On Sequential Decision Problems

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Équipe-projet AOC: Apprentissage, Optimisation, Complexité
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Université Paul Sabatier Toulouse III

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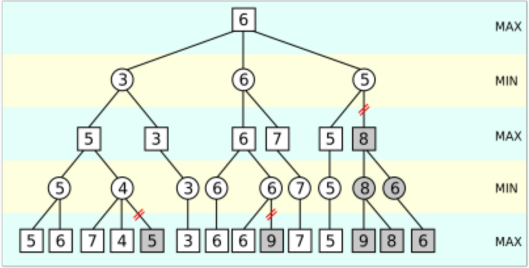
Sequential Decision Problems

Solving a Game

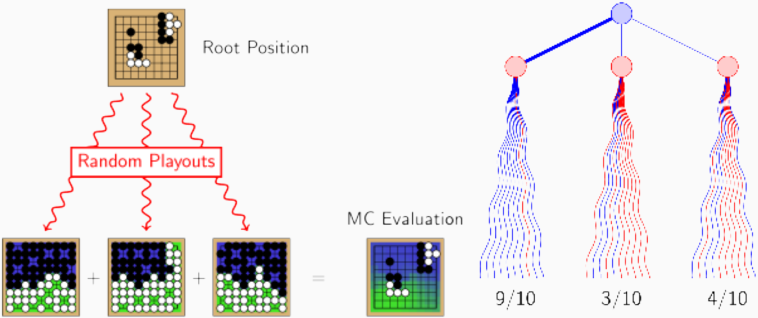
2 player game with finite number of actions



src: `wikipedia.org`

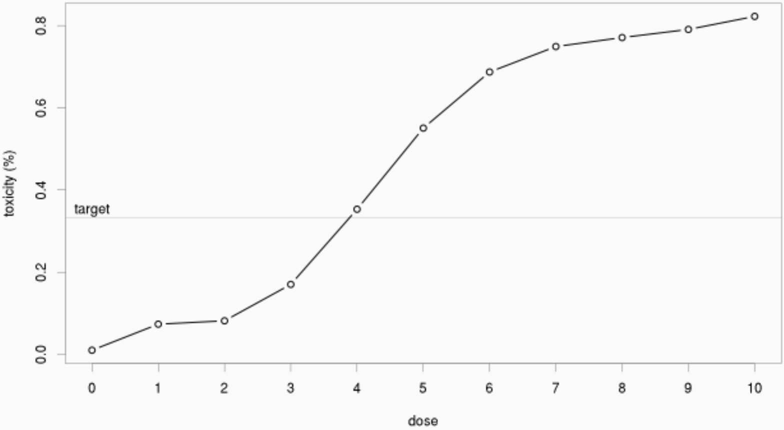
but too deep for exhaustive search of minimax action (by alpha-beta)
Example: Go ($\approx 10^{171}$ possible configurations)

Heuristic search algorithm using random playouts / rollouts

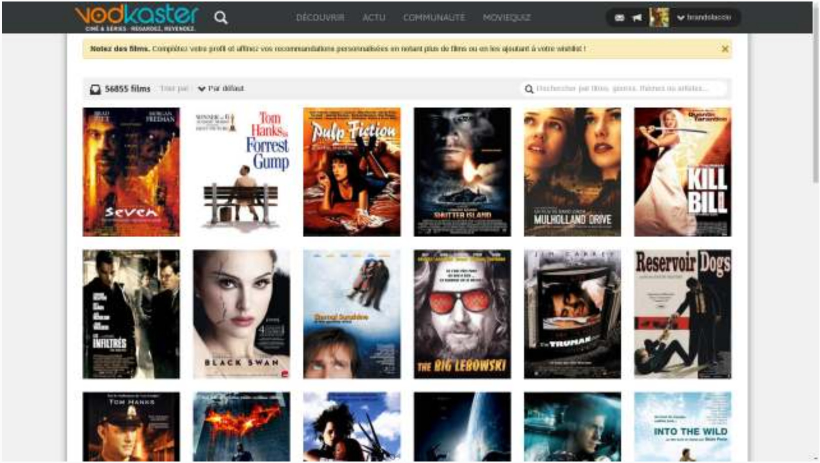


src: https://www.remi-coulom.fr/

Dose Finding

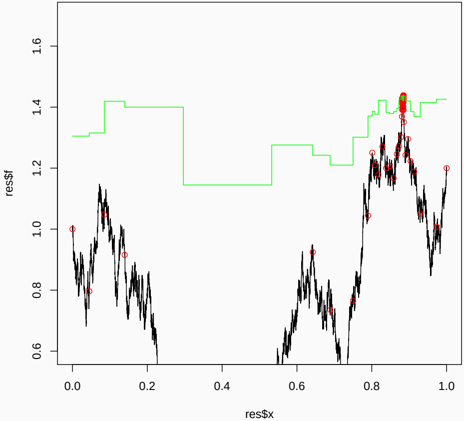


Content Recommandation



Optimization

- Goal : maximize function $f : C \subset \mathbb{R}^d \to \mathbb{R}$ possibly observed with noise
- Applications: computer experiment



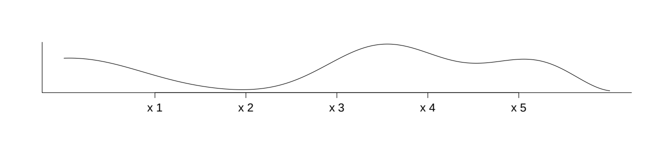
- Model: f comes from a Gaussian Process, or when it has a small norm in the induced RKHS.

The Simple Bandit Model

Best-Arm Identification with Fixed Confidence

K options = probability distributions $\boldsymbol{\nu} = (\nu_a)_{1 \leq a \leq K}$

$\nu_a \in \mathcal{F}$ exponential family parameterized by its expectation μ_a



At round t, you may:

- choose an option $A_t = \phi_t(A_1, X_1, \ldots, A_{t-1}, X_{t-1})) \in \{1, \ldots, K\}$
- observe a new independent sample $X_t \sim \nu_{A_t}$

so as to identify the best option $a^* = \mathrm{argmax}_a\, \mu_a$ and $\mu^* = \max_a \mu_a$
as fast as possible: stopping time τ .

Fixed-budget setting	Fixed-confidence setting
given $\tau = T$ minimize $\mathbb{P}(\hat{a}_\tau \neq a^*)$	minimize $\mathbb{E}[\tau]$ under constraint $\mathbb{P}(\hat{a}_\tau \neq a^*) \leq \delta$

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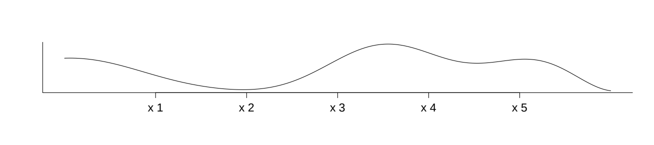

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minimize $\mathbb{P}(\hat{a}_\tau \neq a^*)$	under constraint $\mathbb{P}(\hat{a}_\tau \neq a^*) \leq \delta$

Intuition: a Simple Example

Most simple setting: for all $a \in \{1, \ldots, K\}$,

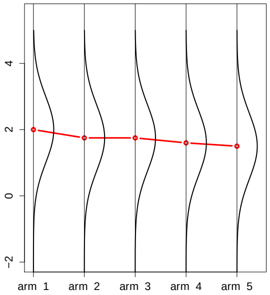
$$\nu_a = \mathcal{N}(\mu_a, 1)$$

For example: $\mu = [2, 1.75, 1.75, 1.6, 1.5]$.

At time t:

➜ you have sampled n_a times the option a

➜ your empirical average is $\bar{X}_{a,n_a}$.



