# Illegitimi non carborundum

Ronald L. Rivest

Viterbi Professor of EECS
MIT, Cambridge, MA

CRYPTO 2011
2011-08-15

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# (Don't let the bastards grind you down!)

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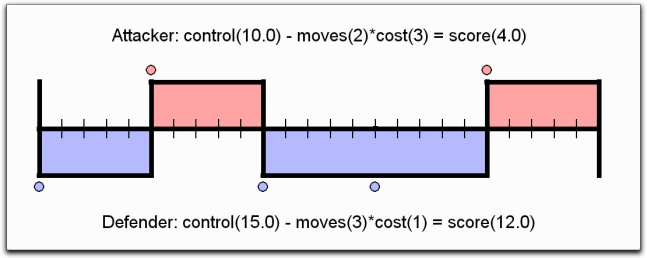


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# Outline

# Cryptography

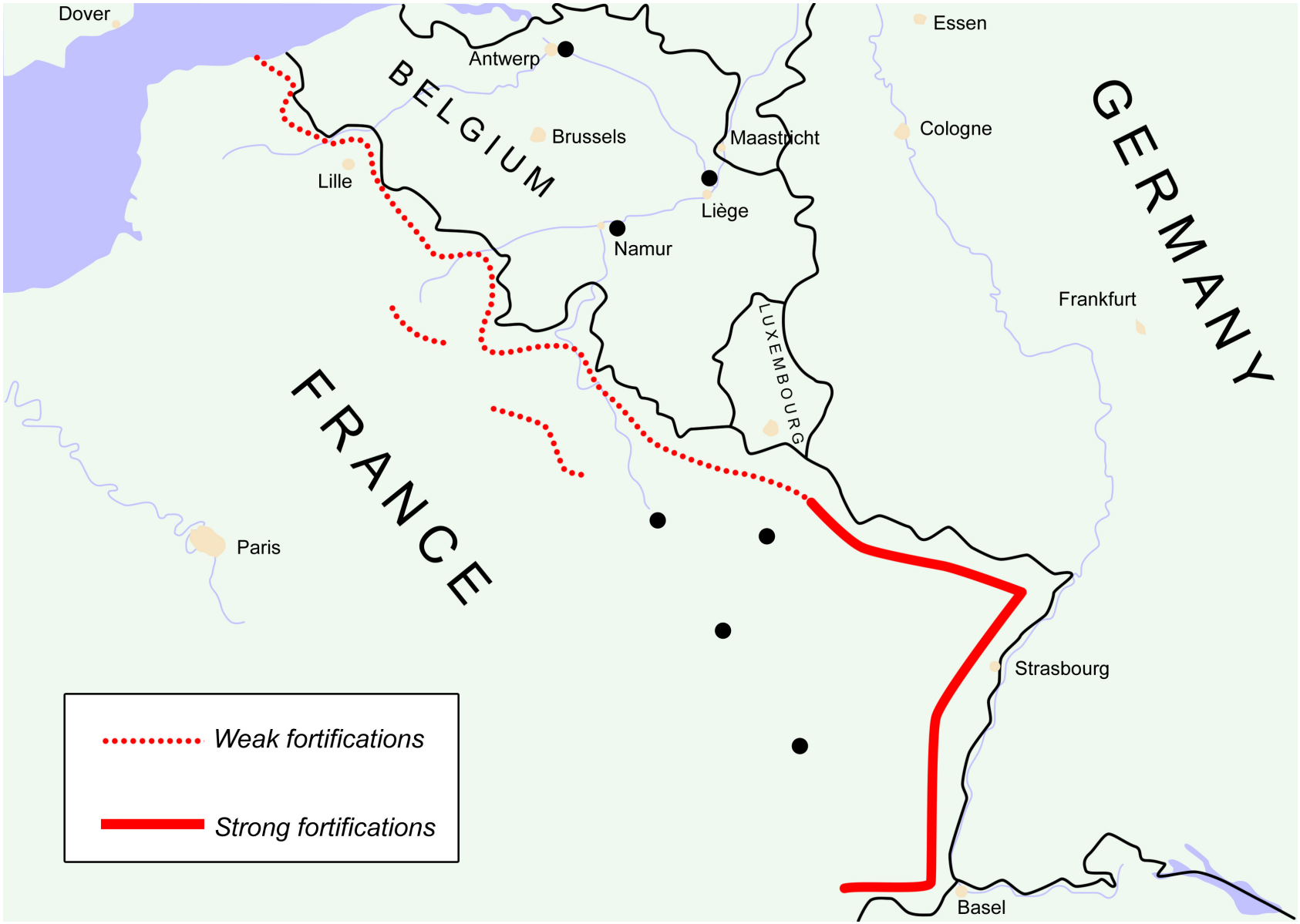
Cryptography is mostly about using *mathematics* and *secrets* to achieve confidentiality, integrity, or other security objectives.

# Assumptions

We make *assumptions* as necessary, such as ability of parties to generate unpredictable keys and to keep them secret, or inability of adversary to perform certain computations.

# Murphy's Law: "If anything can go wrong, it will!"

# Assumptions may fail, badly. (Maginot Line)



# Even worse...

In an adversarial situation, assumption may fail *repeatedly*...

(ref Advanced Persistent Threats)

# Most crypto is like Maginot line...

We work hard to make up good keys and distribute them properly, then we sit back and wait for the attack.

There is a line we assume adversary can not cross (theft of keys).

# Partial key theft

Much research allows adversary to steal *some portion* of key(s).

- secret-sharing [S79,...]
- proactive crypto [HJKY95,...]
- signer-base intrusion-resilience [IR04,...]
- leakage-resilient crypto [MR04,...]

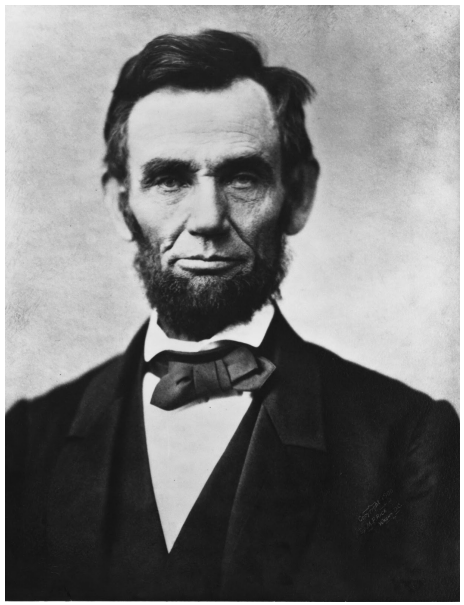
But adversary isn't allowed to steal *everything*, all at once. (Some exceptions, e.g. intrusion-resilient secure channels [IMR'05])

This just moves the line in the digital sand a bit...

# Total key loss

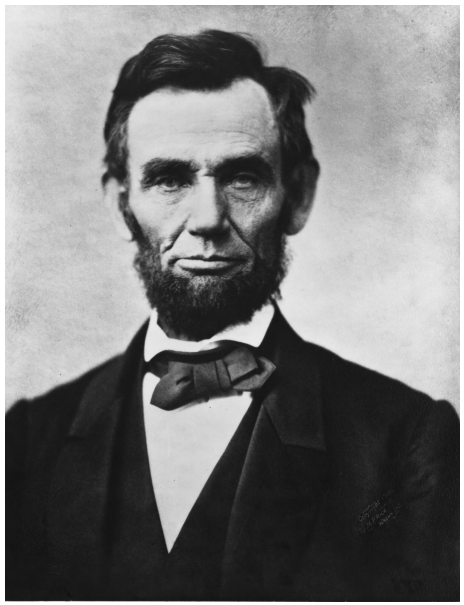
To be a good security professional, there shouldn't be limits on your paranoia!
(The adversary won't respect such limits...)
Are we being sufficiently paranoid??

# Lincoln's Riddle



Q: "If I call the dog's tail a leg, how many legs does it have?"

# Lincoln's Riddle



Q: "If I call the dog's tail a leg, how many legs does it have?"

A: "Four. It doesn't matter what you *call* the tail; it is still a tail."

# Corollary to Lincoln's Riddle

Calling a bit-string a "secret key" doesn't actually make it secret...

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Calling a bit-string a "secret key" doesn't actually make it secret...

Rather, it just identifies it as an interesting target for the adversary!

# Our goal

To develop new models for scenarios involving total key loss.
Especially those scenarios where theft is *stealthy* or *covert*
(not immediately noticed by good guys).

The Game of "FLIPIT"
(aka "Stealthy Takeover")

joint work with
Ari Juels, Alina Oprea, Marten van Dijk
of RSA Labs

# FLIPIT is a two-player game

- Defender = Player 0 = Blue
- Attacker = Player 1 = Red

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FLIPIT is rather symmetric, and we say "player *i*" to refer to an arbitrary player.

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Examples:

- A password

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- A password
- A digital signature key
- A computer system
- A mountain pass

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Time is *continuous*, not discrete.
Players move at same time with probability 0.

# Examples of moves:

- Create new password or signing key.
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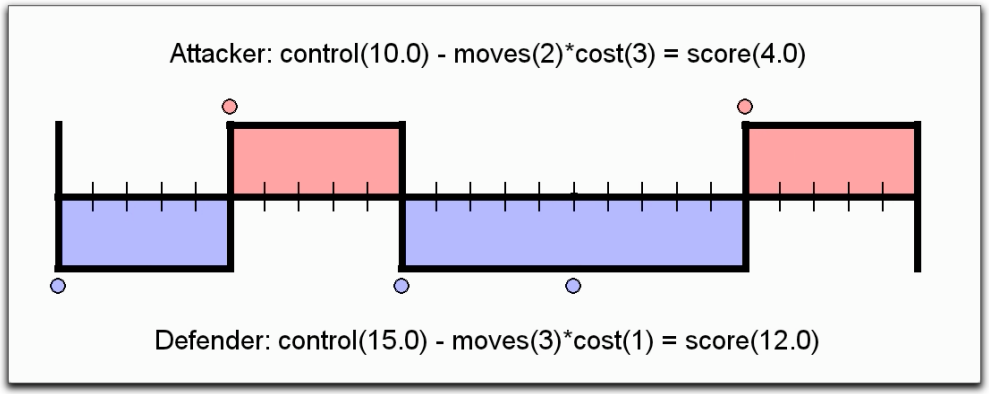
# Continual back-and-forth warfare...

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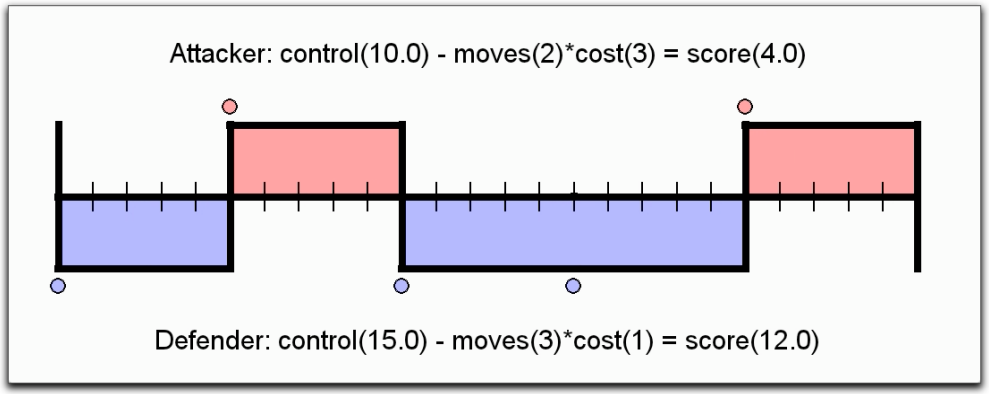


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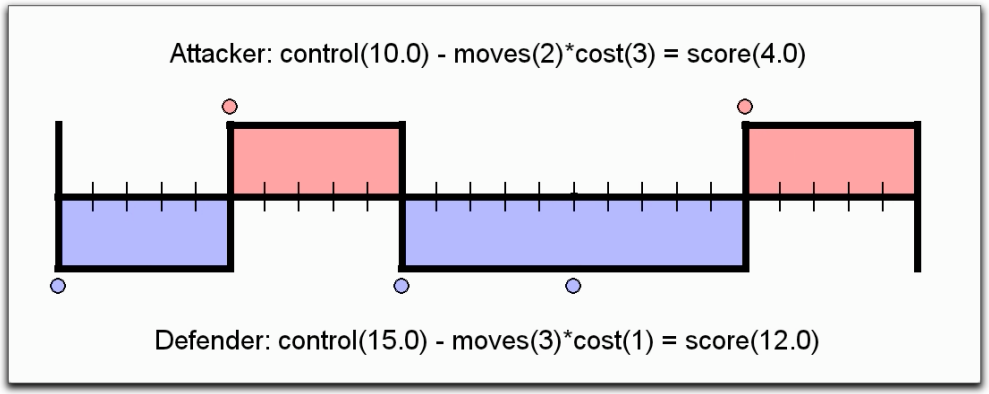


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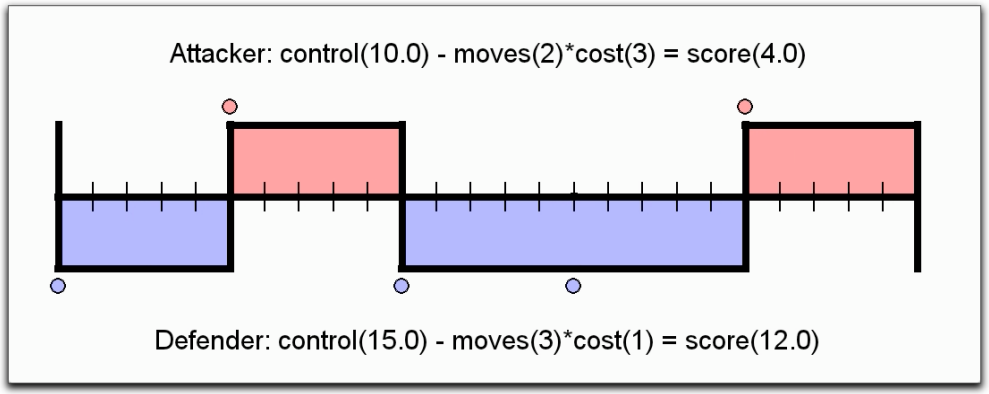


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- The game may go on forever...

