Online learning using limited feedback

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Outline

The multiple-arm bandits problem

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The one armed bandit

The multiple arm bandit problem

Given

Play these machines

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Goal: Maximize expected wealth.

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Mathematical formulation for common Exploration vs. Exploitation dilemma.

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single-iteration reward is in the range $[0, 1]$

Classical analysis

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- Each machine has a different distribution of rewards.
- Basic idea: sample so as to minimize uncertainty in identity of best arm.

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- Can you still find the best machine?
- What does “best machine” mean?

Example adversarial MAB game

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action1
action2
action3
action4
action5
action6
action7
action8

Example adversarial MAB game

	P_1
action1	$1/8$
action2	$1/8$
action3	$1/8$
action4	$1/8$
action5	$1/8$
action6	$1/8$
action7	$1/8$
action8	$1/8$

Example adversarial MAB game

	P_1	i_1
action1	$1/8$	
action2	$1/8$	
action3	$1/8$	
action4	$1/8$	$\Rightarrow$
action5	$1/8$	
action6	$1/8$	
action7	$1/8$	
action8	$1/8$	

Example adversarial MAB game

	P_1	i_1	$\boldsymbol{x}(1)$
action1	$1/8$		.1
action2	$1/8$		.8
action3	$1/8$		.3
action4	$1/8$	$\Rightarrow$	.5
action5	$1/8$		.9
action6	$1/8$		0
action7	$1/8$		1
action8	$1/8$		.8

Example adversarial MAB game

	P_1	i_1	$\boldsymbol{x}(1)$	p_2
action1	$1/8$		.1	.12
action2	$1/8$		.8	.12
action3	$1/8$		.3	.12
action4	$1/8$	$\Rightarrow$	.5	.16
action5	$1/8$		.9	.12
action6	$1/8$		0	.12
action7	$1/8$		1	.12
action8	$1/8$		.8	.12

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action3	$1/8$		.3	.12	
action4	$1/8$	$\Rightarrow$	.5	.16	
action5	$1/8$		.9	.12	
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action2	$1/8$		.8	.12		.5
action3	$1/8$		.3	.12		.2
action4	$1/8$	$\Rightarrow$	.5	.16		.7
action5	$1/8$		.9	.12		1
action6	$1/8$		0	.12		.1
action7	$1/8$		1	.12	$\Rightarrow$	.7
action8	$1/8$		.8	.12		.2

Example adversarial MAB game

	P_1	i_1	$\boldsymbol{x}(1)$	p_2	i_2	$\boldsymbol{x}(2)$	p^3
action1	$1/8$		.1	.12		.1	0.11
action2	$1/8$		.8	.12		.5	0.11
action3	$1/8$		.3	.12		.2	0.11
action4	$1/8$	$\Rightarrow$	.5	.16		.7	0.15
action5	$1/8$		.9	.12		1	0.11
action6	$1/8$		0	.12		.1	0.11
action7	$1/8$		1	.12	$\Rightarrow$	.7	0.19
action8	$1/8$		.8	.12		.2	0.11

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action1	$1/8$		.1	.12		.1	0.11	
action2	$1/8$		.8	.12		.5	0.11	$\Rightarrow$
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action8	$1/8$		.8	.12		.2	0.11		.6

Example adversarial MAB game

	P_1	i_1	$\boldsymbol{x}(1)$	p_2	i_2	$\boldsymbol{x}(2)$	p^3	i_3	$\boldsymbol{x}(3)$	total
action1	$1/8$		.1	.12		.1	0.11		0	.2
action2	$1/8$		.8	.12		.5	0.11	$\Rightarrow$	.2	1.5
action3	$1/8$		.3	.12		.2	0.11		.2	.7
action4	$1/8$	$\Rightarrow$	.5	.16		.7	0.15		.8	2.0
action5	$1/8$		.9	.12		1	0.11		.8	2.7
action6	$1/8$		0	.12		.1	0.11		.2	.3
action7	$1/8$		1	.12	$\Rightarrow$	.7	0.19		.4	2.1
action8	$1/8$		.8	.12		.2	0.11		.6	1.6

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- Why reward instead of loss?
- Because regret bounds that depend on the loss of the best action (rather than T) are impossible.

The basic algorithm (EXP3)

For each $t = 1, 2, \ldots$

1. Set

$$p_i(t) = (1-\gamma)\frac{w_i^t}{\sum_{j=1}^{K} w_j^t} + \frac{\gamma}{K} \qquad i = 1, \ldots, K.$$

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4. For $j = 1, \ldots, K$ set

$$\begin{aligned} \hat{x}_j(t) &= \begin{cases} x_j(t)/p_j(t) & \text{if } j = i_t \\ 0 & \text{otherwise,} \end{cases} \\ w_j^{t+1} &= w_t^j \exp\left(\gamma \hat{x}_j(t)/K\right) . \end{aligned}$$

Basic bound

- Let T be the number of iterations and that algorithm **Exp3** is run with

$$\gamma = \min\left\{1, \sqrt{\frac{K \ln K}{(e-1)T}}\right\}.$$

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- Then

$$G_{\max} - \mathbf{E}[G_{\mathbf{Exp3}}] \leq 2\sqrt{e-1}\sqrt{TK \ln K} \leq 2.63\sqrt{TK \ln K}$$

Ideas of proof

1. Setting

$$\hat{x}_j(t) = \begin{cases} x_j(t)/p_j(t) & \text{if } j = i_t \\ 0 & \text{otherwise,} \end{cases}$$

guarantees that $\mathbf{E}\left(\sum_{t=1}^{t} \hat{x}_j(t)\right) = \sum_{t=1}^{T} x_j(t)$ i.e. estimate of total gain is Unbiased.

