Game Theory 2: Extensive-Form Games and Subgame Perfection
Dynamics in Games

How should we think of strategic interactions that occur in sequence?

Who moves when?

And what can they do at different points in time?

How do people react to different histories?
Modeling Games with Dynamics

Players

Player function
  - Who moves when

Terminal histories
  - Possible paths through the game

Preferences over terminal histories
A strategy is a complete contingent plan

Player $i$’s strategy specifies her action choice at each point at which she could be called on to make a choice
**An Example: International Crises**

Two countries \((A \text{ and } B)\) are competing over a piece of land that \(B\) occupies.

Country \(A\) decides whether to make a demand.

If Country \(A\) makes a demand, \(B\) can either acquiesce or fight a war.

If \(A\) does not make a demand, \(B\) keeps land (game ends).

\(A\)'s best outcome is Demand followed by Acquiesce, worst outcome is Demand and War.

\(B\)'s best outcome is No Demand and worst outcome is Demand and War.
An Example: International Crises

A can choose: Demand \((D)\) or No Demand \((ND)\)

\(B\) can choose: Fight a war \((W)\) or Acquiesce \((A)\)

Preferences

\[ u_A(D, A) = 3 > u_A(ND, A) = u_A(ND, W) = 2 > u_A(D, W) = 1 \]

\[ u_B(ND, A) = u_B(ND, W) = 3 > u_B(D, A) = 2 > u_B(D, W) = 1 \]

How can we represent this scenario as a game (in strategic form)?
**International Crisis Game: NE**

<table>
<thead>
<tr>
<th></th>
<th>Country B</th>
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<tbody>
<tr>
<td></td>
<td>W</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>1, 1</td>
</tr>
<tr>
<td><strong>ND</strong></td>
<td>2, 3</td>
</tr>
</tbody>
</table>

Country A

<p>| |</p>
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<tbody>
<tr>
<td><strong>D</strong></td>
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<tr>
<td><strong>ND</strong></td>
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International Crisis Game: NE

<table>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>W</td>
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<tr>
<td></td>
<td>1, 1</td>
</tr>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>3, 2</td>
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</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>Country A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>1, 1</td>
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<tr>
<td></td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td>2√, 3</td>
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<tr>
<td></td>
<td>2, 3</td>
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</tbody>
</table>
### International Crisis Game: NE

<table>
<thead>
<tr>
<th></th>
<th>Country A</th>
<th>Country B</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1,1</td>
<td>3,2</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ND</strong></td>
<td>2,3</td>
<td>2,3</td>
</tr>
</tbody>
</table>

**Notes:**
- Country A has the option to **D** (declare) or **ND** (not declare).
- Country B can choose between **W** (withdraw) or **A** (attack).
# International Crisis Game: NE

<table>
<thead>
<tr>
<th></th>
<th>Country A</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>W</td>
</tr>
<tr>
<td>Country B</td>
<td>1,1</td>
<td>3✓, 2✓</td>
</tr>
<tr>
<td>ND</td>
<td>2✓, 3</td>
<td>2, 3</td>
</tr>
</tbody>
</table>

- **D** (Defend) results in a tie for both countries.  
- **ND** (No Defense) results in an outcome where Country A gains 3 units and Country B gains 2 units.
### International Crisis Game: NE

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
</tr>
<tr>
<td>D</td>
<td>1, 1</td>
</tr>
<tr>
<td>ND</td>
<td>2√, 3√</td>
</tr>
</tbody>
</table>

Country A

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND</td>
<td></td>
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</table>
# International Crisis Game: NE

<table>
<thead>
<tr>
<th></th>
<th>Country A</th>
<th>Country B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D$</td>
<td>$W$</td>
</tr>
<tr>
<td>$1, 1$</td>
<td>$3^\triangledown, 2^\triangledown$</td>
<td></td>
</tr>
<tr>
<td>$2^\triangledown, 3^\triangledown$</td>
<td>$2, 3^\triangledown$</td>
<td>$3^\triangledown, 2^\triangledown$</td>
</tr>
</tbody>
</table>

International Crisis Game: NE

Country A

Country B

\[
\begin{array}{c|c|c}
& W & A \\
\hline
D & 1, 1 & 3\checkmark, 2\checkmark \\
\hline
ND & 2\checkmark, 3\checkmark & 2, 3\checkmark \\
\end{array}
\]

- Is there something funny here?
International Crisis Game: NE

<table>
<thead>
<tr>
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<th>Country B</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$D$</td>
<td>$W$</td>
<td>$A$</td>
</tr>
<tr>
<td>$ND$</td>
<td>2, 3✓</td>
<td>2, 3✓</td>
<td>$3✓, 2✓$</td>
</tr>
<tr>
<td></td>
<td>1, 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Is there something funny here?
- Specifically, $(ND, W)$?
Is there something funny here?