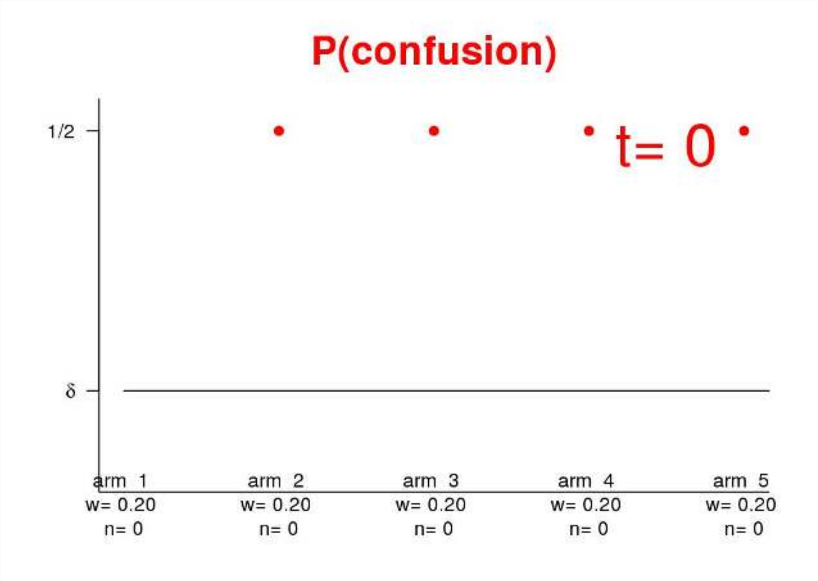
$\longrightarrow$ if you stop at time t, your probability of prefering arm $a \geq 2$ to arm $a^* = 1$ is:

$$\mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right) = \mathbb{P}\left(\frac{\bar{X}_{a,n_a} - \mu_a - (\bar{X}_{1,n_1} - \mu_1)}{\sqrt{1/n_1 + 1/n_a}} > \frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right)$$

$$= \bar{\Phi}\left(\frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right)$$

where $\bar{\Phi}(u) = \int_u^\infty \frac{e^{-u^2/2}}{\sqrt{2\pi}} du$

Uniform Sampling



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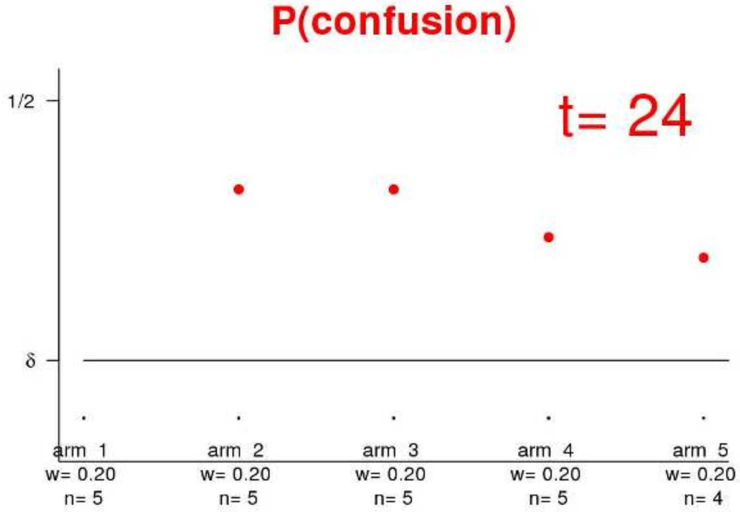

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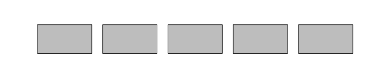

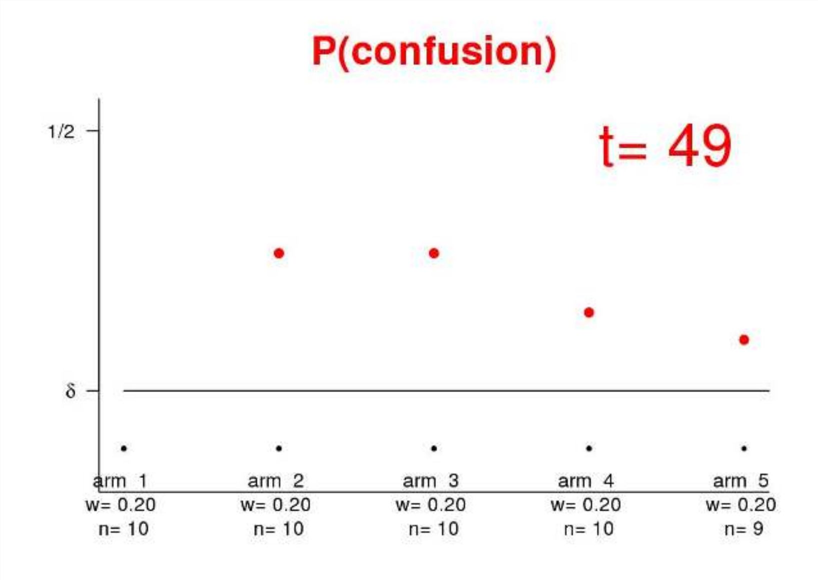

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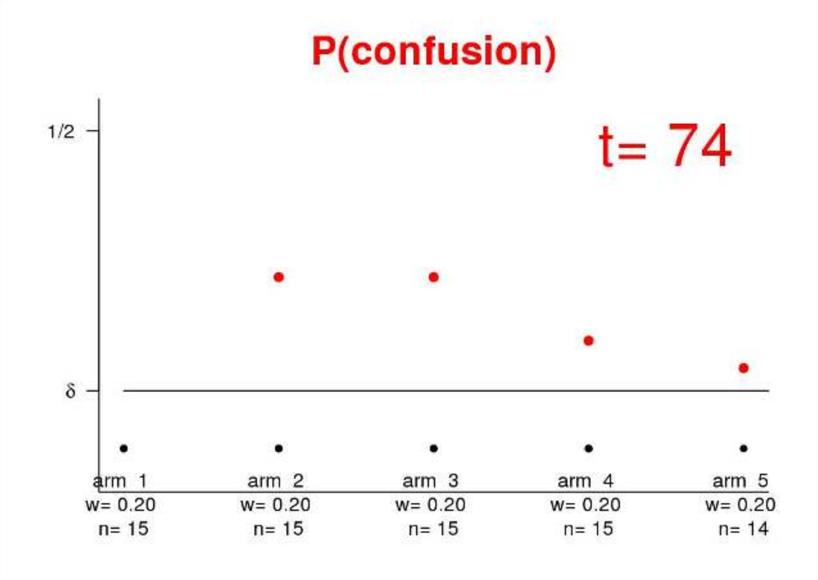

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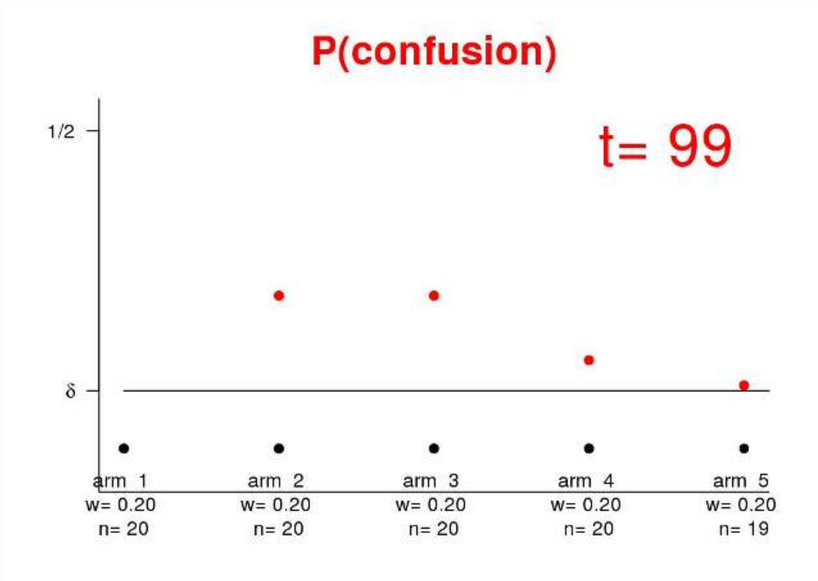