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- Uncertainty means flops are unavoidable.

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- In variants, move reveals only current state, or time since other player last moved...

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- Being in control yields gain!
- Player earns one point for each second he is in control.

# How well are you playing? (Notation)

- Let $N_i(t)$ denote number moves by player $i$ up to time $t$. His average rate of play is

$$\alpha_i(t) = N_i(t)/t \ .$$

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- Let $G_i(t)$ denote the number of seconds player $i$ is in control, up to time $t$.
  His rate of gain up to time $t$ is

$$\gamma_i(t) = G_i(t)/t \ .$$

# How well are you playing? (Notation)

- Score (net benefit) $B_i(t)$ up to time $t$ is TimeInControl - CostOfMoves:

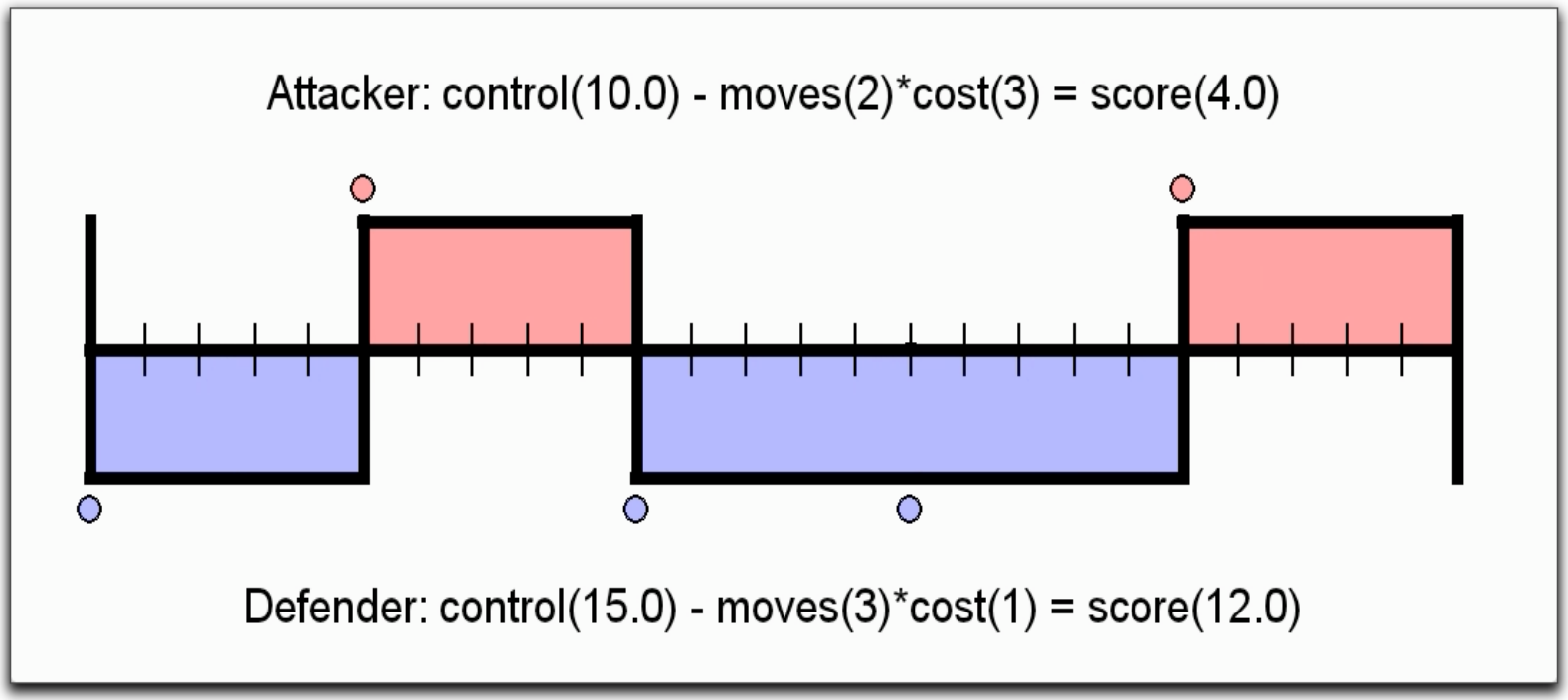
$$B_i(t) = G_i(t) - k_i \cdot N_i(t)$$

- Benefit rate is

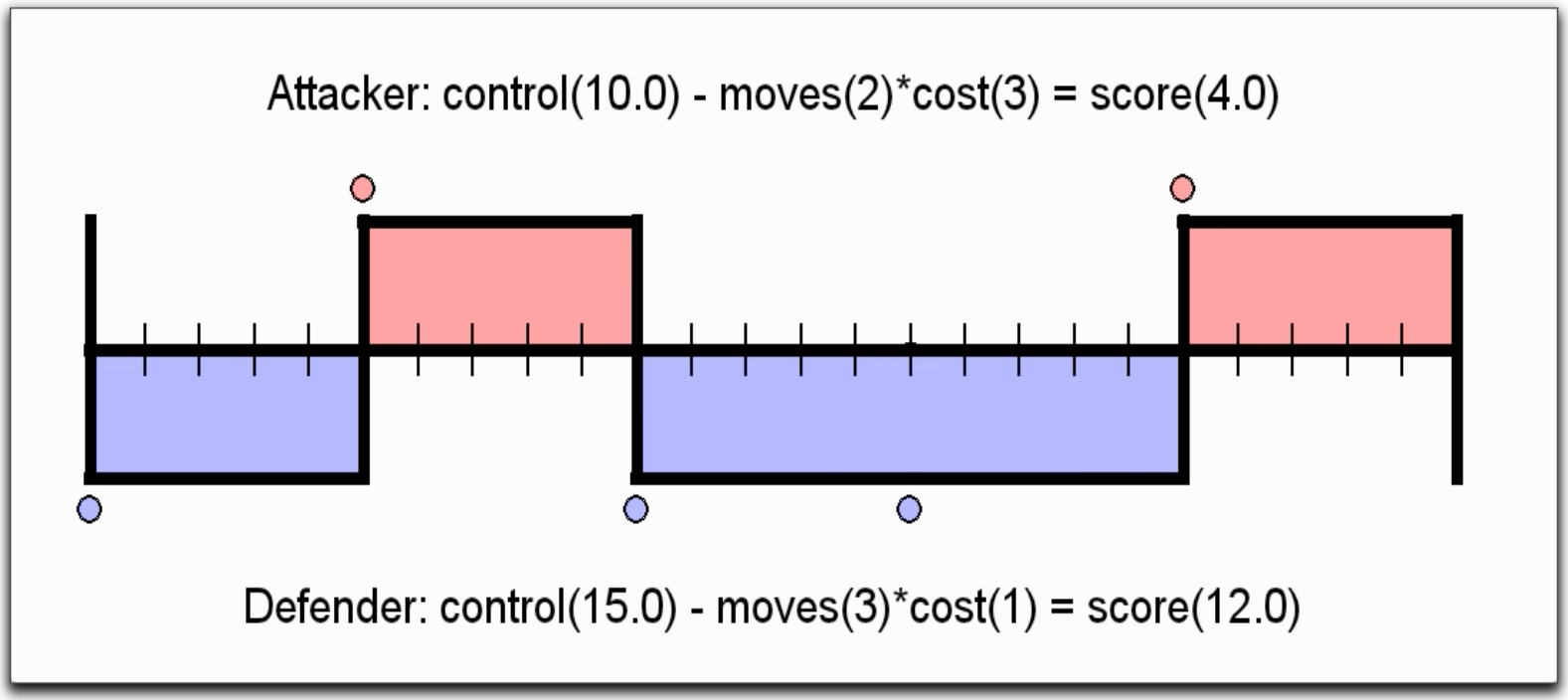
$$\begin{aligned} \beta_i(t) &= B_i(t)/t \\ &= \gamma_i(t) - k_i \cdot \alpha_i(t) \end{aligned}$$

- Player wishes to maximize $\beta_i = \lim_{t\to\infty} \beta_i(t)$.

# Movie of FLIPIT Game – Global View



# Movie of FLIPIT Game – Defender View



# How to play well?

# Non-Adaptive Play

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- Some interesting non-adaptive strategies:
  - *Periodic* play
  - *Exponential* (memoryless) play
  - *Renewal* strategies: iid intermove times

# Periodic play

Player *i* may play *periodically*
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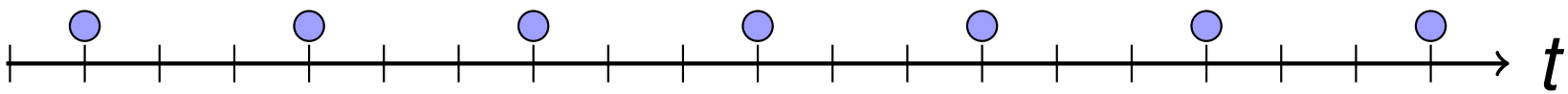
E.g. for $\alpha_0 = 1/3$, we might have:



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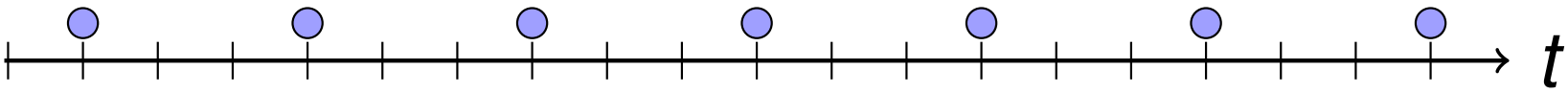



It is convenient to assume that periodic play involves miniscule amounts of jitter or drift; play is effectively periodic but will drift out of phase with truly periodic.