Specifically, $(ND, W)$?

The threat of war deters the demand, but would $B$ follow through?
**Non-Credible Threats**

The equilibrium \((ND, W)\) depends on a “non-credible threat”

Once \(A\) makes a demand, \(B\) does not want to fight a war

But to rule out such behavior, we need a stronger solution concept

One that incorporates the fact that actions are taken in sequence
Why Rule out Non-credible Threats

Equilibrium as a steady state

War is only a best-response for $B$ because when no demand is made, $B$ is indifferent

If $A$ accidentally made a demand, war is not a sequential best-response for $B$. $B$ should acquiesce instead

- Read the strategy $W$ as “if $A$ makes a demand, I will go to war”
Subgame Perfect Nash Equilibrium

A strategy specifies what a player will do at every decision point
  ▶ Complete contingent plan

Strategy in a SPNE must be a best-response at each node, given the strategies of other players

Backward Induction
But First!

Let’s introduce a way of incorporating the timing of actions into the game explicitly.

Use a game tree to represent the sequential aspect of choices.
AN EXAMPLE: INTERNATIONAL CRISIS

\[ A \]

\[ ND \]

\[ D \]

(2, 3)
An Example: International Crises

A

ND

(2, 3)

D

B

War

Acq
An Example: International Crises

\[
\begin{array}{c}
A \\
\text{ND} \\
(2, 3) \\
\text{D} \\
\text{War} \\
(1, 1) \\
\text{Acq} \\
(3, 2) \\
B
\end{array}
\]
An Example: International Crises

A

\[ ND \quad D \]

(2, 3) (1, 1) (3, 2)

B

War

Acq
An Example: International Crises

A

ND

(2, 3)

D

(3, 2)
AN EXAMPLE: INTERNATIONAL CRISIS

\[
\begin{align*}
A & \\
ND & D \\
(2, 3) & (3, 2)
\end{align*}
\]
An Example: International Crises

\[ (2, 3) \quad (1, 1) \quad (3, 2) \]
## Another Example

<table>
<thead>
<tr>
<th></th>
<th>Player 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>5, 3</td>
<td>0, 0</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>0, 0</td>
<td>3, 5</td>
</tr>
</tbody>
</table>

Player 2

<table>
<thead>
<tr>
<th></th>
<th><strong>C</strong></th>
<th><strong>D</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td></td>
<td>0, 0</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>0, 0</td>
<td>3, 5</td>
</tr>
</tbody>
</table>
### Another Example

<table>
<thead>
<tr>
<th></th>
<th>Player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>5✓, 3✓</strong></td>
</tr>
<tr>
<td><strong>B</strong></td>
<td><strong>0, 0</strong></td>
</tr>
</tbody>
</table>

Player 1

---

Another Example
Another Example

Represent this as a game tree under the assumption that player 1 moves first.
Another Example

```
1
 / \   /
A   B
/ \   /
2   2
 / \   /
C   D  C   D
/   0\   /   0\  /   3\  /   5\
5   0 \  0   0 \  0   3 \  5
```
Another Example

```
      1
     / \  /  \
    A   B
   / \  /  \
  2   2
 / \  /  \
C   D C   D
5 0 0 3
3 0 0 5
```

Red arrow indicates the path chosen.
Another Example
**Another Example**

```
  1
 /   \
A    B
|
2    2
|
C   D
|
3  5
```

A: 5
B: 3
C: 0
D: 0

Another example of a game tree. The numbers represent payoffs for player A.
Another Example

SPNE: \((A, (C, D))\)
What if Player 2 Moves First?
What if Player 2 Moves First?

```
    2
   / \  /  \
  C   D
 /     /
1     1
/     /
A     B
/     /
5 0 0 3
| | | |
3 0 0 5
```
What if Player 2 Moves First?
What if Player 2 Moves First?
What if Player 2 Moves First?