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2. Setting $\gamma = O(\sqrt{\frac{K \log K}{T}})$ guarantees variance of estimator is not too large.
3. **Exp3** mimicks **Hedge** sufficiently well.

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- $K-1$ actions use probs $(1/2, 1/2)$.
- One action (chosen at random) uses probs $1/2+\epsilon, 1/2-\epsilon$.
- The Bayes optimal algorithm has expected regret at least

$$\frac{1}{20}\min\left(\sqrt{KT}, T\right)$$

Tuning γ online

Algorithm Exp3.1
Initialization: Let $t = 1$, and $\hat{G}_i(1) = 0$ for $i = 1, \ldots, K$

Repeat for $r = 0, 1, 2, \ldots$

1. Let $g_r = (K \ln K)/(e-1)\, 4^r$.
2. Restart **Exp3** choosing $\gamma_r = \min\left\{1, \sqrt{\frac{K \ln K}{(e-1)g_r}}\right\}$.
3. **While** $\max_i \hat{G}_i(t) \le g_r - K/\gamma_r$ **do:**
   (a) Let i_t be the random action chosen by **Exp3** and $x_{i_t}(t)$ the corresponding reward.
   (b) $\hat{G}_i(t+1) = \hat{G}_i(t) + \hat{x}_i(t)$ for $i = 1, \ldots, K$.
   (c) $t := t + 1$

Bound for Exp3.1

$$G_{\max} - \mathbf{E}[G_{\mathbf{Exp3.1}}] \leq 8\sqrt{e-1}\sqrt{G_{\max} K \ln K} + 8(e-1)K + 2K \ln K$$

Bound for Exp3.1

$$
\begin{aligned}
G_{\max} - \mathbf{E}[G_{\mathbf{Exp3.1}}] &\leq 8\sqrt{e-1}\sqrt{G_{\max} K \ln K} + 8(e-1)K + 2K \ln K \\
&\leq 10.5\sqrt{G_{\max} K \ln K} + 13.8\, K + 2K \ln K
\end{aligned}
$$

Allowing switching actions

Algorithm Exp3.S
Parameters: Reals $\gamma \in (0, 1]$ and $\alpha > 0$.
Initialization: $w_i(1) = 1$ for $i = 1, \ldots, K$.

For each $t = 1, 2, \ldots$

1. Set
$$p_i(t) = (1-\gamma)\frac{w_i(t)}{\sum_{j=1}^{K} w_j(t)} + \frac{\gamma}{K} \qquad i = 1, \ldots, K.$$
2. Draw i_t according to the probabilities $p_1(t), \ldots, p_K(t)$.
3. Receive reward $x_{i_t}(t) \in [0, 1]$.
4. For $j = 1, \ldots, K$ set
$$\begin{aligned} \hat{x}_j(t) &= \begin{cases} x_j(t)/p_j(t) & \text{if } j = i_t \\ 0 & \text{otherwise,} \end{cases} \\ w_j(t+1) &= w_j(t)\exp\left(\gamma \hat{x}_j(t)/K\right) + \frac{e\alpha}{K}\sum_{i=1}^{K} w_i(t)\,. \end{aligned}$$

Bound for Exp3.S

- Hardness of sequence = number of switches offline is allowed:

$$S \geq \mathrm{H}(j_1, \ldots, j_T) \stackrel{\text{def}}{=} 1 + |\{1 \leq \ell < T \; : \; j_\ell \neq j_{\ell+1}\}| \; .$$

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- Assume $\alpha = 1/T$ and $\gamma = \min\left\{1, \sqrt{\frac{K(S\ln(KT)+e)}{(e-1)T}}\right\}$.
- Then

$$G_{j^T} - \mathbf{E}\left[G_{\mathbf{Exp3.S}}\right] \leq 2\sqrt{e-1}\sqrt{KT\left(S\ln(KT)+e\right)}$$

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- Considering experts as actions, we get a bound $O(\sqrt{gN \log N})$ on the regret.
- By acting smarter, we can get a bound $O(\sqrt{gK \log N})$

Allowing switching actions

For each $t = 1, 2, \ldots$

1. Get advice vectors $\boldsymbol{\xi}^1(t), \ldots, \boldsymbol{\xi}^N(t)$.
2. Set $W_t = \sum_{i=1}^{N} w_i(t)$ and for $j = 1, \ldots, K$ set
$$p_j(t) = (1-\gamma) \sum_{i=1}^{N} \frac{w_i(t)\xi_j^i(t)}{W_t} + \frac{\gamma}{K} .$$
3. Draw action i_t randomly according to the probabilities $p_1(t), \ldots, p_K(t)$.
4. Receive reward $x_{i_t}(t) \in [0, 1]$.
5. For $j = 1, \ldots, K$ set
$$\hat{x}_j(t) = \begin{cases} x_j(t)/p_j(t) & \text{if } j = i_t \\ 0 & \text{otherwise,} \end{cases}$$
6. For $i = 1, \ldots, N$ set
$$\begin{aligned} \hat{y}_i(t) &= \boldsymbol{\xi}^i(t) \cdot \hat{\boldsymbol{x}}(t) \\ w_i(t+1) &= w_i(t) \exp\left(\gamma \hat{y}_i(t)/K\right) . \end{aligned}$$

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- If we have many strategies N but only few actions K we can achieve bounds of the form $O(\sqrt{TK \log N})$.
- Example application: choosing a route for an IP packet.
- Next class: what happends when both opponents use **Hedge**?