# Adaptive play against a periodic opponent

An *adaptive* Attacker can easily learn the period and phase of a periodic Defender, so that periodic play is useless against an adaptive opponent, unless it is very fast.
Examples:

- a sentry makes his regular rounds
- 90-day password reset

# Periodic Attacker

## Theorem

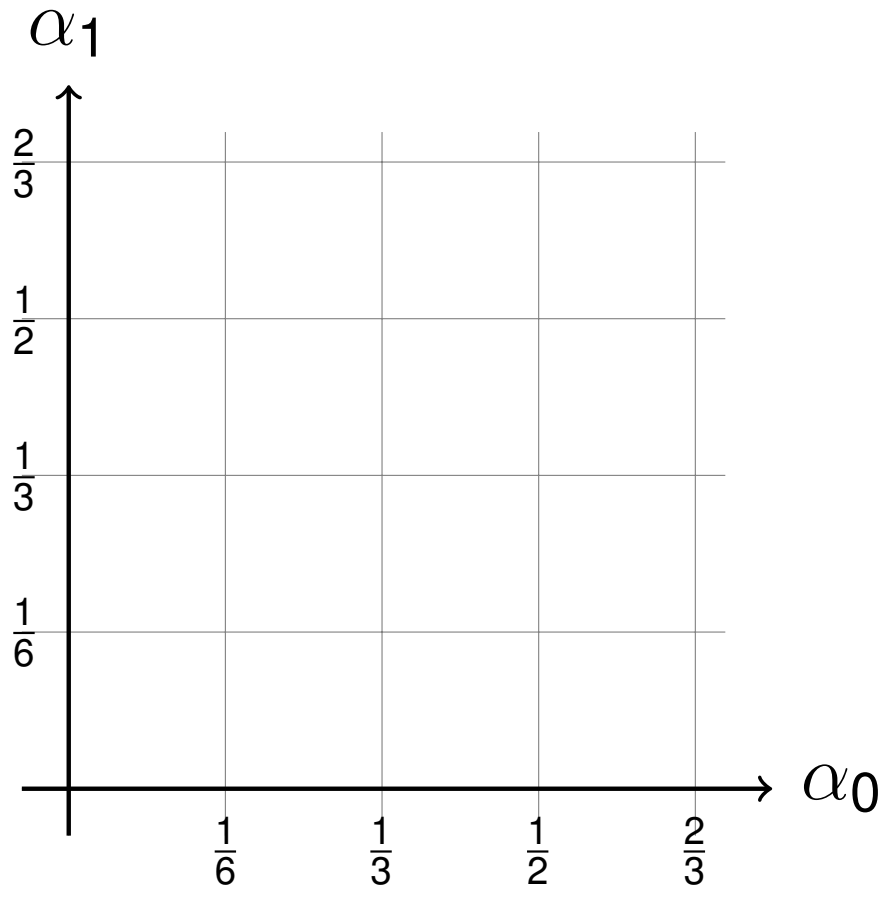
*If Attacker moves periodically at rate* $\alpha_1$ *(and period* $1/\alpha_1$*, with unknown phase), then optimum non-adaptive Defender strategy is*

- *if* $\alpha_1 > \frac{1}{2k_0}$*, don't play(!),*
- *if* $\alpha_1 = \frac{1}{2k_0}$*, play periodically at any rate* $\alpha_0$*,* $0 \leq \alpha_0 \leq \frac{1}{2k_0}$*,*
- *if* $\alpha_1 < \frac{1}{2k_0}$*, play periodically at rate*

$$\alpha_0 = \sqrt{\frac{\alpha_1}{2k_0}} > \alpha_1$$

# Graph for Periodic Attacker and Periodic Defender

($k_0 = 1, k_1 = 1.5$)



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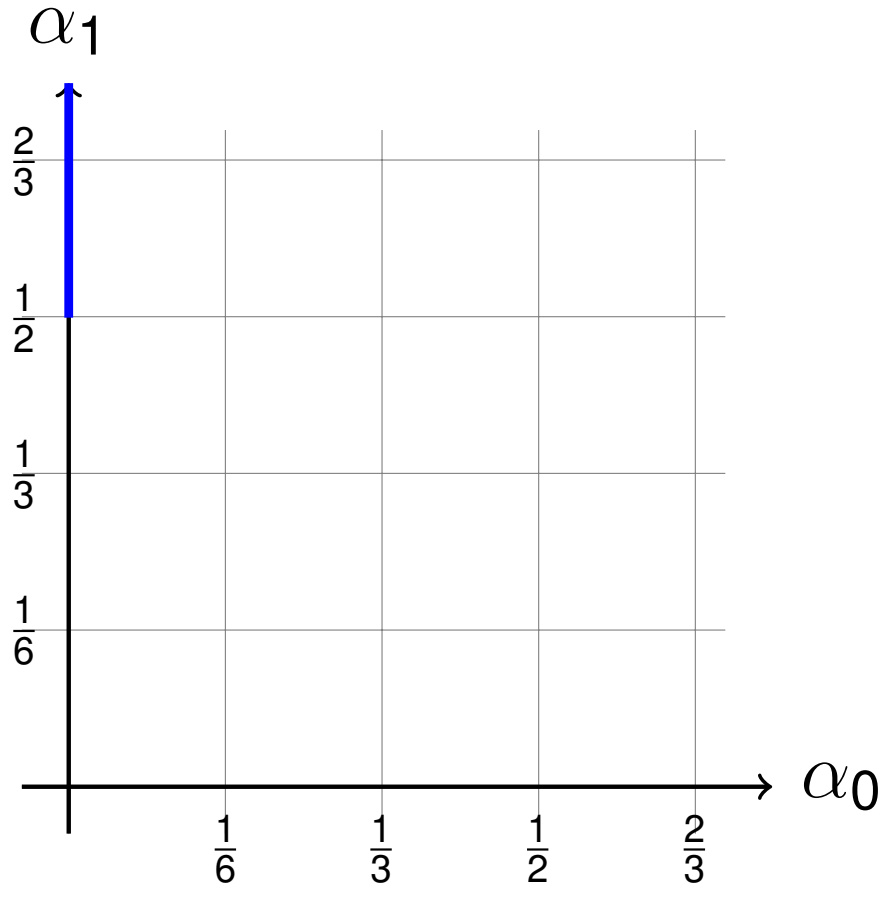

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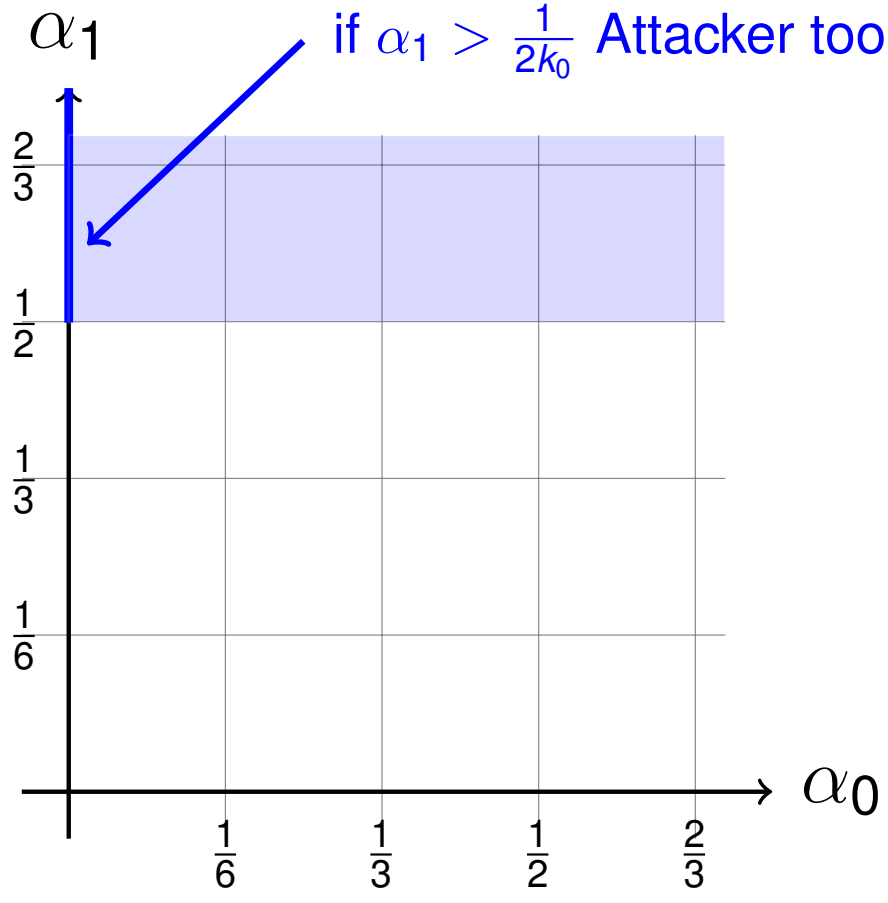

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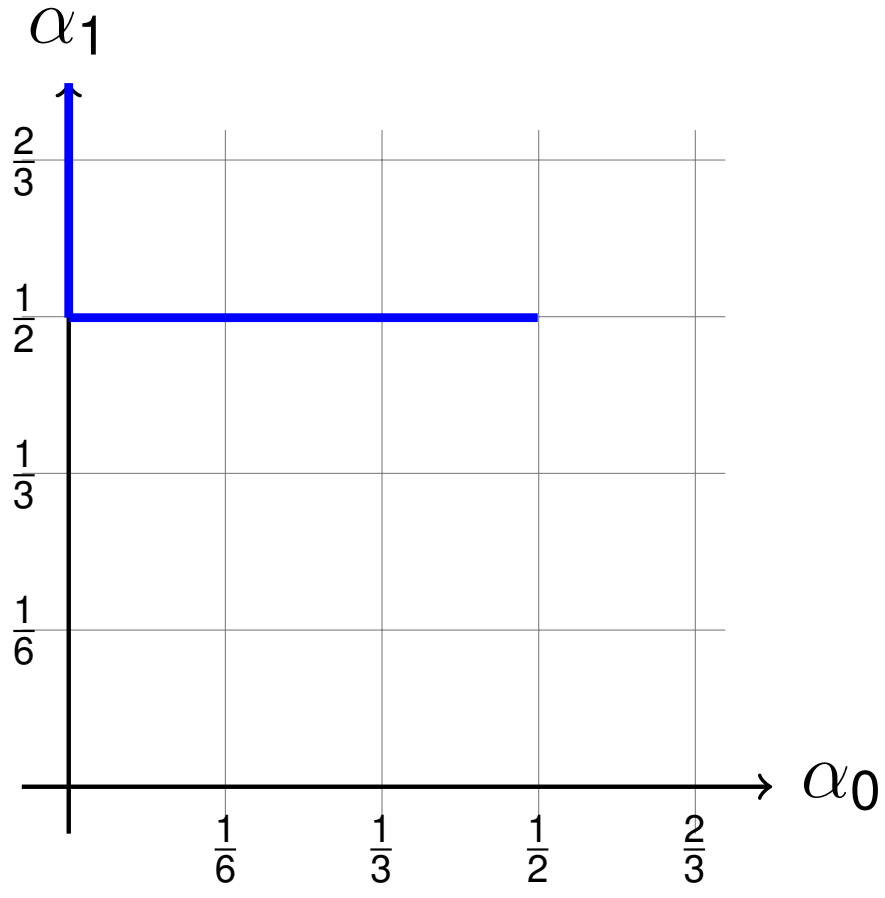

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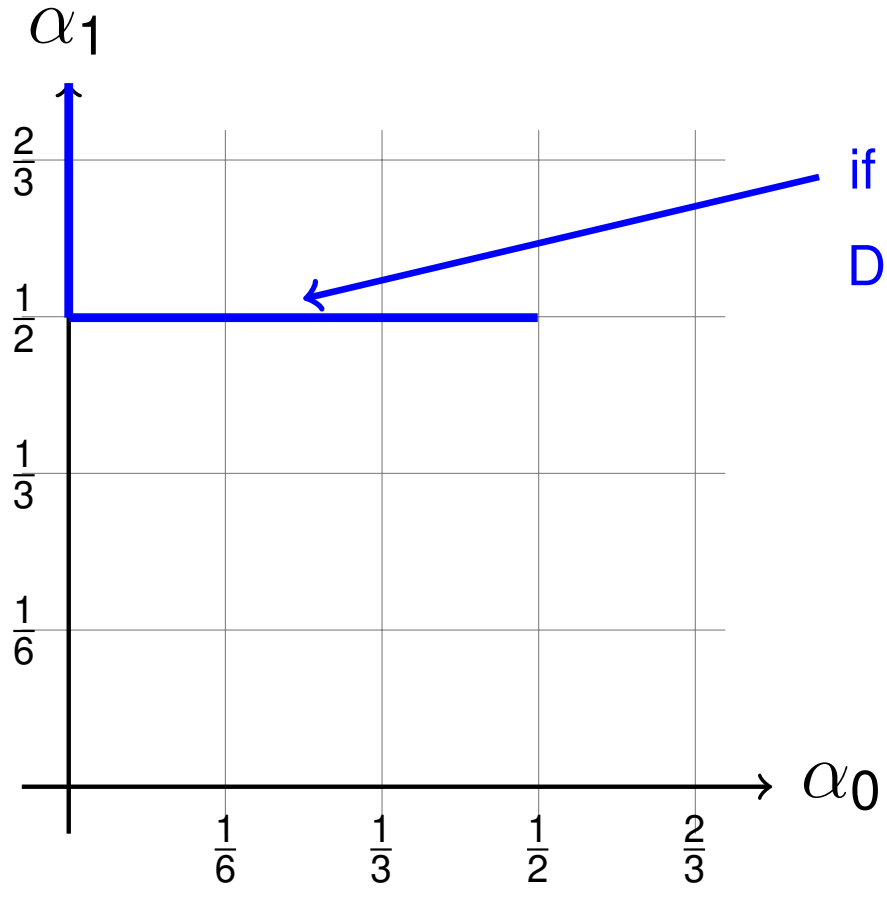