SPNE: $((A, B), D)$
The Order of Action Matters

The outcome depends on who chooses first

- When 1 moves first: \((A, C)\) with payoffs 5, 3
- When 2 moves first: \((D, B)\) with payoffs 3, 5

In this game, there is an advantage to moving first
The Centipede Game

\[ \begin{array}{cccccc}
1 & C & 2 & C & 1 & C \\
E & E & E & E & E & E \\
1 & 0 & 5 & 2 & 4 & 7 \\
1 & 3 & 2 & 7 & & \\
\end{array} \]
The Centipede Game
The Centipede Game

1 \quad C \quad 2 \quad C \quad 1 \quad C \quad 2 \quad C

E \quad E \quad E \quad E

1 \quad 0 \quad 5 \quad 4

1 \quad 3 \quad 2 \quad 7
The Centipede Game

\[ \begin{array}{c}
1 & C & 2 & C & 1 & C & 2 & C \\
E & E & E & E & E & E & E & E \\
1 & 0 & 5 & 4 & 3 & 2 & 7 & 6 \\
1 & 3 & 2 & 7 & 6 & 6 & 6 & 6
\end{array} \]
The Centipede Game

1 \rightarrow C \rightarrow 2 \rightarrow C \rightarrow 1 \rightarrow C \rightarrow 2 \rightarrow C

E \rightarrow E \rightarrow E \rightarrow E

1 \rightarrow 0 \rightarrow 5 \rightarrow 4

1 \rightarrow 3 \rightarrow 2 \rightarrow 7
The Centipede Game

Unique SPNE: $((E, E), (E, E))$

Equilibrium payoffs (1, 1)

Pareto dominated by 3 outcomes!
Multiple Equilibria
Multiple Equilibria

The diagram illustrates a game with multiple equilibria. The nodes and branches represent the decision points and outcomes for players. The payoffs are shown at the end of each branch.

- Node 1: Player 1 chooses between D and U.
  - D: 3
  - U: 2

- Node 2: Player 2 chooses between B and A.
  - B: 3
  - A: 2

- Branches:
  - L: 1
    - D: 3
      - L: 1
        - 1
      - R: 3
        - 1
    - U: 1
      - L: 3
        - 3
      - R: 5
        - 5
  - R: 2
    - D: 2
      - L: 0
        - 0
      - R: 2
        - 2
    - U: 4
      - L: 0
        - 0
      - R: 4
        - 4
Multiple Equilibria
Multiple Equilibria

\[ \begin{array}{cc}
\text{D} & \text{B} \\
3 & 3 \\
L & L \\
1 & 2 \\
1 & 4 \\
0 & 2 \\
\end{array} \]

\[ \begin{array}{cc}
\text{U} & \text{A} \\
1 & 2 \\
\end{array} \]
**Multiple Equilibria**

SPNE 1: (D, A, (R,L))
Multiple Equilibria

SPNE 1: (D, A, (R,L))
Multiple Equilibria

1

U

2

A

D

L

R

3

1

1

1

5

B

L

R

2

0

2

4

4

2

2

2
Multiple Equilibria

SPNE 1: (D, A, (R,L))
SPNE 2: (U,B,(R,R))
A Familiar Example: Public Good in a Team

Two players: 1 & 2

Each can choose a level to contribute to a public good: $s_i$

Payoff for individual $i$ are

$$u_i(s_1, s_2) = s_1 + s_2 + \frac{s_1 s_2}{2} - \frac{s_i^2}{2}$$
Nash Equilibrium

\[ s_1^* = 2 \quad s_2^* = 2 \]

Individual player’s equilibrium payoff:

\[ 2 + 2 + \frac{2 \cdot 2}{2} - \frac{2^2}{2} = 4 \]
Consider an extensive form version

Player 1 must make her choice first

Before Player 2 decides how much to put in, she observes how much Player 1 puts in

How might this change contributions?