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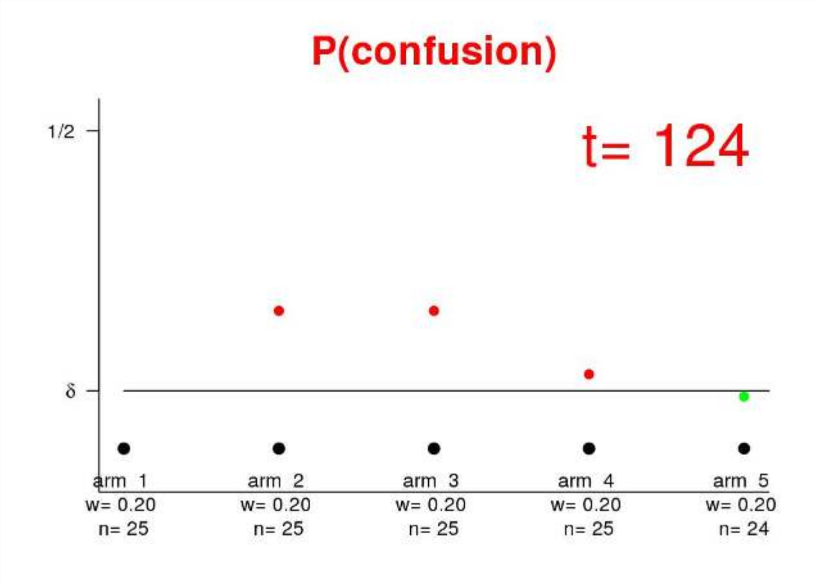

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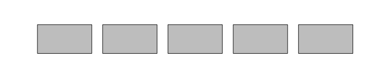

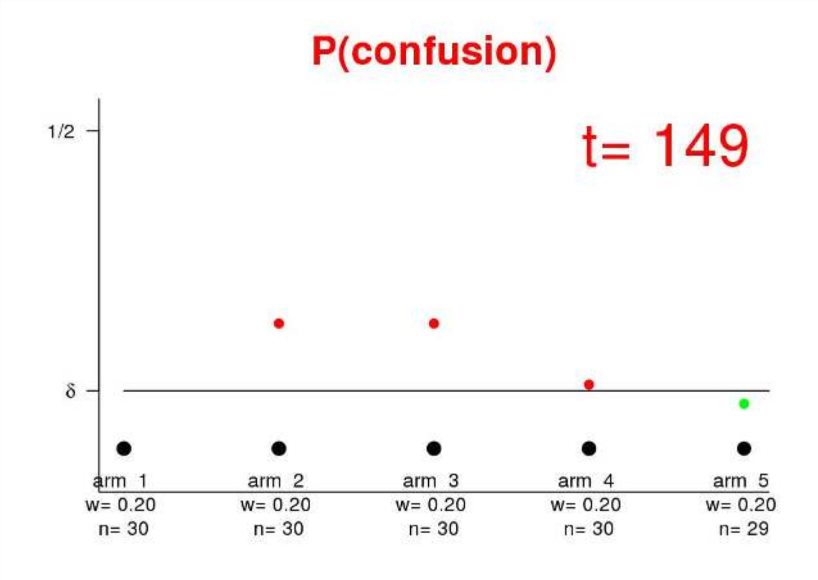

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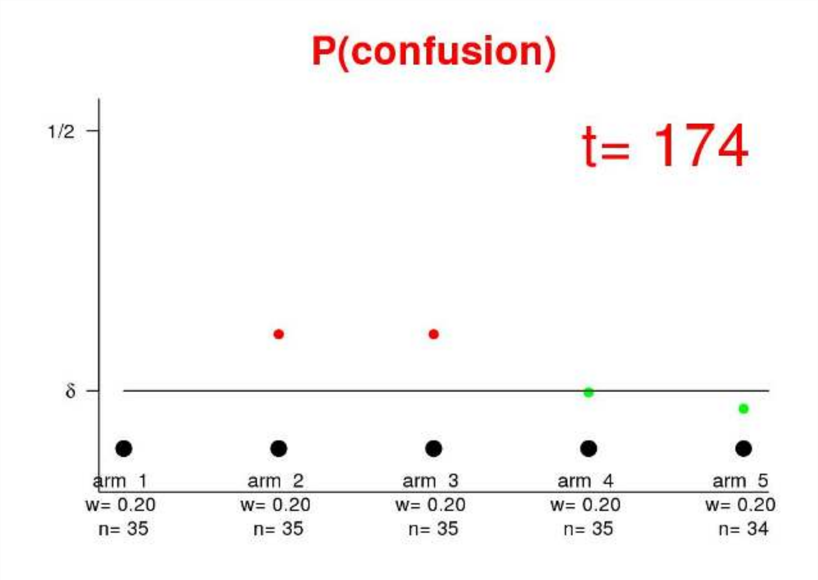

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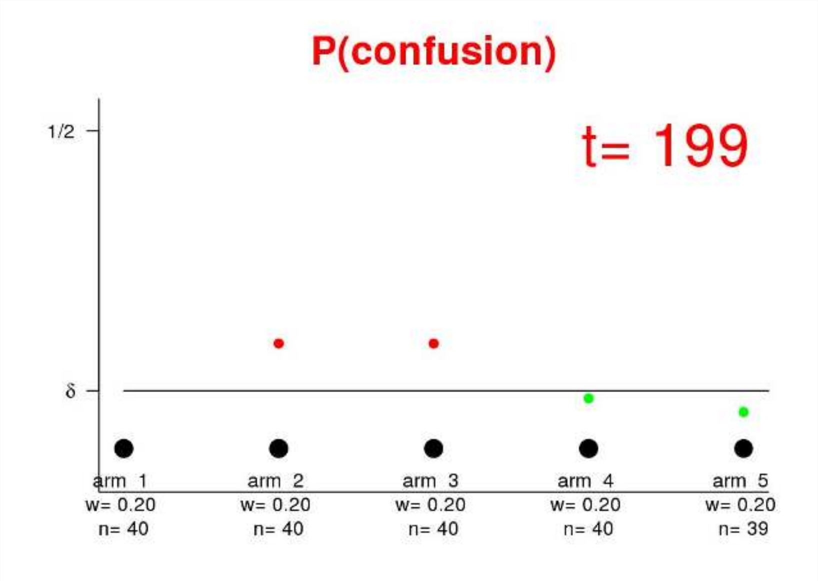

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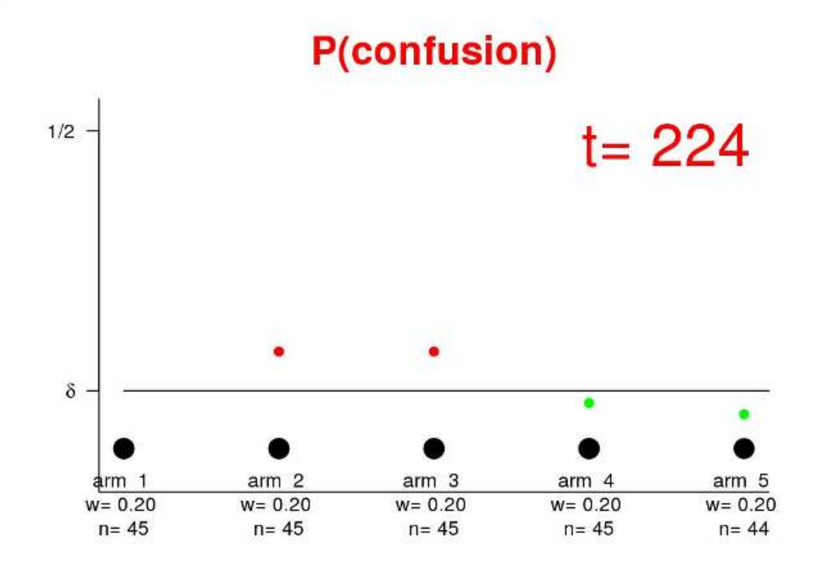

