**
  - As in first best, government has full control over firm operations and full information
  - Add social cost of public funds $\lambda > 0$ (Laffont & Tirole 1993, Snow & Warren 1995)

- **Solution**
  - Similar corner solution to first best
  - Just scale all vaccine cost terms by $1 + \lambda$
  - In threshold formulas, as if vaccine benefits discounted by reciprocal of $1 + \lambda$



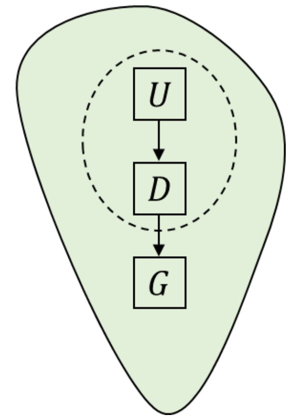
$$\hat{k}^{**} = \frac{s}{1-s}\left(\frac{\theta\beta h}{1+\lambda} - c\right)t_\ell$$

$$\bar{k}^{**} = \left(\frac{\theta\beta h}{1+\lambda} - c\right)(t_e - t_a - t_\ell)$$

Third Best: Domestic Supply

- **Setup**
  - Government has no direct control over firms' operations
  - Must induce supply via procurement contract
  - Faces social cost of public funds
  - Firms have private information about k, random with pdf f and cdf F
  - Assume domestic, integrated firm to start

B. Integrated domestic supply



- **Revelation mechanism**
  - Firm announces type $\tilde{k}$
  - Required to install capacities $X_r(\tilde{k})$ and $X_n(\tilde{k})$
  - Required to produce outputs $Q_1(\tilde{k})$ and $Q_2(\tilde{k})$
  - Paid per-dose bonus price $p_1(\tilde{k})$ for early doses and $p_2(\tilde{k})$ later
  - Paid per-unit capacity subsidies $\sigma_r(\tilde{k})$ and $\sigma_n(\tilde{k})$
  - Truth-telling and participation constraints

- **Solution has simple form**
  - Price set to cover production cost: $p_1(\tilde{k}) \ = p_1(\tilde{k}) = c$
  - For $\tilde{k}$ low, firm fully invests at risk, receiving capacity subsidy σ_r
  - For $\tilde{k}$ moderate, firm fully invests not at risk, receiving capacity subsidy σ_n
  - For $\tilde{k}$ high, firm does not invest

Third Best: Domestic Supply

- **Optimization problem**

$$\int_0^{\hat{k}} \{s[\theta\beta h - (1+\lambda)c](t_e - t_a) - (1+\lambda)\sigma_r + \Pi_r(k)\} f(k)dk$$

$$+ \int_{\hat{k}}^{\bar{k}} \{s[\theta\beta h - (1+\lambda)c](t_e - t_a - t_\ell) - s(1+\lambda)\sigma_n + \Pi_n(k)\} f(k)dk$$

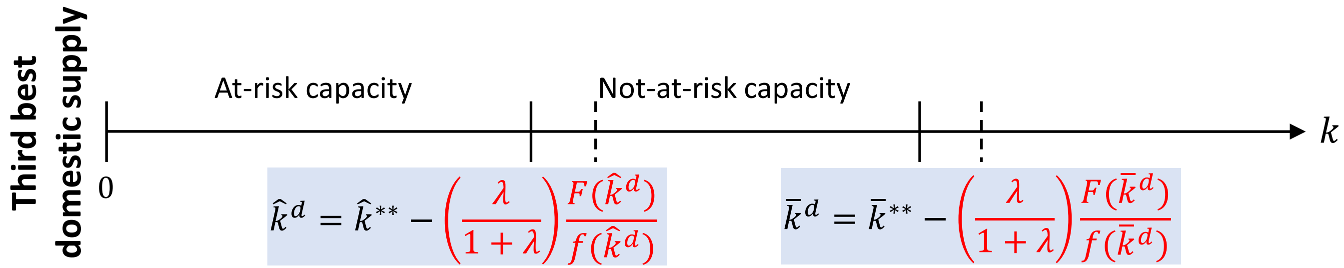
$$s.t. \quad \begin{array}{ll} \Pi_r(k) \geq \Pi_n(k)\ \forall k \in [0, \hat{k}] & \text{(ICR)} \\ \Pi_n(k) \geq \Pi_r(k)\ \forall k \in [\hat{k}, \bar{k}] & \text{(ICN)} \\ \Pi_r(k) \geq 0\ \forall k \in [0, \hat{k}] & \text{(IRR)} \\ \Pi_n(k) \geq 0\ \forall k \in [\hat{k}, \bar{k}] & \text{(IRN)} \end{array}$$