if $\alpha_1 = \frac{1}{2k_0}$

Defender can play with 0 benefit

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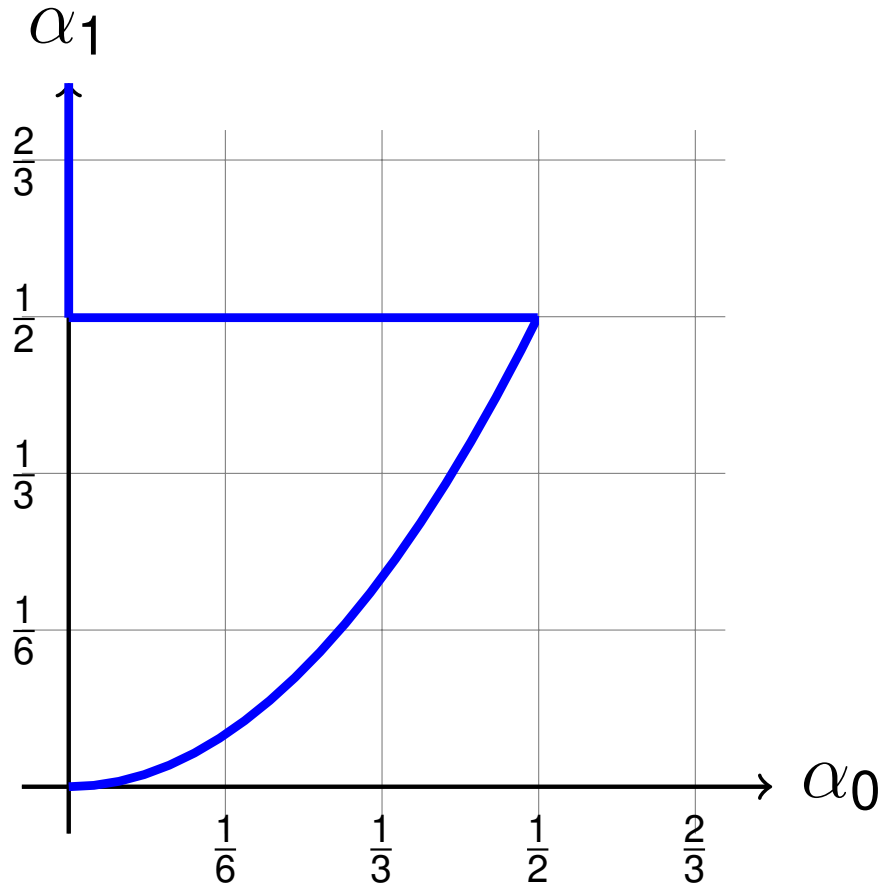

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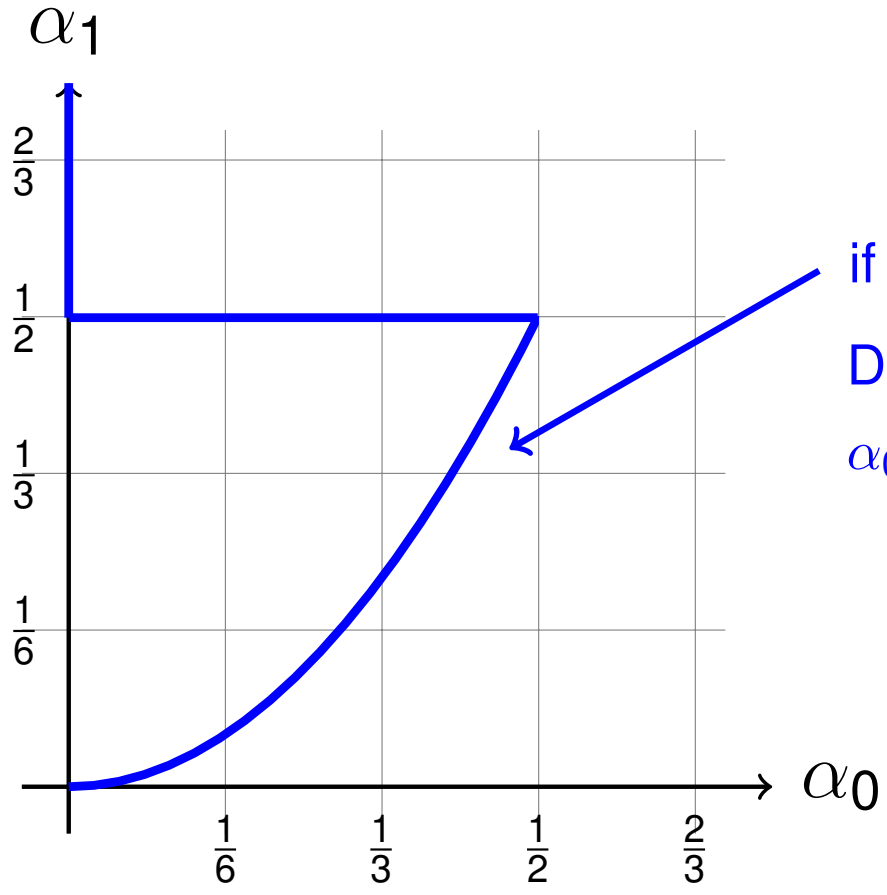


if $\alpha_1 < \frac{1}{2k_0}$

Defender maximizes benefit with

$\alpha_0 = \sqrt{\frac{\alpha_1}{2k_0}}$

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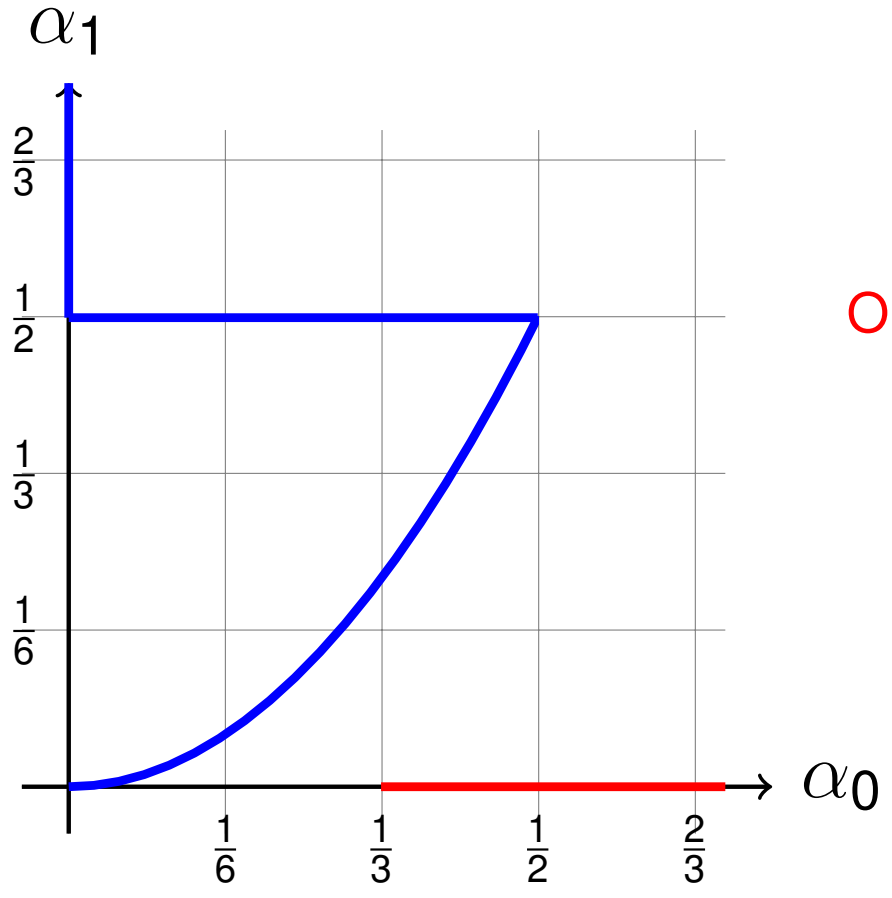


Optimal Attacker play

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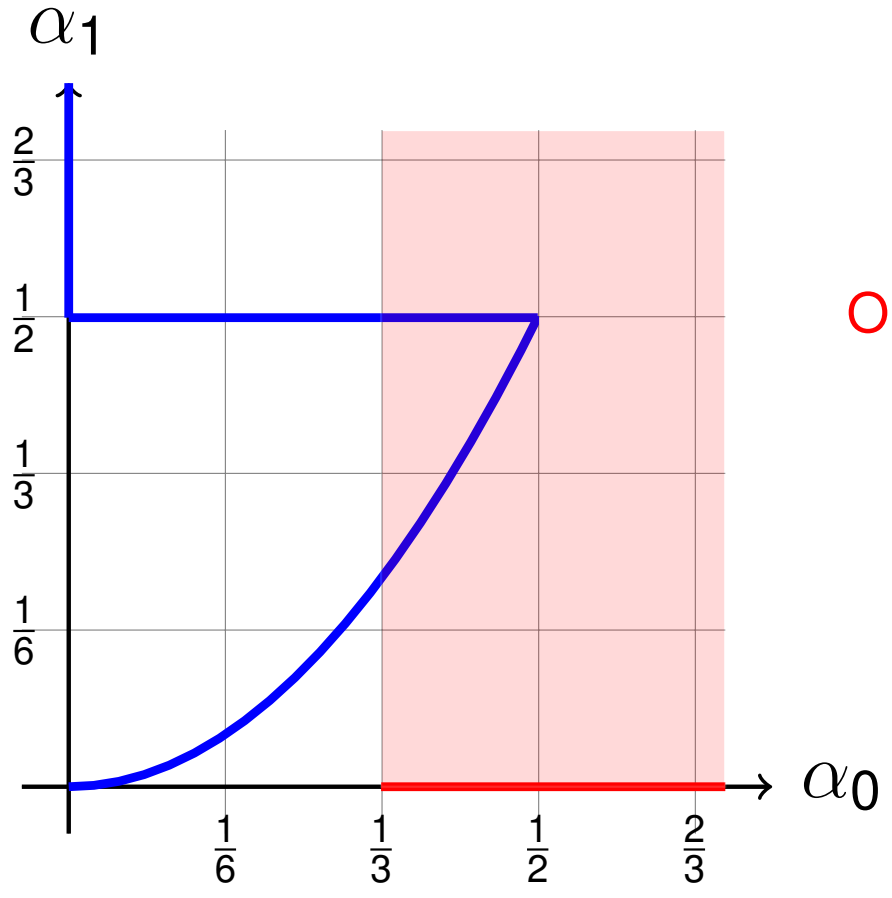


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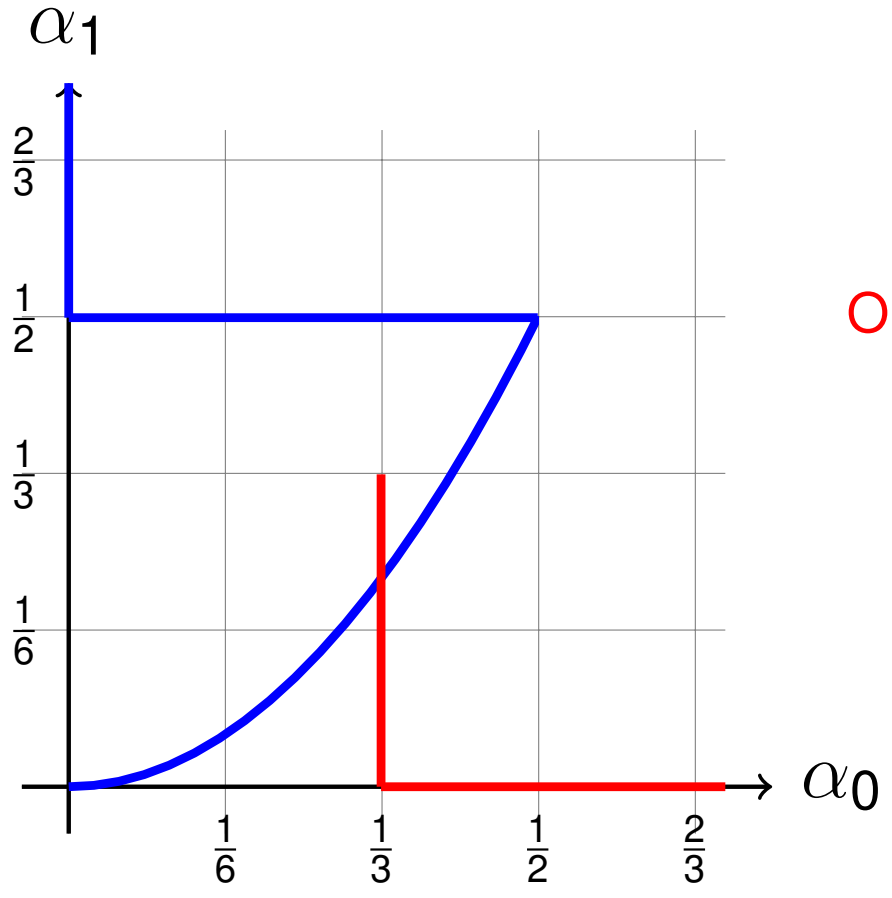