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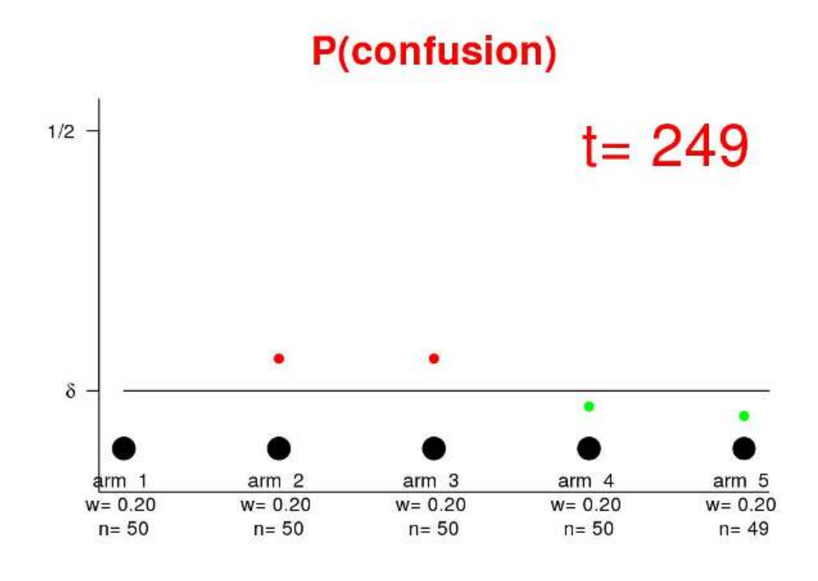

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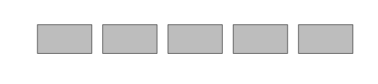

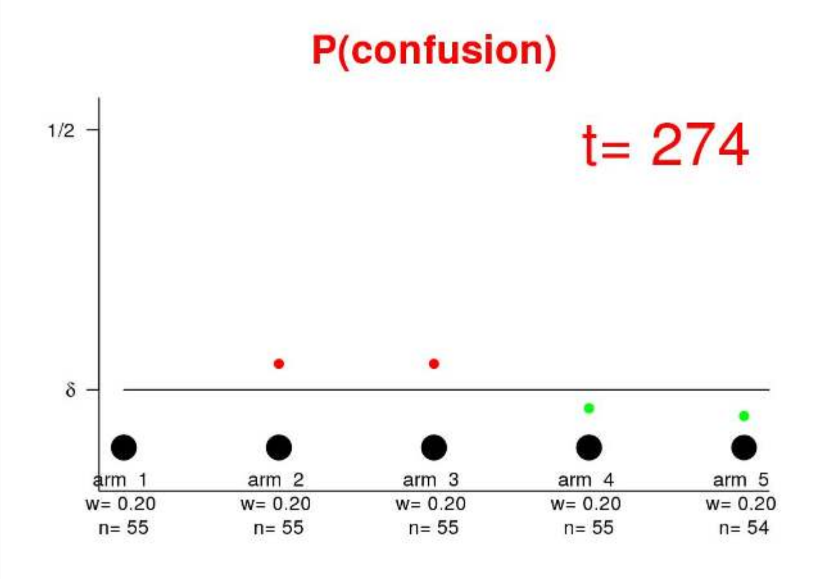

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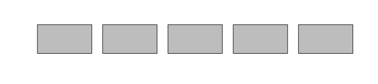

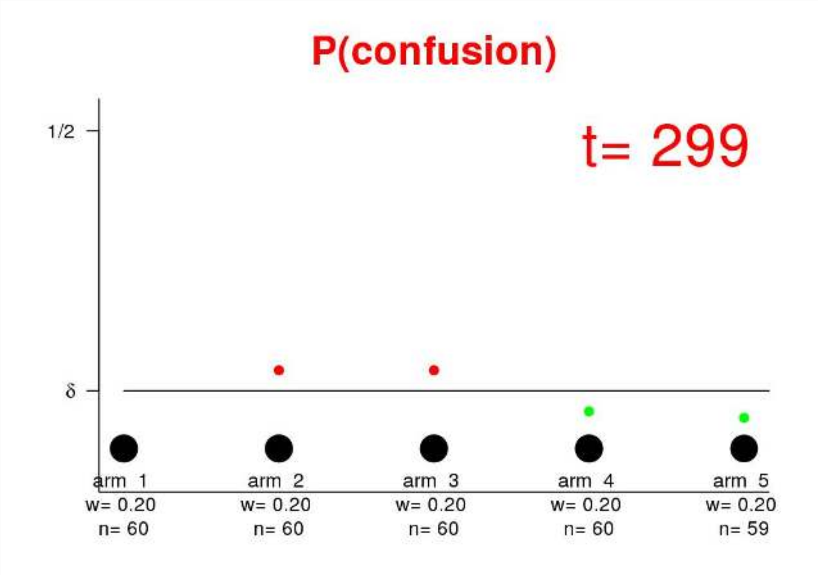

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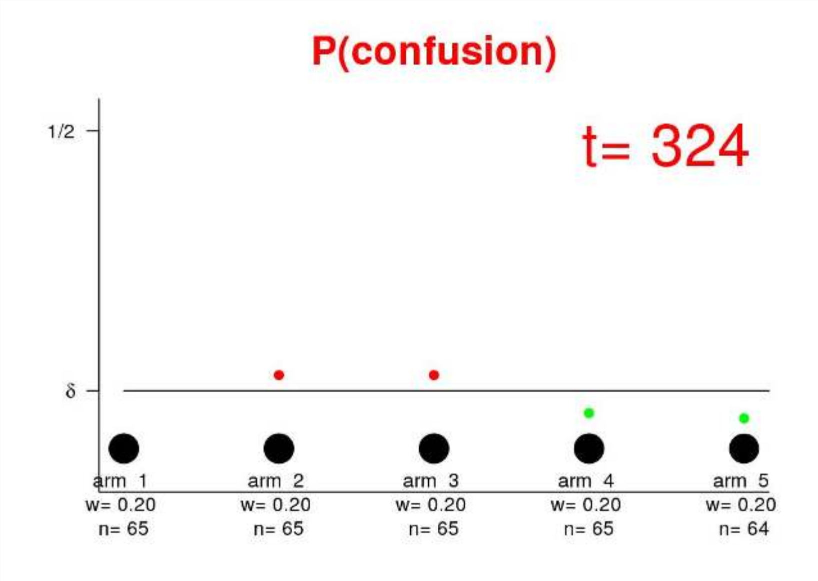

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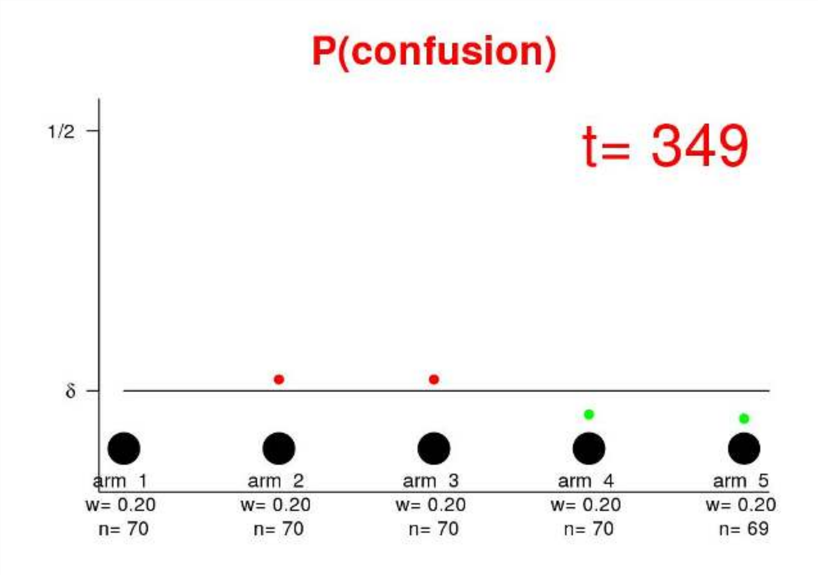