where

$$\Pi_r(k) = \sigma_r - k$$
$$\Pi_n(k) = s(\sigma_n - k)$$

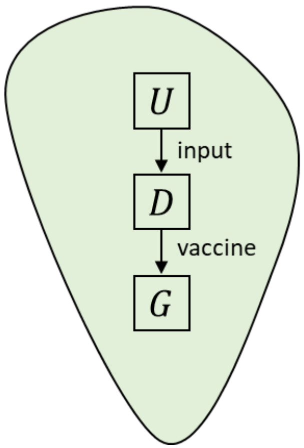
- **Solution**
  - Only two constraints bind: (ICR) for type $\hat{k}$ and (IRN) for type $\bar{k}$
  - Solving simultaneously gives subsidies $\sigma_n = \bar{k}$, $\sigma_r = (1-s)\hat{k} + s\bar{k}$
  - Substitute and take first-order conditions with respect to thresholds

Third Best: Domestic Supply



- **Unintegrated domestic supply**
  - Suppose bargain efficiently over operation decisions
  - Nash bargaining with weights ϕ, $1-\phi$
  - No effect on optimum

A. Unintegrated domestic supply

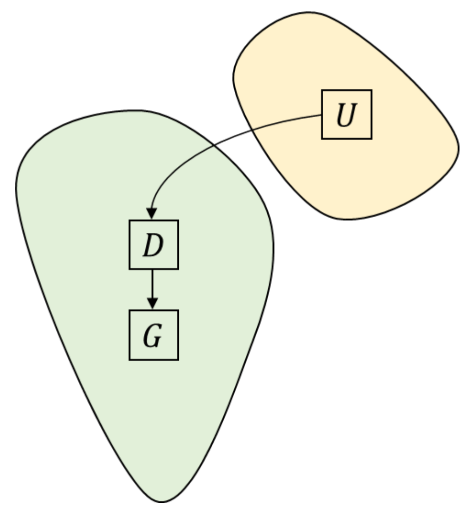


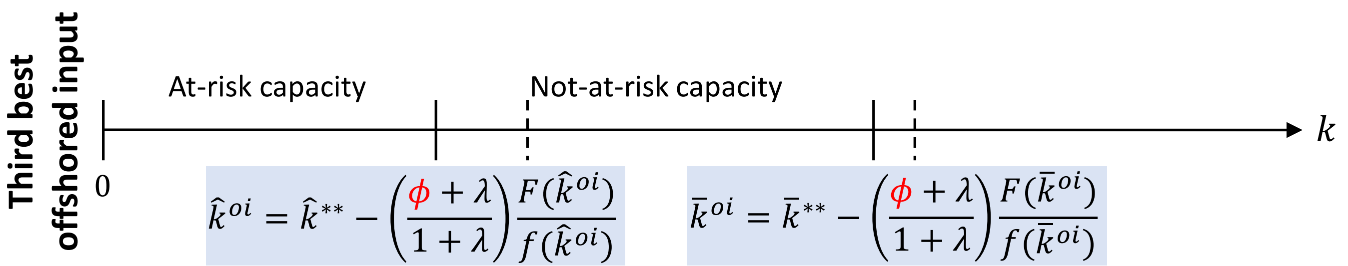
Third Best: Offshored Input

- **Setup**
  - Input supplied by offshore U, final good by domestic D
  - Continue to assume efficient Nash bargaining with weights ϕ, $1-\phi$

- **Economic impact**
  - Government does not internalize profit of foreign establishment
  - Dislikes leakage of information rent to foreign firm even more
  - Effect arises even without social cost of public funds
  - Distorts incentives downward to extract more information rent

C. Offshored input supply

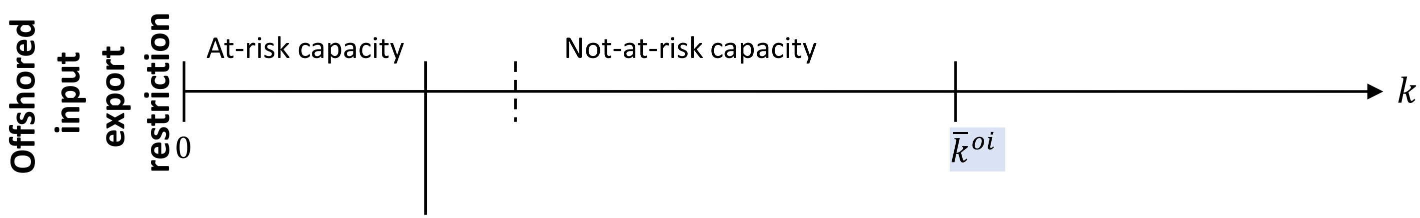




Third Best: Export Restrictions

- **Setup**
  - Return to case of offshored input
  - Assume foreign country can restrict exports to keep supplies for citizens
  - Exogenous probability ξ