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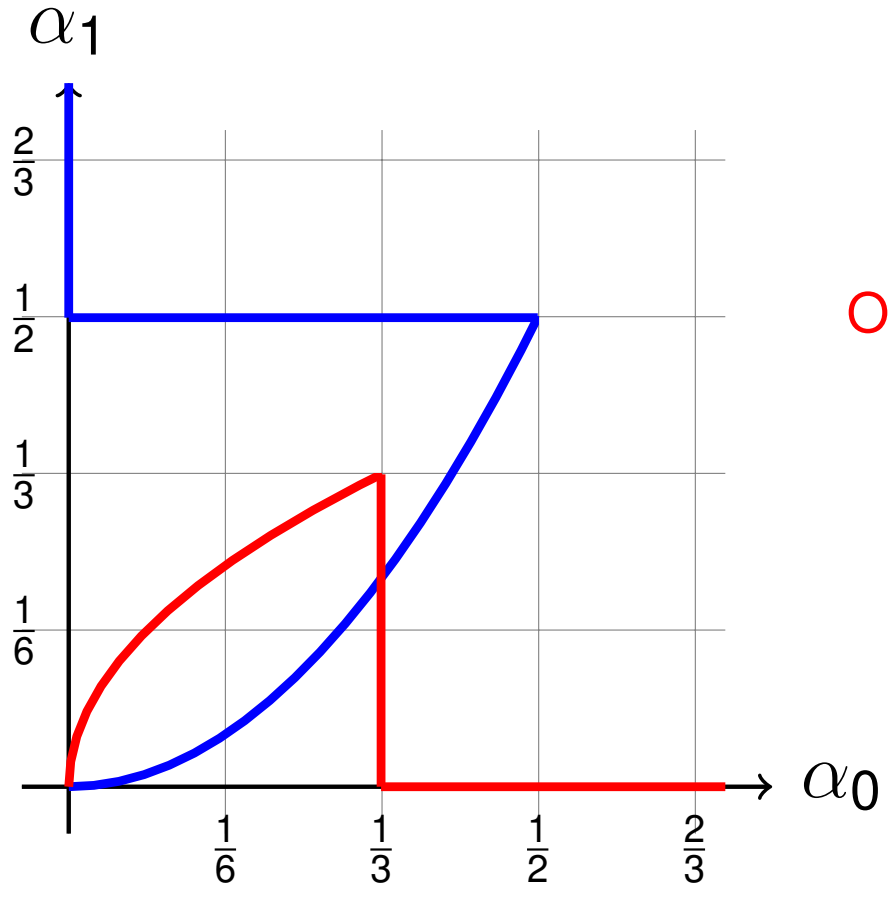


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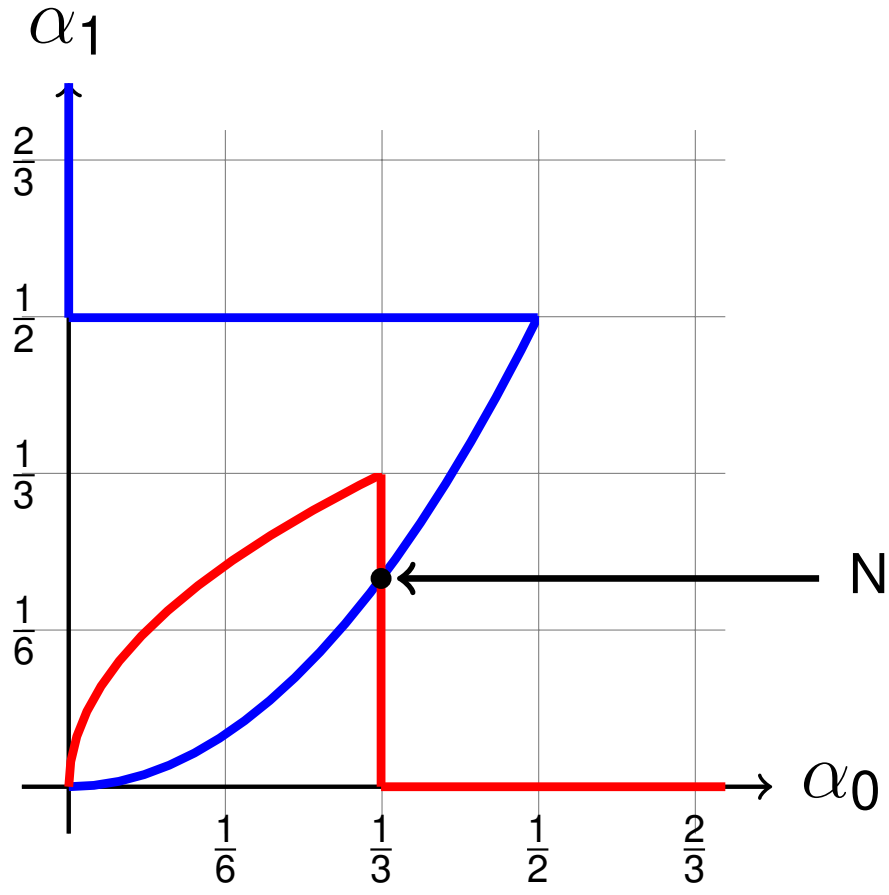


Nash equilibrium at $(\alpha_0, \alpha_1) = (\frac{1}{3}, \frac{2}{9})$

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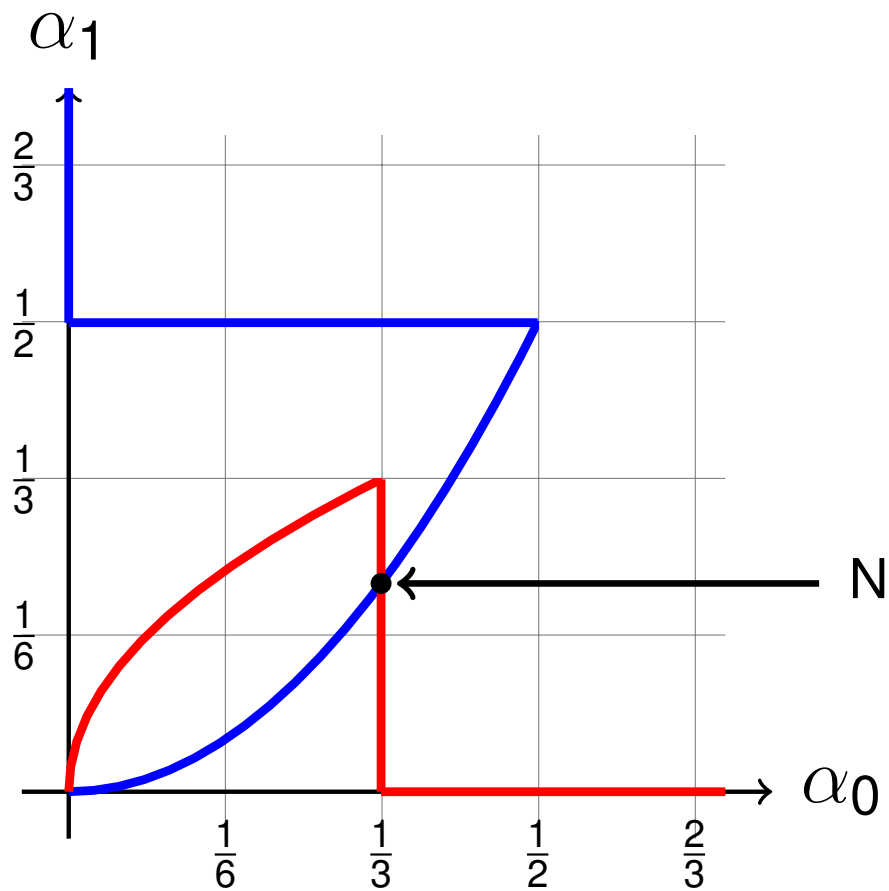



Nash equilibrium at $(\alpha_0, \alpha_1) = (\frac{1}{3}, \frac{2}{9})$

$(\gamma_0, \gamma_1) = (\frac{2}{3}, \frac{1}{3})$

$(\beta_0, \beta_1) = (\frac{1}{3}, 0)$

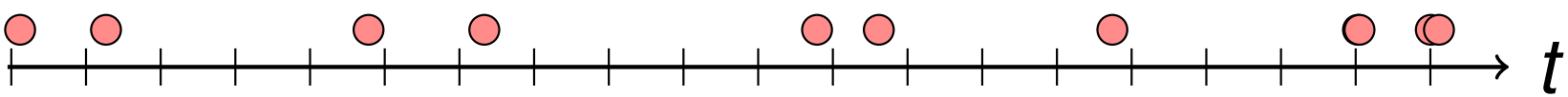
# Exponential Attacker

If Attacker plays exponentially with rate $\alpha_1$, then his moves form a memoryless Poisson process; he plays independently in each interval of time of size *dt* with probability $\alpha_1$ *dt*

Probability that intermove delay is at most *x* is

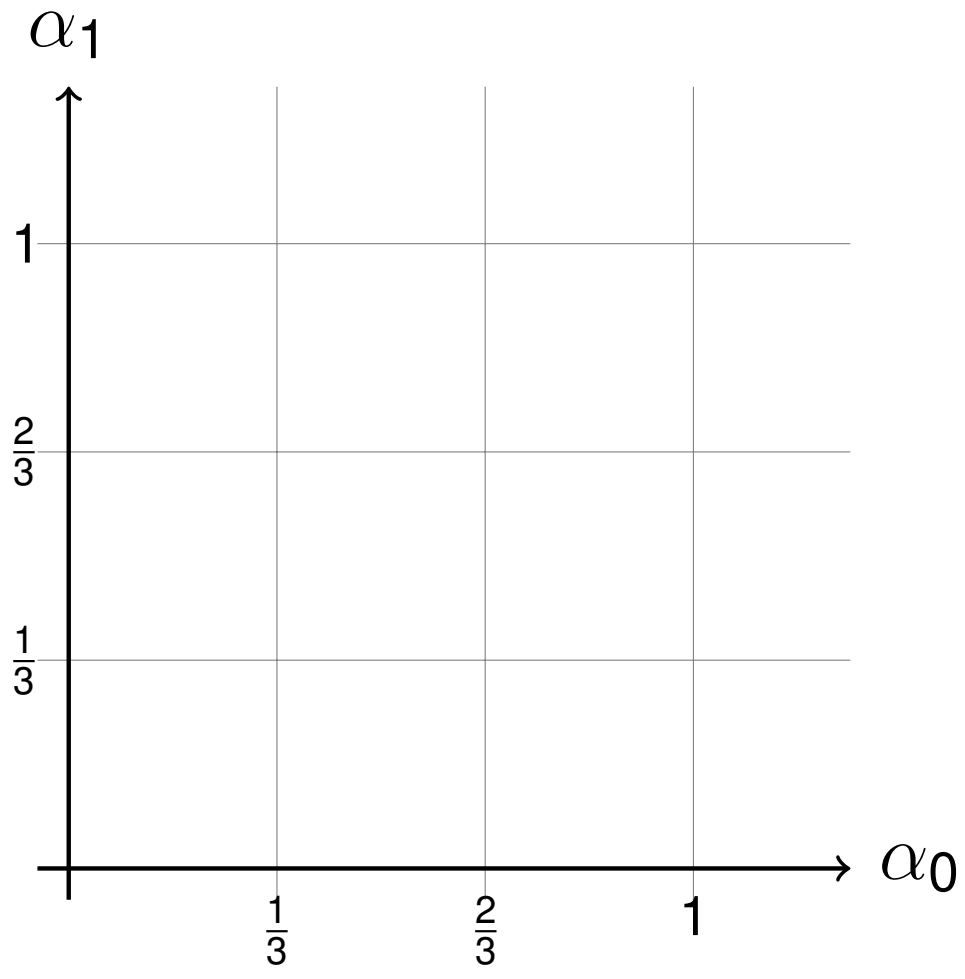
$$1 - e^{-\alpha_1 x}$$

For $\alpha_1 = 0.5$, we might have:



# Graph for Exponential Attacker and Defender)

($k_0 = 1, k_1 = 1.5$)