We will use backward induction
Best Response for Player 2

The payoff function for player 2:

$$u_2(s_1, s_2) = s_1 + s_2 + \frac{s_1 s_2}{2} - \frac{s_2^2}{2}$$

How do we determine the best response of player 2?
Best Response for Player 2

The payoff function for player 2:

\[ u_2(s_1, s_2) = s_1 + s_2 + \frac{s_1s_2}{2} - \frac{s_2^2}{2} \]

How do we determine the best response of player 2?

\[ \frac{\partial u_2(s_1, s_2)}{\partial s_2} = 1 + \frac{s_1}{2} - s_2 \]
Best Response for Player 2

The payoff function for player 2:

\[ u_2(s_1, s_2) = s_1 + s_2 + \frac{s_1 s_2}{2} - \frac{s_2^2}{2} \]

How do we determine the best response of player 2?

\[ \frac{\partial u_2(s_1, s_2)}{\partial s_2} = 1 + \frac{s_1}{2} - s_2 \]

Setting equal to zero (\( \frac{\partial u_2(s_1, s_2)}{\partial s_1} = 0 \)), Player 2’s best-response to \( s_1 \) is

\[ \text{BR}_2(s_1) = 1 + \frac{s_1}{2} \equiv s_2^\check{\bullet}(s_1) \]
Best Response for Player 1

Player 1’s best response must account for how Player 2 will respond to whatever she chooses.
**Best Response for Player 1**

Player 1’s best response must account for how Player 2 will respond to whatever she chooses:

$$u_1(s_1, s_2^\gamma(s_1))$$
Player 1’s best response must account for how Player 2 will respond to whatever she chooses:

\[ u_1(s_1, s_2^\uparrow(s_1)) = s_1 + s_2^\uparrow(s_1) + \frac{s_1 s_2^\uparrow(s_1)}{2} - \frac{s_1^2}{2} \]
Player 1’s best response must account for how Player 2 will respond to whatever she chooses:

\[ u_1(s_1, s_2^\vee(s_1)) \]

\[ u_1(s_1, s_2^\vee(s_1)) = s_1 + s_2^\vee(s_1) + \frac{s_1 s_2^\vee(s_1)}{2} - \frac{s_1^2}{2} \]

\[ u_1(s_1, s_2^\vee(s_1)) = s_1 + \left(1 + \frac{s_1}{2}\right) + \frac{s_1}{2} \left(1 + \frac{s_1}{2}\right) - \frac{s_1^2}{2} \]
Best Response for Player 1

Player 1’s best response must account for how Player 2 will respond to whatever she chooses:

\[ u_1(s_1, s_2'(s_1)) \]

\[ u_1(s_1, s_2'(s_1)) = s_1 + s_2'(s_1) + \frac{s_1 s_2'(s_1)}{2} - \frac{s_1^2}{2} \]

\[ u_1(s_1, s_2'(s_1)) = s_1 + \left(1 + \frac{s_1}{2}\right) + \frac{s_1}{2} \left(1 + \frac{s_1}{2}\right) - \frac{s_1^2}{2} \]

\[ u_1(s_1, s_2'(s_1)) = 1 + \frac{3}{2} s_1 + \frac{s_1}{2} + \frac{s_1^2}{4} - \frac{s_1^2}{2} \]
Best Response for Player 1

We can write Player 1’s problem as:

\[ u_1(s_1, s_2^*(s_1)) = 1 + 2s_1 - \frac{s_1^2}{4} \]

Solve for Player 1’s optimal choice:

\[ 2 - \frac{s_1}{2} = 0 \]

\[ s_1^* = 4 \]
**Best Response for Player 1**

We can write Player 1’s problem as:

$$u_1(s_1, s_2^*(s_1)) = 1 + 2s_1 - \frac{s_1^2}{4}$$

Solve for Player 1’s optimal choice:

$$2 - \frac{s_1}{2} = 0$$

$$s_1^* = 4$$

Go back to Player 2:

$$s_2^* = s_2^*(4) = 1 + \frac{1}{2}(4) = 3$$
Public Good in a Team

So each player contributes more:

\[ s_1^* = 4 \quad s_2^* = 3 \]
Public Good in a Team

So each player contributes more:

\[ s_1^* = 4 \quad s_2^* = 3 \]

and equilibrium utilities:

\[ u_1^* = 6 \quad u_2^* = 8.5 \]

They each are better off, but it’s better to move second
Subgame Perfect Nash Equilibrium

Subgame Perfect Nash Equilibrium is a refinement of Nash Equilibrium

It rules out equilibria that rely on incredible threats in a dynamic environment

All SPNE are identified by backward induction