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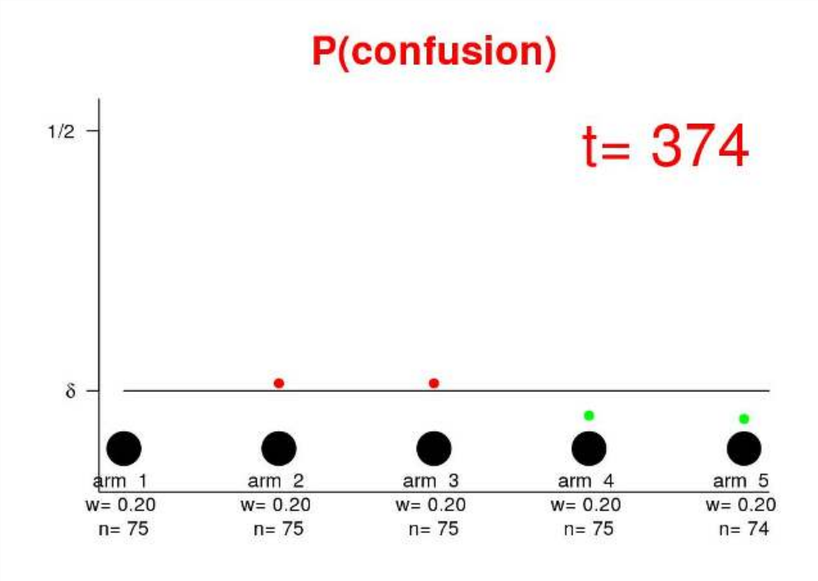

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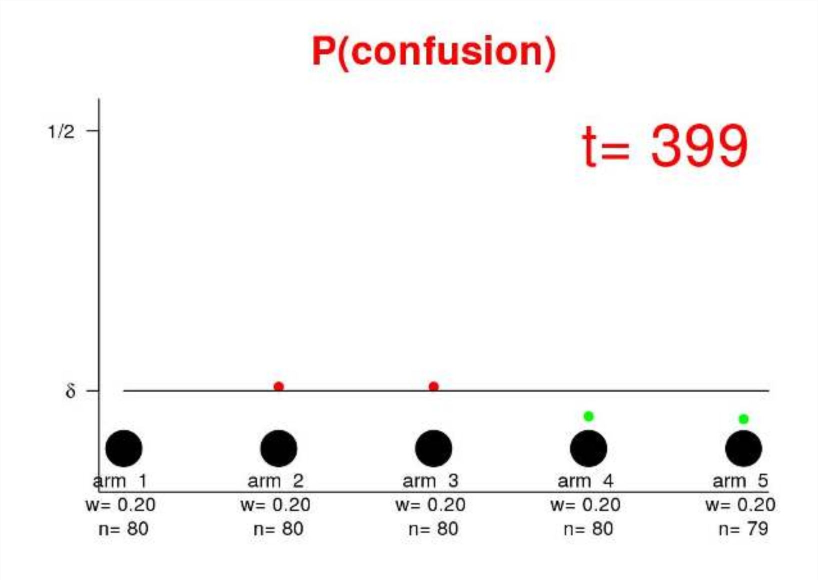

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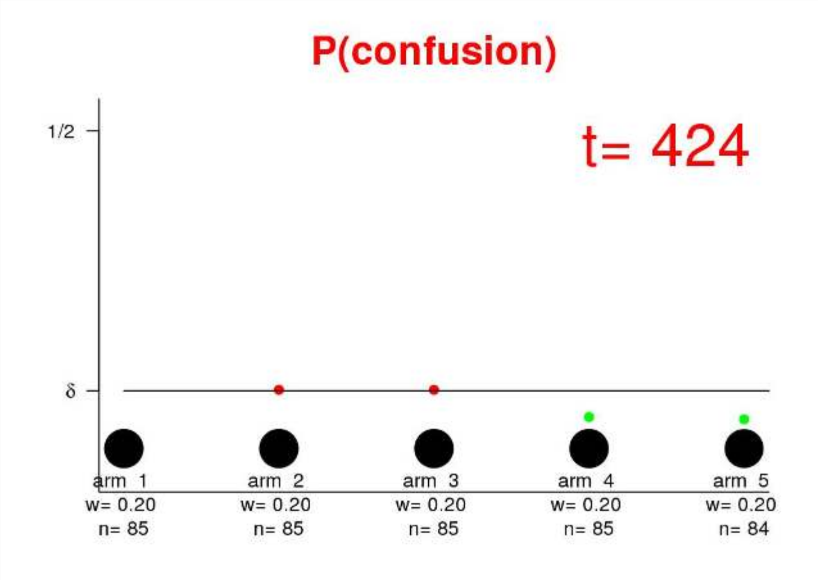

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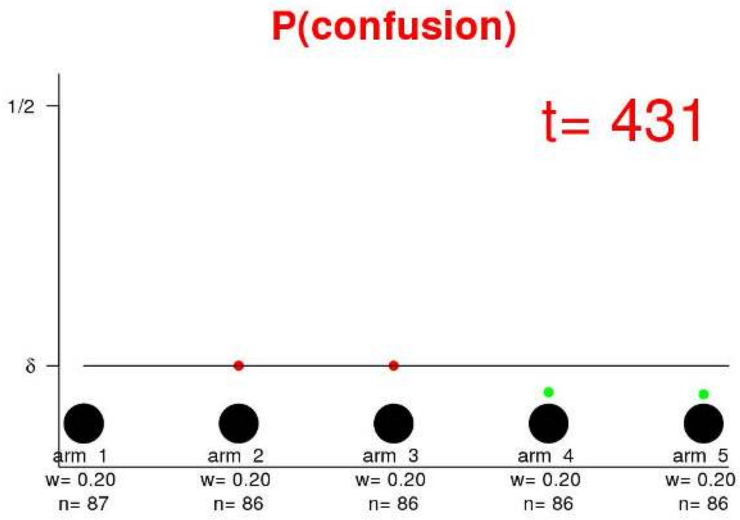

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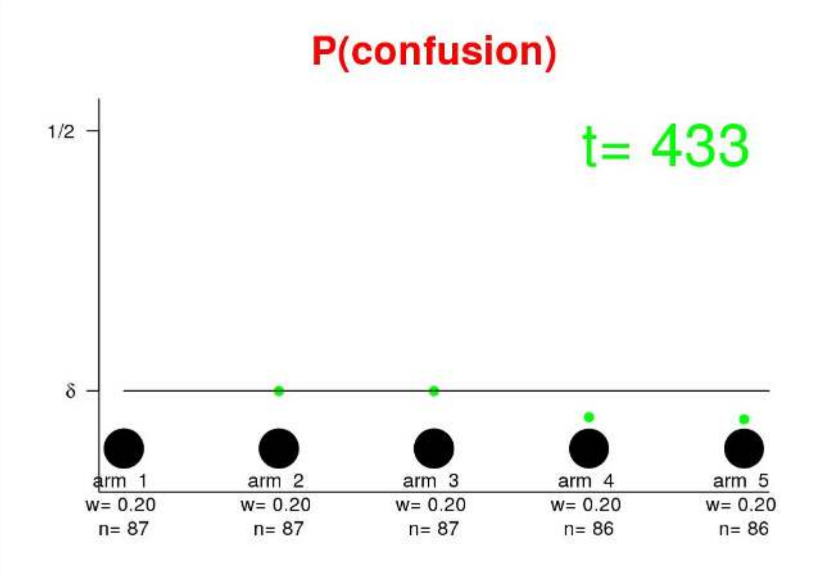
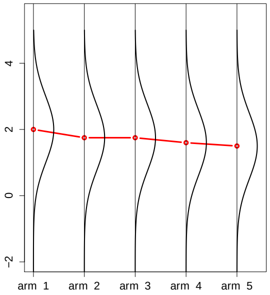


Intuition: Equalizing the Probabilities of Confusion

Most simple setting: for all $a \in \{1, \ldots, K\}$,

$$\nu_a = \mathcal{N}(\mu_a, 1)$$

For example: $\mu = [2, 1.75, 1.75, 1.6, 1.5]$.