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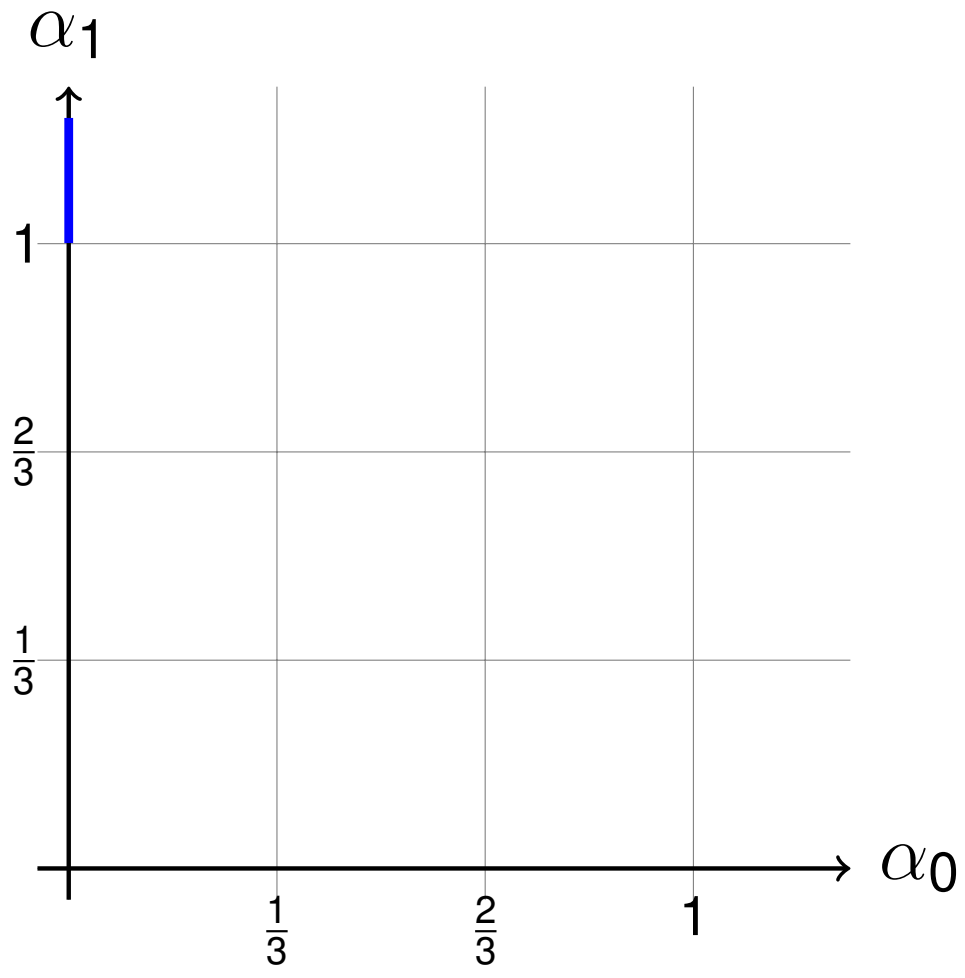

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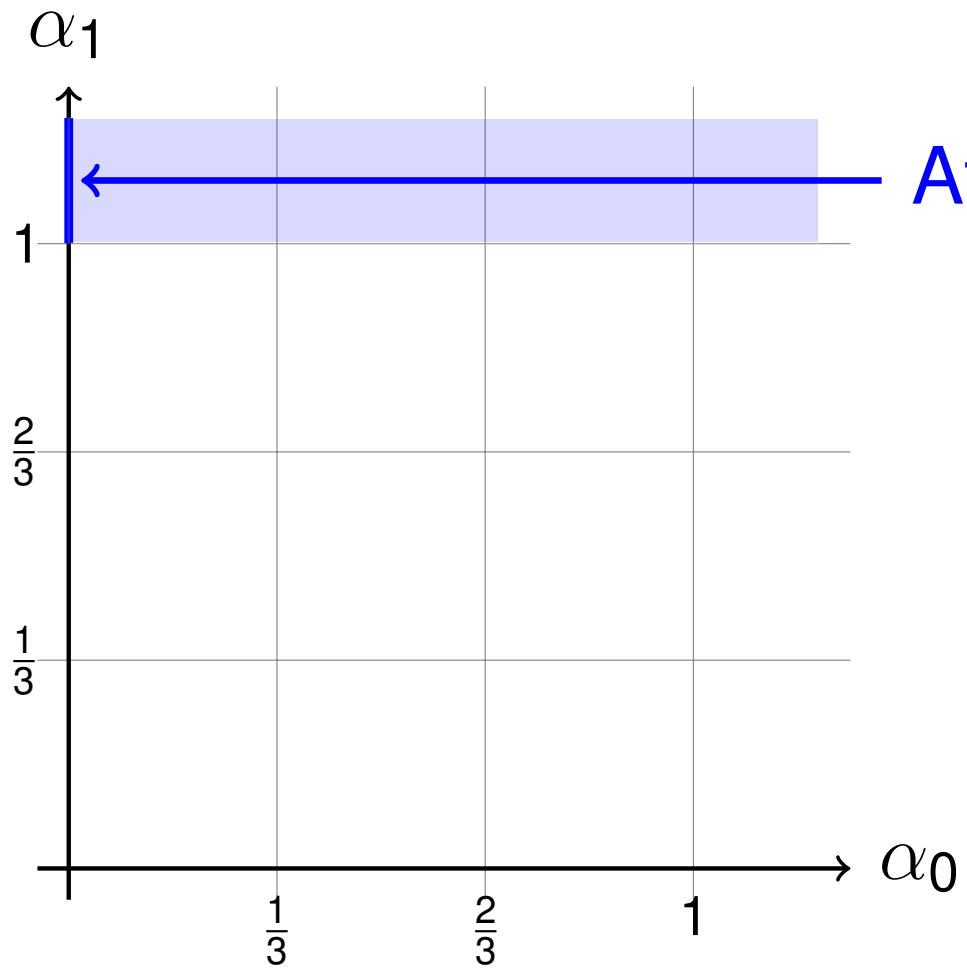


Attacker too fast if $\alpha_1 > 1$

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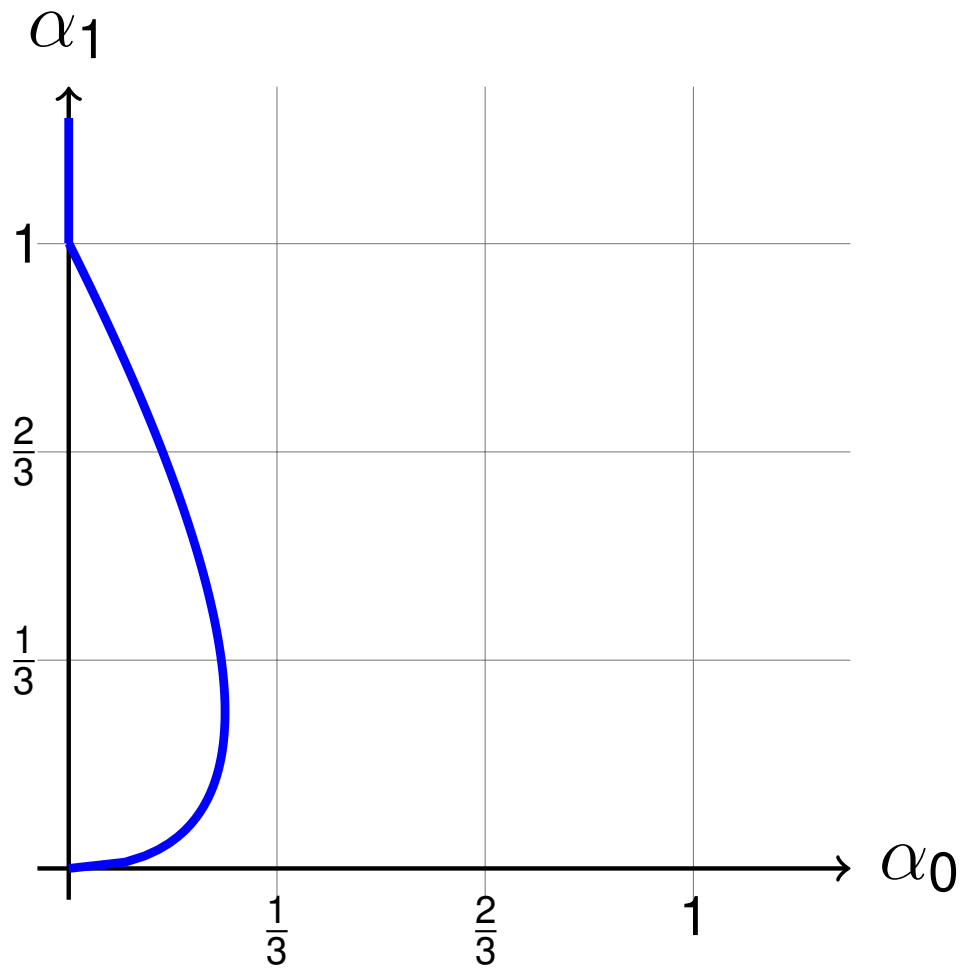

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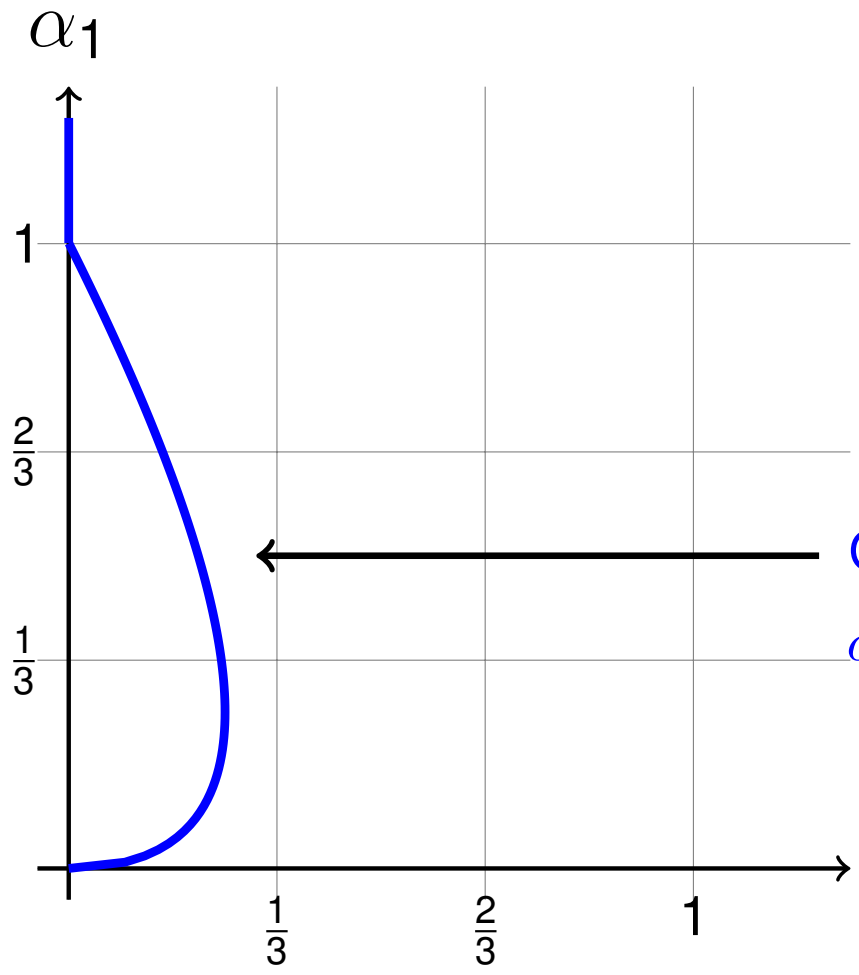


