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
  o High disease harm relative to production cost
  o Long capacity lag
  o High likelihood of success
  o Low contractual frictions (social cost of public funds, variance of private information)

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

• International cooperation
  o Ban export restrictions
  o Encourage capacity subsidies internalizing externality on foreign firms
  o Distortions may be bad enough to deter otherwise efficient offshoring, hiding distortions because domestic subsidies are conditionally efficient
  o 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
• **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 $\beta$
  - 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 $\theta$
  - 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 $t_\ell$ periods
  - Unit production cost $c$ for vaccine input
  - $D$ costlessly transforms input into final vaccine
Model: Timeline

0. Clinical trials start
1. Vaccine developed

0. Clinical trials completed
1. Regulatory approval

0. Q₁ doses each period
1. Pandemic ends

0. Q₂ doses each period

Xᵣ

Xₙ
Model: Alternative Structures

A. Unintegrated domestic supply

B. Integrated domestic supply

C. Offshored input supply

D. Offshored vaccine supply

International decision making
- Independent
- Cooperative
First Best

• Setup
  o Government has full control over firms’ operations
  o No social cost of public funds
  o Government has full information about $k$

• Components of government surplus
  o Expected harm avoided $s \beta h \theta Q_1 t_\ell + s \beta h \theta Q_2 (t_e - t_a - t_\ell)$
  o Expected production costs $sc Q_1 t_\ell + sc Q_2 (t_e - t_a - t_\ell)$
  o Expected capacity costs $k X_r + sk X_n$

• Optimization problem
  $$\max_{X_r, X_n, Q_1, Q_2 \geq 0} \{ s (\theta h - c) [Q_1 t_\ell + Q_2 (t_e - t_a - t_\ell)] - k X_r - sk X_n \}$$

  $Q_1, Q_2 \leq 1$
  s. t. $Q_1 \leq X_r$
  $Q_2 \leq X_r + X_n$
First Best

• No excess capacity
  o \( Q_1 = X_r \)
  o \( Q_2 = X_r + X_n \)

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

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

\[
\hat{k}^* = \frac{s}{1 - s} (\theta \beta h - c) t_e
\]
\[
\bar{k}^* = (\theta \beta h - c)(t_e - t_a - t_\ell)
\]
• **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 $1 + \lambda$

\[
\hat{k}^{**} = \frac{s}{1 - s} \left( \frac{\theta \beta h}{1 + \lambda} - c \right) t_e
\]

\[
\hat{k}^{**} = \left( \frac{\theta \beta h}{1 + \lambda} - c \right) (t_e - t_a - t_f)
\]
Third Best: Domestic Supply

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

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

• Solution has simple form
  o Price set to cover production cost: $p_1(\tilde{k}) = p_1(\tilde{k}) = c$
  o For $\tilde{k}$ low, firm fully invests at risk, receiving capacity subsidy $\sigma_r$
  o For $\tilde{k}$ moderate, firm fully invests not at risk, receiving capacity subsidy $\sigma_n$
  o For $\tilde{k}$ high, firm does not invest
Third Best: Domestic Supply

• Optimization problem

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

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

\[ \Pi_r(k) \geq \Pi_n(k) \forall k \in [0, \hat{k}] \quad \text{(ICR)} \]

\[ \Pi_n(k) \geq \Pi_r(k) \forall k \in [\hat{k}, \bar{k}] \quad \text{(ICN)} \]

\[ \Pi_r(k) \geq 0 \forall k \in [0, \hat{k}] \quad \text{(IRR)} \]

\[ \Pi_n(k) \geq 0 \forall k \in [\hat{k}, \bar{k}] \quad \text{(IRN)} \]

where

\[ \Pi_r(k) = \sigma_r - k \]
\[ \Pi_n(k) = s(\sigma_n - k) \]

• Solution
  
  o Only two constraints bind: (ICR) for type \( \hat{k} \) and (IRN) for type \( \bar{k} \)
  
  o Solving simultaneously gives subsidies \( \sigma_n = \bar{k}, \sigma_r = (1 - s)\hat{k} + s\bar{k} \)
  
  o 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 \( \phi, 1 - \phi \)
  - No effect on optimum

\[
\hat{k}^d = \hat{k}^{**} - \left( \frac{\lambda}{1 + \lambda} \right) \frac{F(\hat{k}^d)}{f(\hat{k}^d)}
\]

\[
\bar{k}^d = \bar{k}^{**} - \left( \frac{\lambda}{1 + \lambda} \right) \frac{F(\bar{k}^d)}{f(\bar{k}^d)}
\]
• Setup
  o Input supplied by offshore $U$, final good by domestic $D$
  o Continue to assume efficient Nash bargaining with weights $\phi, 1 - \phi$

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

\[
\hat{k}^{oi} = \hat{k}^{**} - \left( \frac{\phi + \lambda}{1 + \lambda} \right) \frac{F(\hat{k}^{oi})}{f(\hat{k}^{oi})}
\]
\[
\hat{k}^{oi} = \bar{k}^{**} - \left( \frac{\phi + \lambda}{1 + \lambda} \right) \frac{F(\bar{k}^{oi})}{f(\bar{k}^{oi})}
\]
**Third Best: Export Restrictions**

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

**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

\[
\kappa^o = \frac{s(1-\xi)}{1-s(1-\xi)} \left( \frac{\theta \beta h}{1+\lambda} - c \right) t^ - \left( \frac{\phi + \lambda}{1+\lambda} \right) F(\kappa^o) F(\kappa^o)
\]
Third Best: International Cooperation

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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>At-risk capacity</th>
<th>Any capacity</th>
<th>Expected net program benefit (bil. $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First best</td>
<td>0.324</td>
<td>0.604</td>
<td>467</td>
</tr>
<tr>
<td>Second best</td>
<td>0.220</td>
<td>0.515</td>
<td>384</td>
</tr>
<tr>
<td>Third best domestic vaccine</td>
<td>0.179</td>
<td>0.434</td>
<td>320</td>
</tr>
<tr>
<td>Third best foreign input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>● No export restriction ($\xi = 0$)</td>
<td>0.135</td>
<td>0.357</td>
<td>258</td>
</tr>
<tr>
<td>● Export restriction ($\xi = 0.5$)</td>
<td>0.011</td>
<td>0.295</td>
<td>125</td>
</tr>
<tr>
<td>Third best foreign vaccine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>● No export restriction ($\xi = 0$)</td>
<td>0.107</td>
<td>0.306</td>
<td>217</td>
</tr>
<tr>
<td>● Export restriction ($\xi = 0.5$)</td>
<td>0.008</td>
<td>0.257</td>
<td>105</td>
</tr>
</tbody>
</table>
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