Active Learning

➜ **You allocate a relative budget w_a to option a, with $w_1 + \cdots + w_K = 1$.**

At time t:

➜ you have sampled $\mathbf{n_a} \approx \mathbf{w_a t}$ times the option a

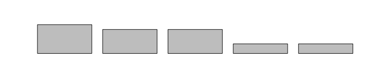
➜ your empirical average is $\bar{X}_{a,n_a}$.

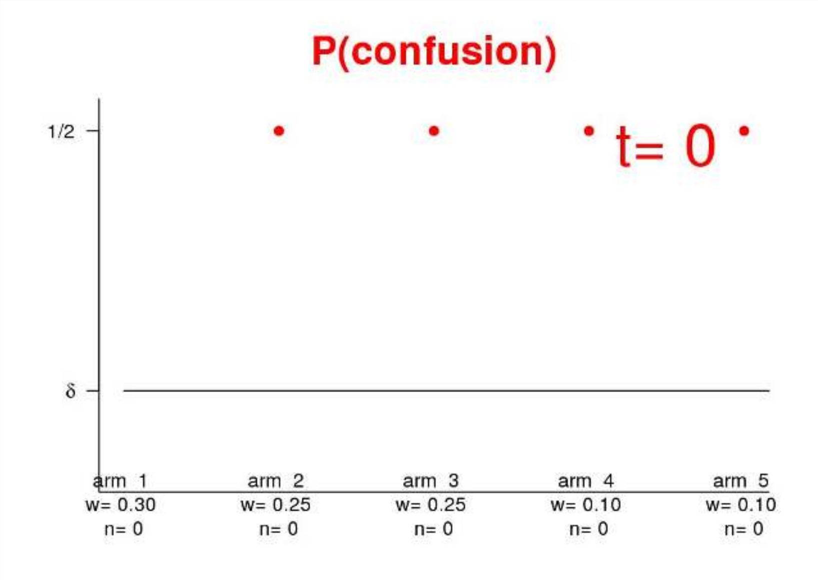
$\longrightarrow$ if you stop at time t, your probability of prefering arm $a \geq 2$ to arm $a^* = 1$ is:

$$\mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right) = \mathbb{P}\left(\frac{\bar{X}_{a,n_a} - \mu_a - (\bar{X}_{1,n_1} - \mu_1)}{\sqrt{1/n_1 + 1/n_a}} > \frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right)$$

$$= \bar{\Phi}\left(\frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right)$$

Improving: trial 1





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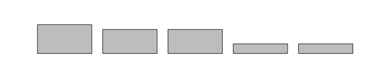

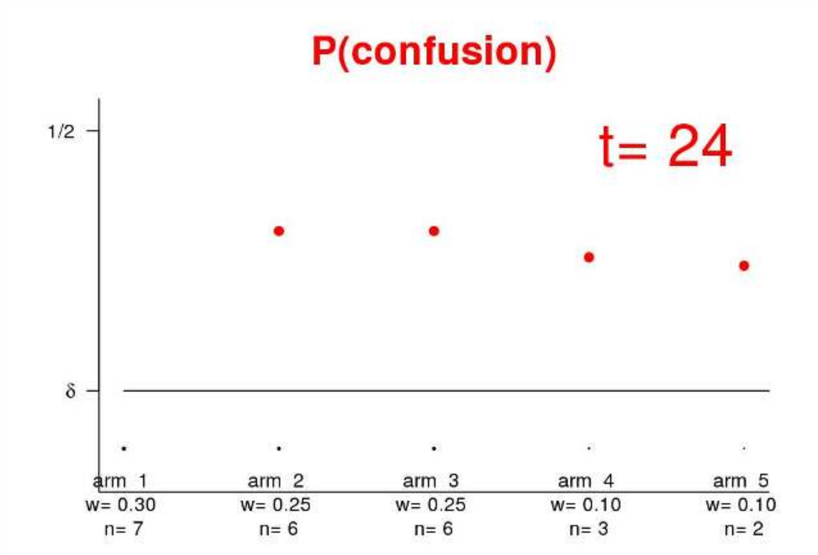

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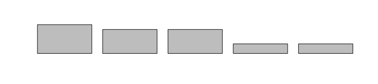

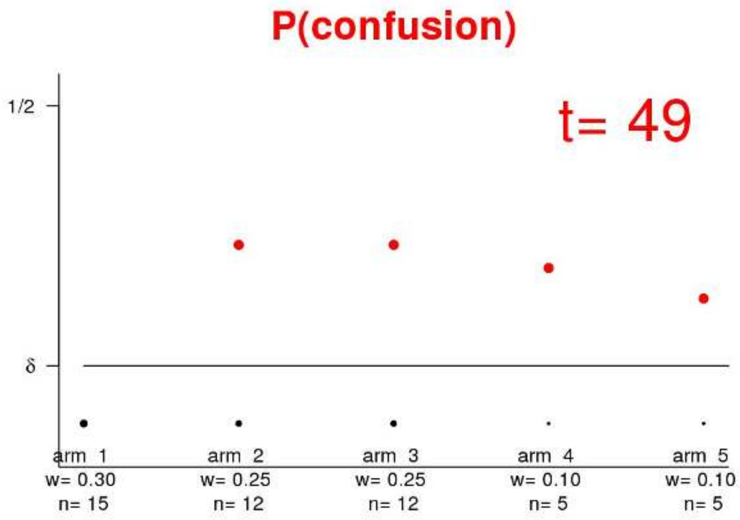

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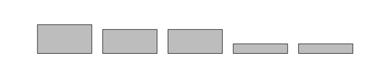

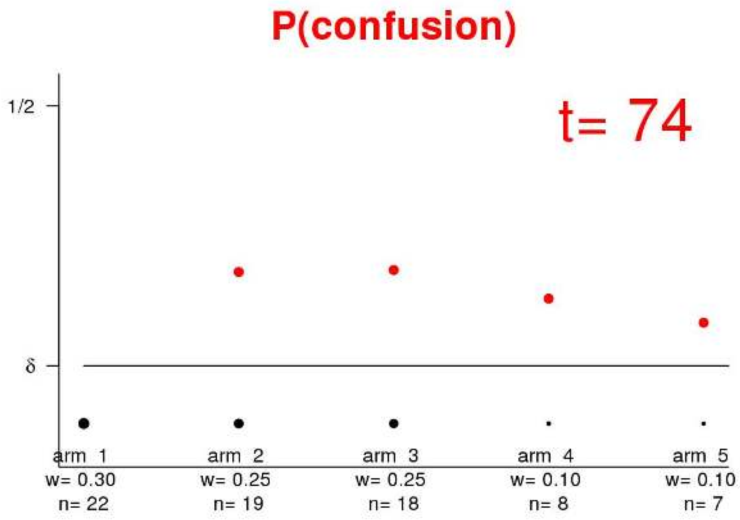

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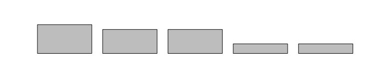

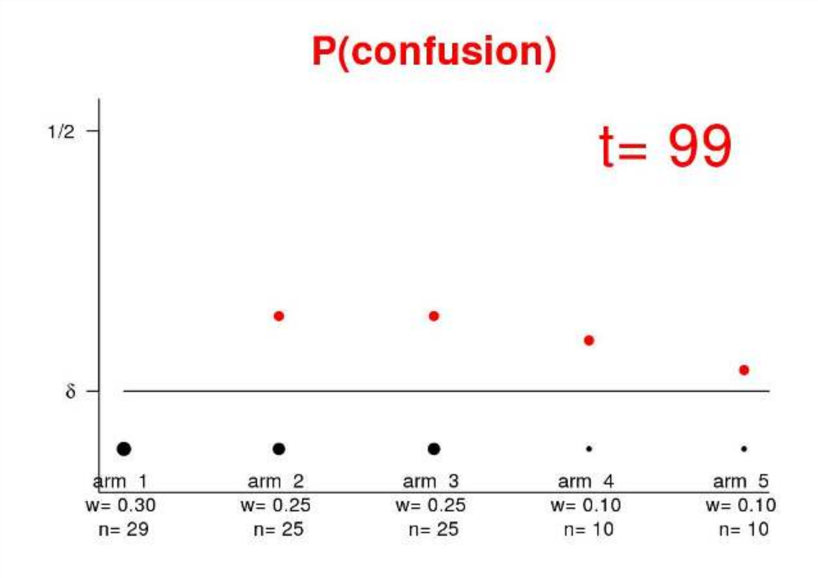

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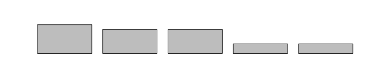