Optimal Defender play for $\alpha_1 < 1$

$\alpha_0 = \sqrt{\frac{\alpha_1}{k_0}} - \alpha_1$

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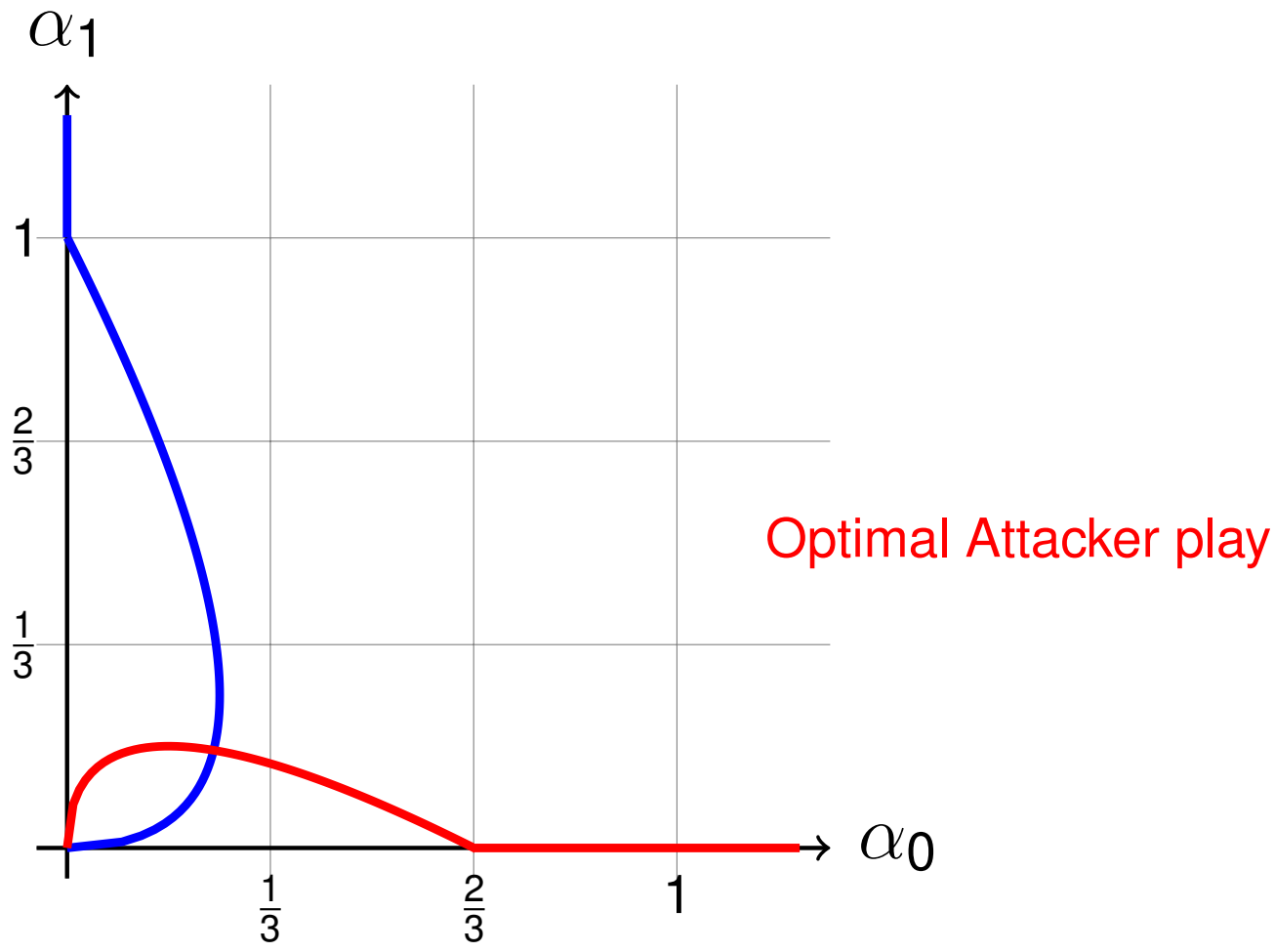

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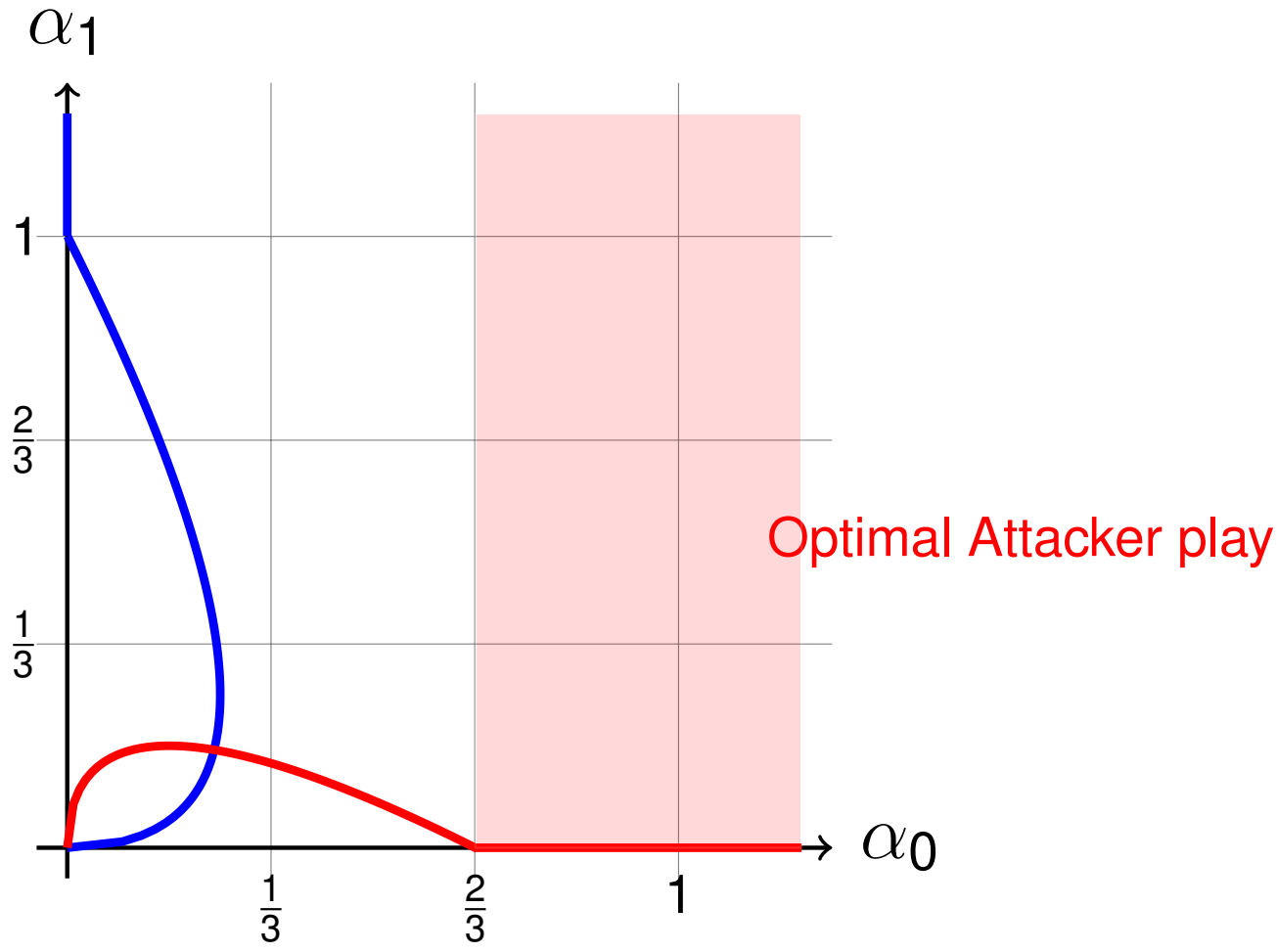

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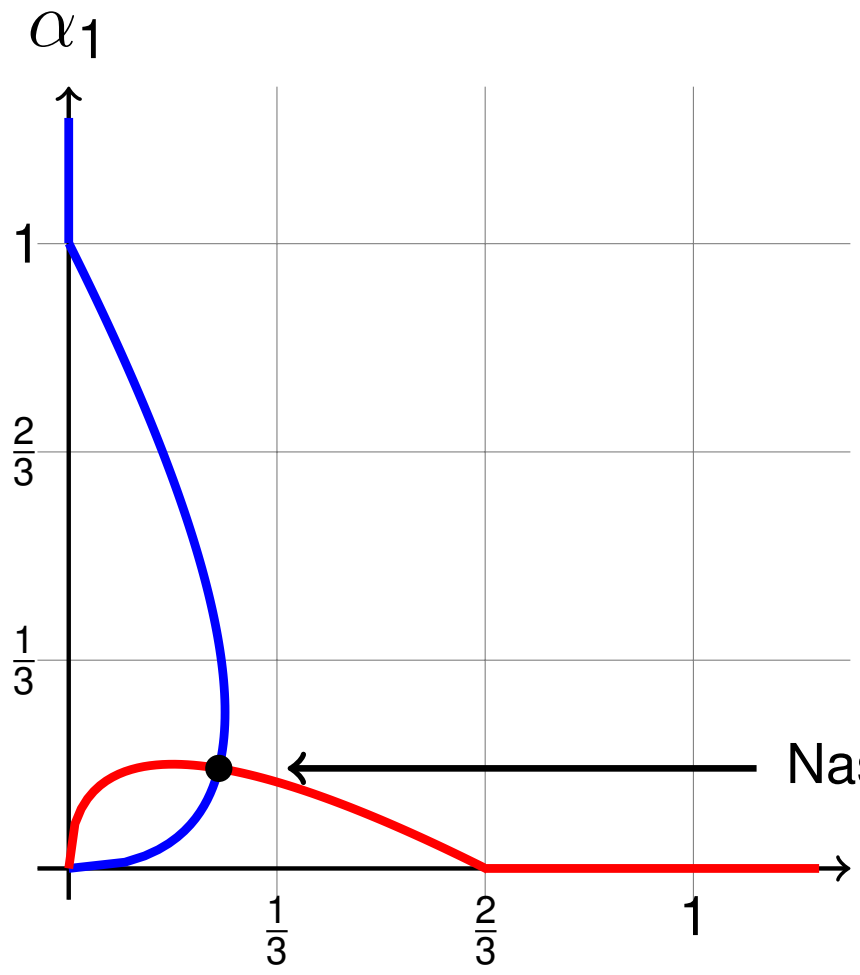


Nash equilibrium at $(\alpha_0, \alpha_1) = (\frac{6}{25}, \frac{4}{25})$

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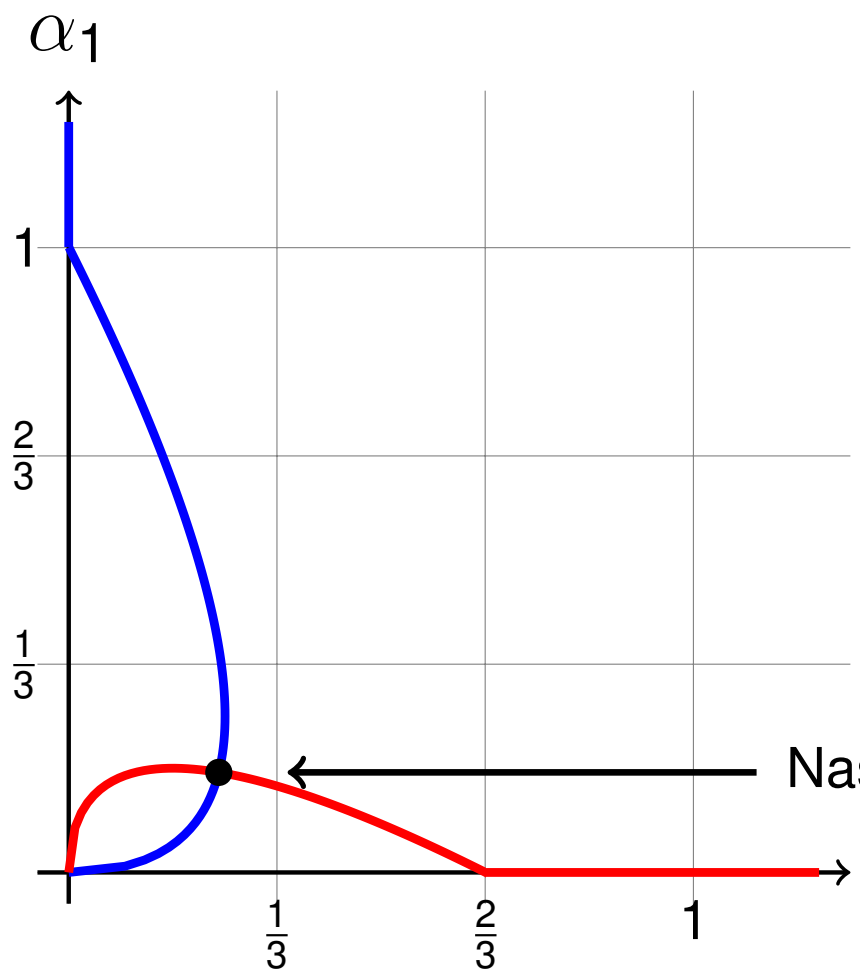


Nash equilibrium at $(\alpha_0, \alpha_1) = (\frac{6}{25}, \frac{4}{25})$

$(\gamma_0, \gamma_1) = (\frac{3}{5}, \frac{2}{5})$

$(\beta_0, \beta_1) = (\frac{9}{25}, \frac{6}{25})$

# Renewal Strategies

A *renewal strategy* is non-adaptive with iid intermove delays for player $i$'s moves:

$$\Pr(\text{delay} \leq x) = F_i(x)$$

for some distribution $F_i$.

Renewal strategies are a large class; periodic, exponential, etc. are special cases...
Origin of term: player's moves form a *renewal process*.

# Optimal (renewal) play against a renewal strategy.

One of our major results is the following:

Theorem

*The optimal renewal strategy against any renewal strategy is either periodic or not playing.*

# Proof notes

Average time between buses

$\neq$

Average waiting time for a bus

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$\neq$

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Proof considers *size-biased* interval sizes...

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$\neq$

Average waiting time for a bus

Proof considers *size-biased* interval sizes...

Note that a periodic strategy minimizes variance of interval sizes, and thus minimizes size-biased interval size.