- **Economic impact**
  - Creates hold-up problem with government capacity subsidy, firm investment
  - Potentially severe direct effect, cutting off vaccine supply
  - Isomorphic to reduction in probability of success



$$\hat{k}^{oi} = \frac{s(1-\xi)}{1-s(1-\xi)}\left(\frac{\theta\beta h}{1+\lambda} - c\right)t_\ell - \left(\frac{\phi+\lambda}{1+\lambda}\right)\frac{F(\hat{k}^{oi})}{f(\hat{k}^{oi})}$$

Third Best: International Cooperation

- **Setup**
  - Scope for raising global welfare via international cooperation
  - Here, two countries striking agreement to maximize net joint surplus

- **Provisions**
  - Correct two distortions
  - Ban export restrictions: ($\xi = 0$)
  - Not just allow capacity subsidies but encourage them
  - Increase to level as if internalized foreign-firm surplus
  - Achieve third best with domestic sourcing

Third Best: Endogenous Input Location

- **Setup**
  - Up to now, location exogenous
  - Due to historical accident, specialized inputs, comparative advantage
  - Endogenize location
  - Government can effectively dictate location via incentive-contract terms
  - So far, offshoring modeled as only presenting problems
  - Generate tradeoff with production-cost advantage $c - \Delta$ offshore

- **Distortions**
  - If choose offshored inputs, underinvestment due to two distortions
    - Concern about subsidy leakage (ϕ)
    - Concern about export restrictions (ξ)
    - Also potentially large direct effect of export restrictions on vaccine supply
  - If choose domestic sourcing, distortion at the extensive margin
    - Lose production-cost advantage

- **International cooperation**
  - Obvious role if choose offshoring, to correct distortions there
  - Less obvious if choose domestic sourcing since investment conditionally efficient
  - Correct location distortion in that case

Calibrations

Parameter	Definition	Source or note
$t_a = 1$	Approval lag	1 period = 6 months
$t_\ell = 1$	Capacity lag	1 period = 6 months
$t_e = 6$	Pandemic duration	6 periods = 3 years
$\theta = 0.75$	Vaccine efficacy	Ssentongo et al. (2022) *BMC Infectious Disease*
$\lambda = 0.3$	Social cost funds	Snow & Warren (1995) *J Pub. Ec.*
$s = 0.4$	Prob. success	Lo et al. (2020) *Har. Data Sci. Rev.*
$\phi = 0.5$	Foreign bargaining weight	Equal bargaining power
$\xi = 0.5$	Prob. export restriction	Maximum entropy
$N = 250$ mil	Vaccinations	US government seeks 75% coverage
$c = \$10$	Unit production cost	Kazaz et al. (2021) *CGD note*
$\beta h = \$2{,}160$	E(benefit) per course	Snyder et al. (2020) *Health Aff.* $360/month in US
$\mu_k = \$13.4$	Unit capacity cost mean	Snyder et al. (2020) lognormal from CEPI data
$\sigma_k = \$13.6$	Unit capacity cost std. dev.	Snyder et al. (2020) lognormal from CEPI data

Calibrations

Table 1: Calibration Results

Scenario	Probability of investment: At-risk capacity	Probability of investment: Any capacity	Expected net program benefit (bil. $)
First best	0.324	0.604	467
Second best	0.220	0.515	384
Third best domestic vaccine	0.179	0.434	320
Third best foreign input			
• No export restriction ($\xi = 0$)	0.135	0.357	258
• Export restriction ($\xi = 0.5$)	0.011	0.295	125
Third best foreign vaccine			
• No export restriction ($\xi = 0$)	0.107	0.306	217
• Export restriction ($\xi = 0.5$)	0.008	0.257	105

Extensions

- **Progressing**
  - ✓ Linear-price contracts, no private information
  - ✓ Convex capacity costs
  - ✓ Hold-up problem for foreign input supplier a la Antras and Staiger (2012)
  - ✓ Repurposed rather than greenfield capacity
  - ✓ Calibrate to enriched capacity-cost model
  - ✓ Alternative epidemiology with durable protection

- **Future work**
  - ❖ Alternative SIR epidemiology with reduction in transmission
  - ❖ Oligopoly suppliers
  - ❖ Supply chain exporting vaccine back to countries imported inputs from