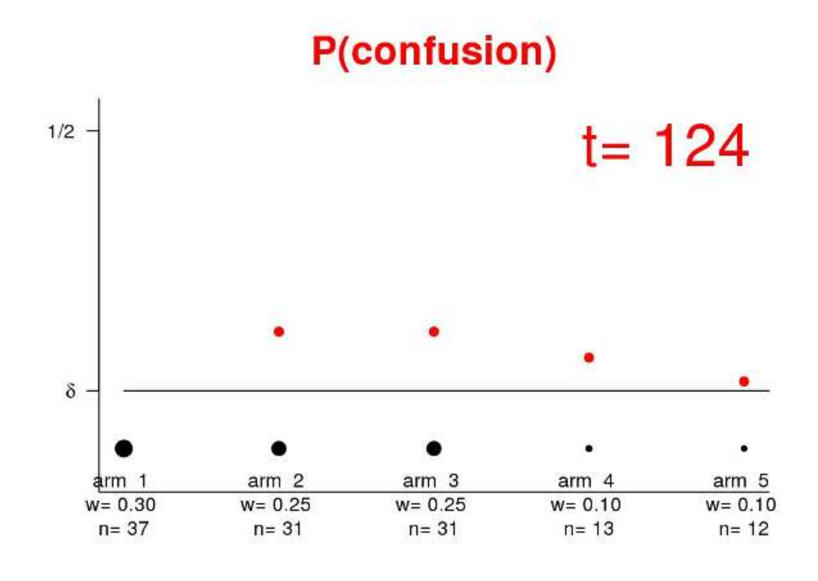

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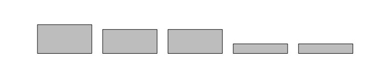

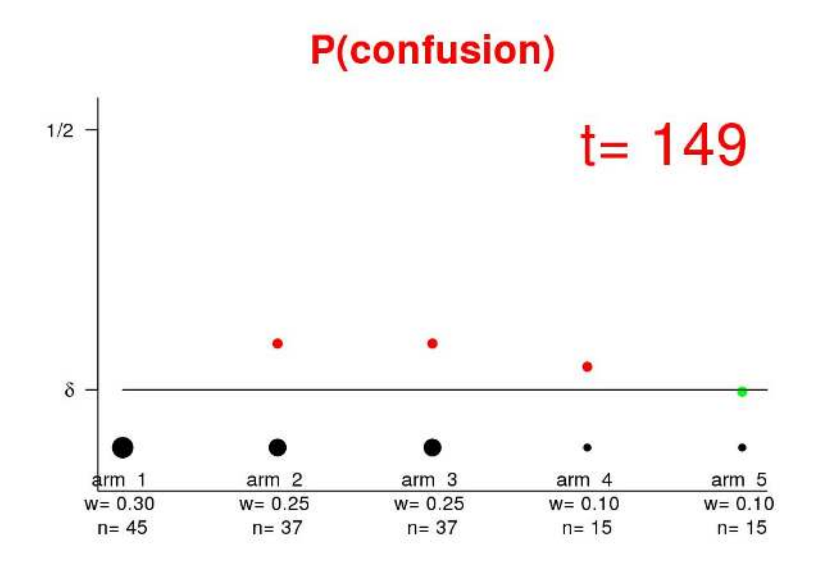

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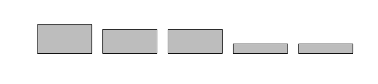

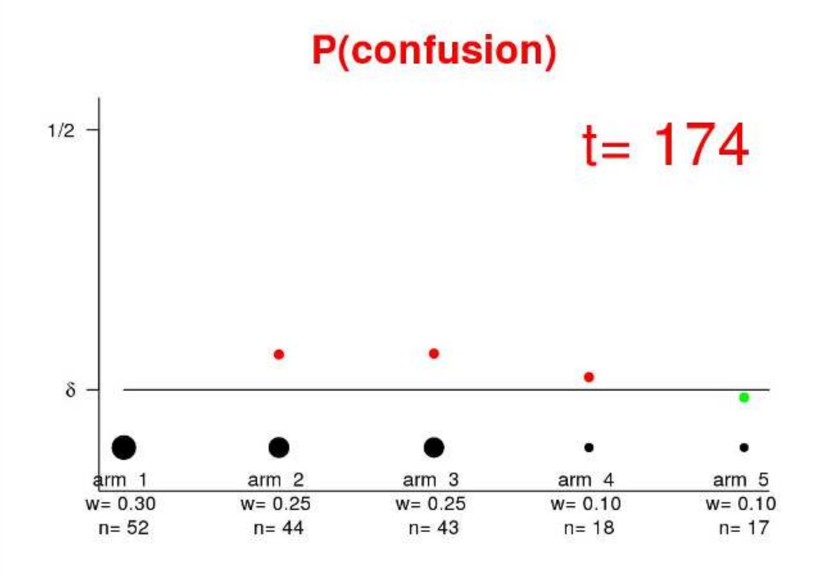

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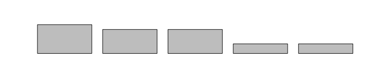

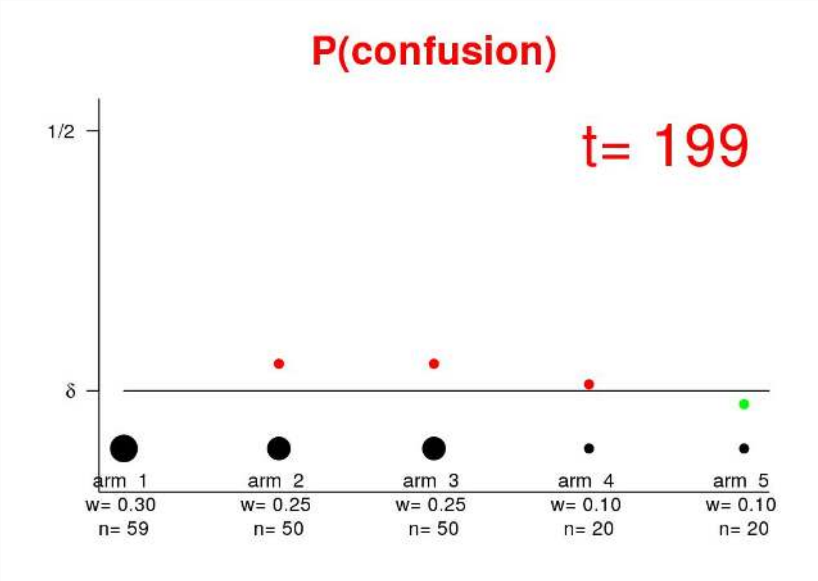

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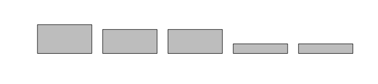