# Adaptive Play

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- Periodic strategy not very effective against *adaptive* Attacker, who can learn to move just after each Defender move.
- FLIPIT with adaptive strategies can be complicated – generalizes iterated Prisoner's Dilemma—e.g. for periodic play:

| | slow($\alpha_1 = 0.1$) | fast($\alpha_1 = 0.2$) |
|---|---|---|
| slow($\alpha_0 = 0.1$) | 0.40,0.40 | -0.10,0.55 |
| fast($\alpha_0 = 0.2$) | 0.55,-0.10 | 0.30,0.30 |

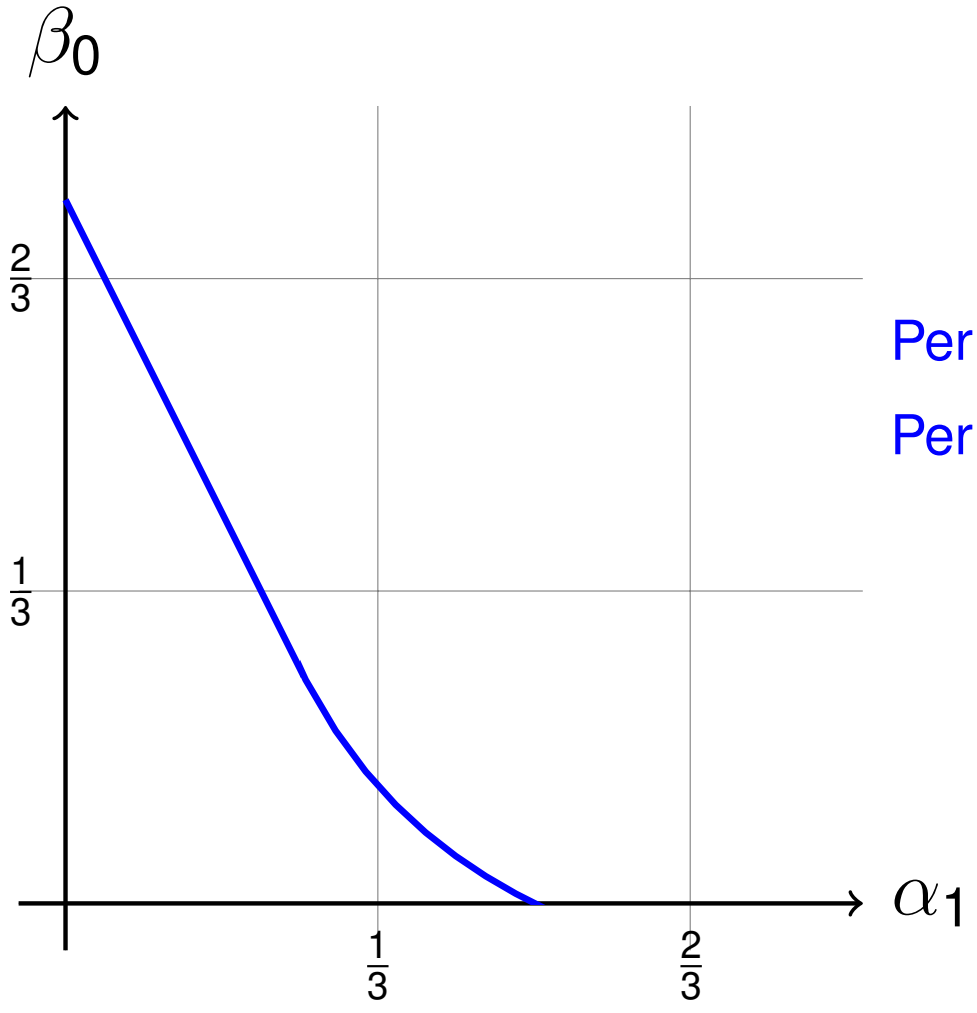
# Exponential works well even against adaptive strategies

Theorem

*The optimal strategy (of any sort, even adaptive) against an exponential strategy is either periodic or not playing.*

Defender can always play exponential strategy against a potentially adaptive Attacker; Attacker can't then do better than playing periodically (or not playing).

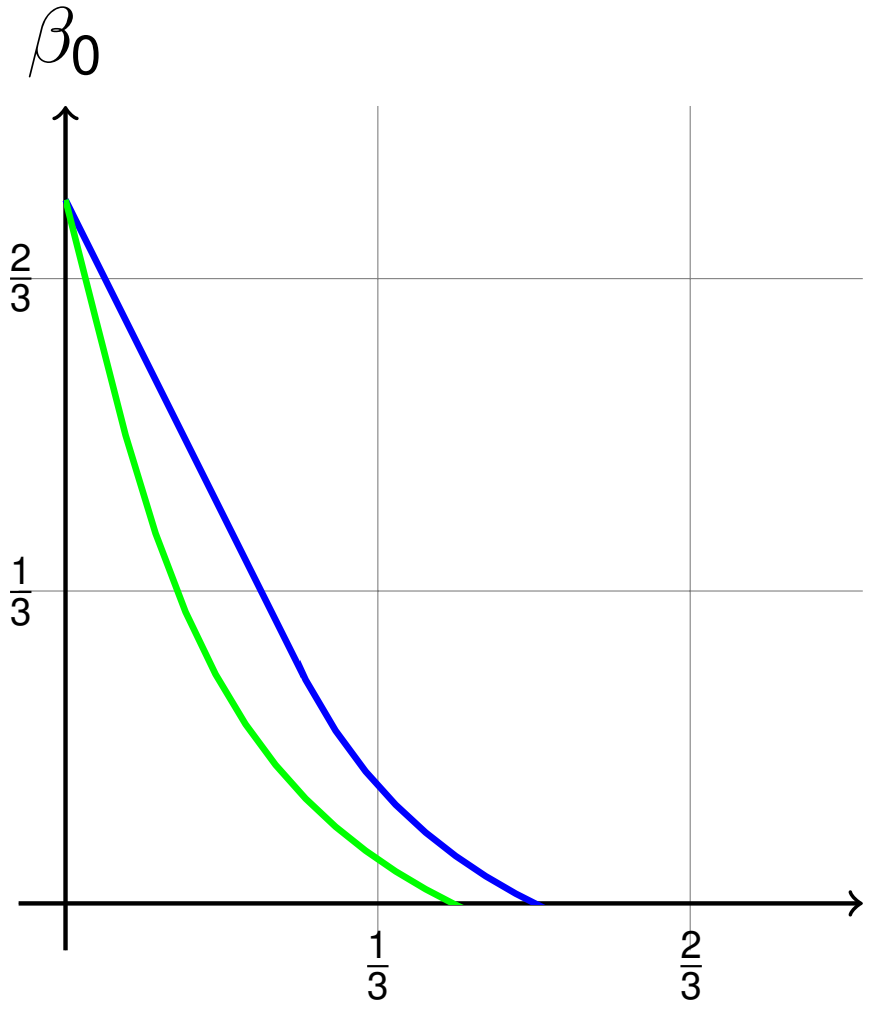
# Defender's ($\alpha_0 = 0.25$) net benefit $\beta_0$ against optimal (periodic) Attacker ($\alpha_1$ *variable*)




Periodic Attacker

Periodic Defender

# Defender's ($\alpha_0 = 0.25$) net benefit $\beta_0$ against optimal (adaptive) Attacker ($\alpha_1$ *variable*)




Periodic Attacker

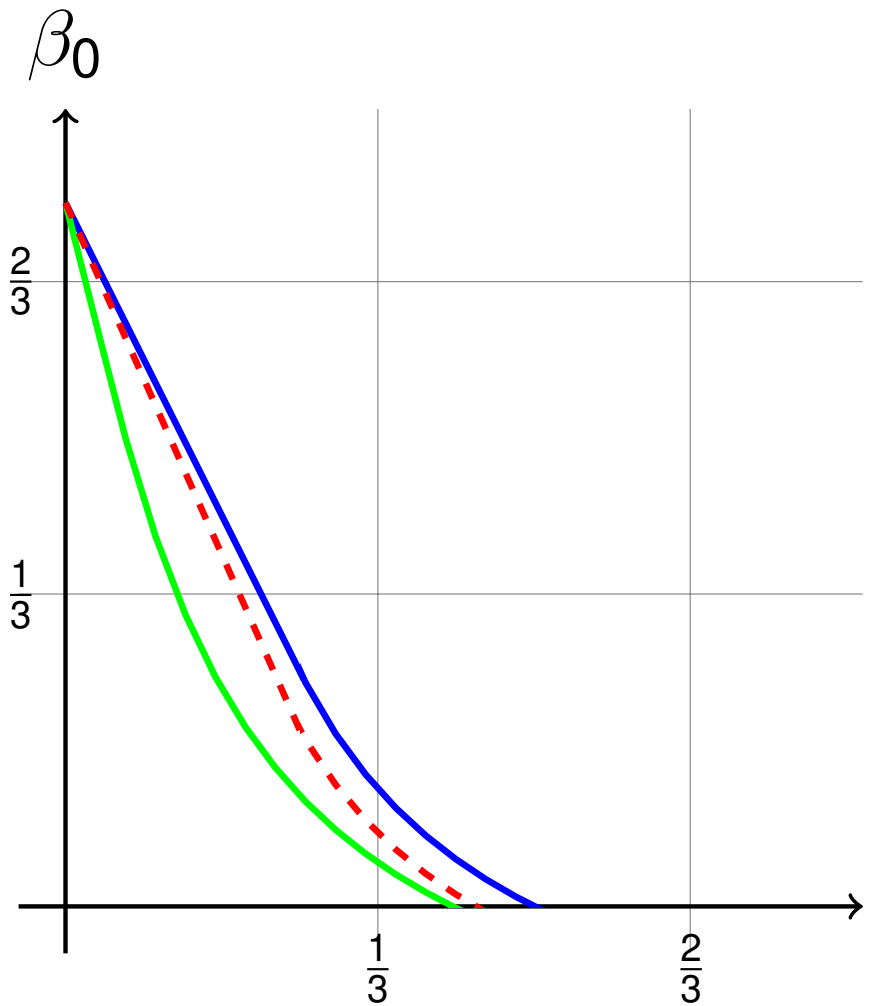
Periodic Defender

$\Downarrow$

Adaptive Attacker

Exponential Defender

# Defender's ($\alpha_0 = 0.25$) net benefit $\beta_0$ against optimal (adaptive) Attacker ($\alpha_1$ *variable*)




Periodic Attacker

Periodic Defender

$\Downarrow$

Adaptive Attacker

Exponential Defender

$\exists$ ? Better Defender ?

# Lessons and Open Questions

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- Be prepared to deal with repeated total failure (loss of control).

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  (Reboot server frequently; change password often)

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- Be prepared to deal with repeated total failure (loss of control).
- Play fast! Aim to make opponent drop out! (Agility!)
  (Reboot server frequently; change password often)
- Arrange game so that your moves cost much less than your opponent's!
  (Cheap to refresh passwords or keys, easy to reset system to pristine state (as with a virtual machine))

# Open question 1

Conjecture: The optimal non-adaptive strategy against a renewal strategy is periodic.

(We proved only that optimal *renewal* strategy is periodic; not every non-adaptive strategy is a renewal strategy.)

# Open question 2

What is “optimal” renewal strategy against an adaptive rate-limited Attacker?
(e.g. $N_1(t)/t \leq \alpha_1$ for all $t$)?

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What is “optimal” renewal strategy against an adaptive rate-limited Attacker?
(e.g. $N_1(t)/t \leq \alpha_1$ for all $t$)?

That is, how to balance trade-off between periodic play, which has low-variance intervals but is predictable, and exponential, which has high-variance intervals but is very unpredictable?

Perhaps using gamma-distributed intervals or delayed exponentials?

# Open question 3

Are there information-theoretic bounds on how well a rate-limited Attacker can do against a fixed renewal strategy by Defender?

# Open question 4

What learning theory algorithms yield adaptive strategies provably optimal against renewal strategies?

# Open questions 5, 6, 7, ...

5. Multi-player FLIPIT
6. Other feedback models (e.g. add low-cost "check")
7. How to structure PKI when any party (including CA's) may get "hacked" at any time?

... ...

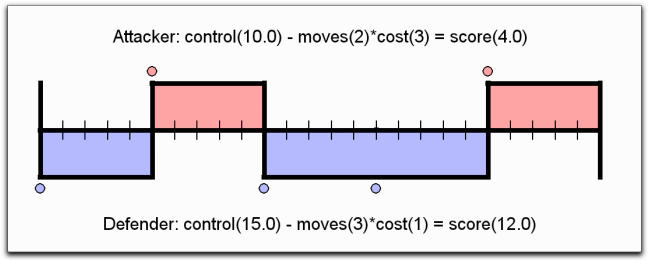
# Online version of FLIPIT

More information on FLIPIT, including an online interactive version of the game, will be available in the next few weeks at:

www.rsa.com/flipit

Enjoy!

# The End


Attacker: control(10.0) - moves(2)*cost(3) = score(4.0)
Defender: control(15.0) - moves(3)*cost(1) = score(12.0)