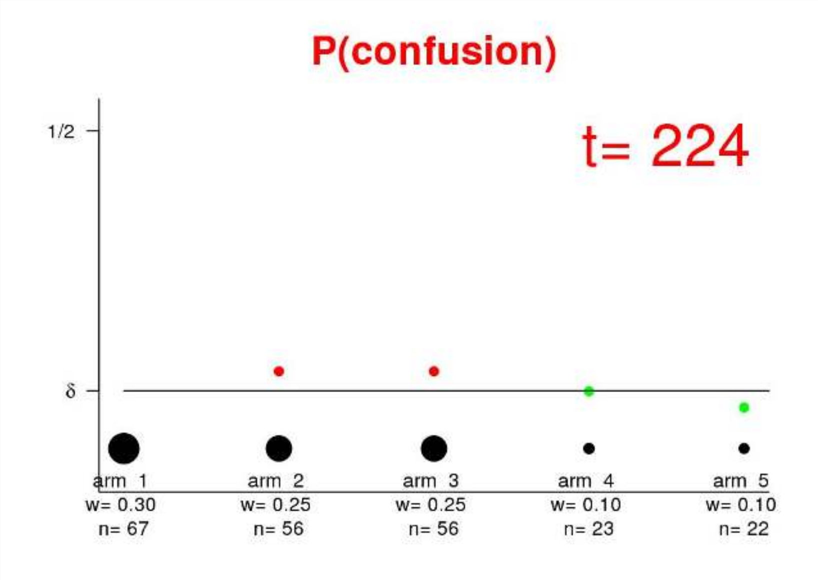

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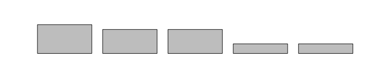
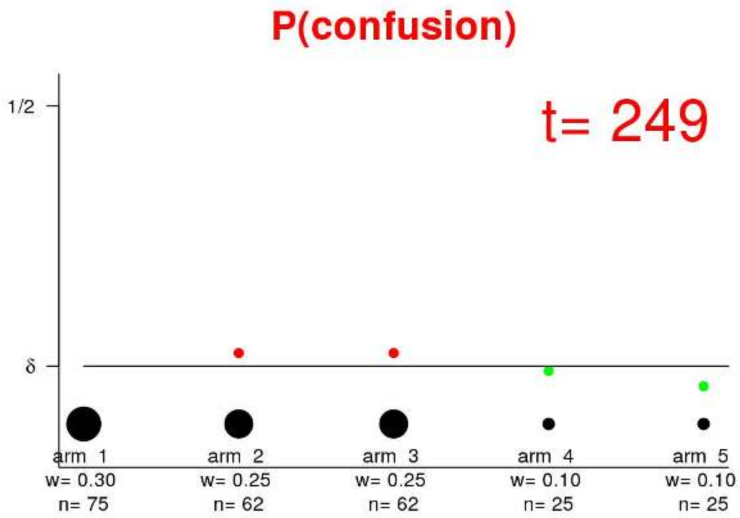

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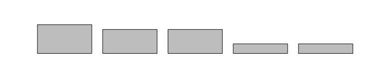

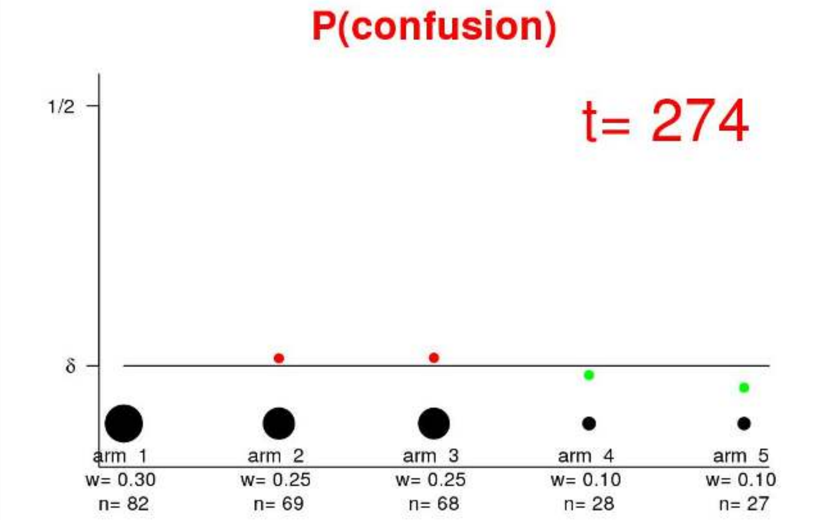

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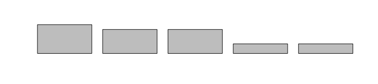

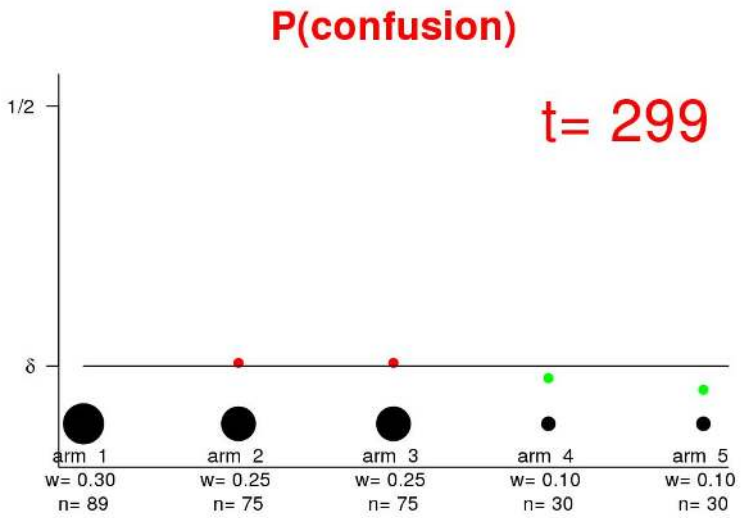

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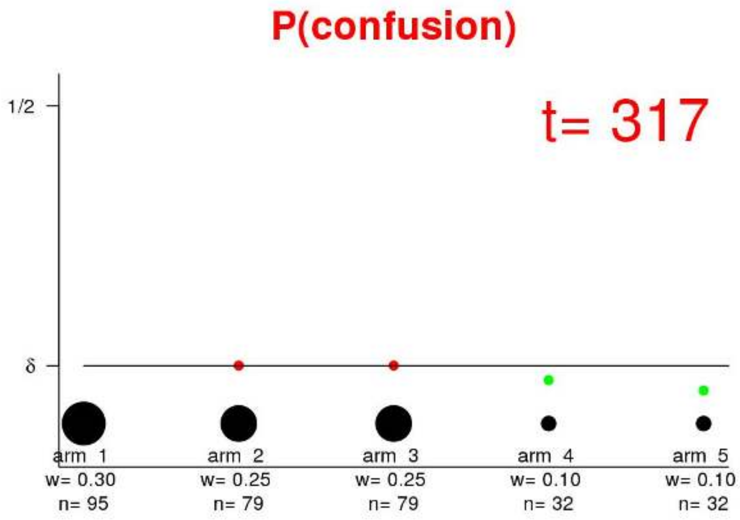
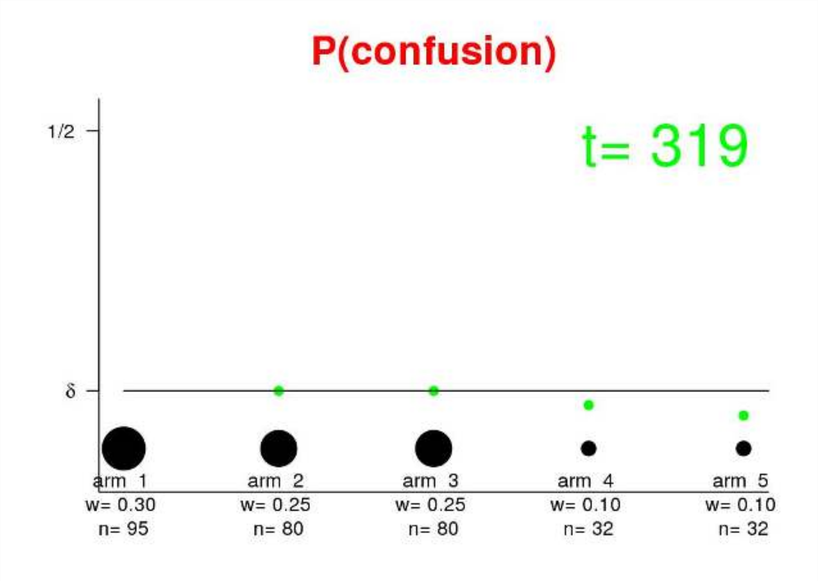
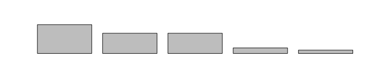
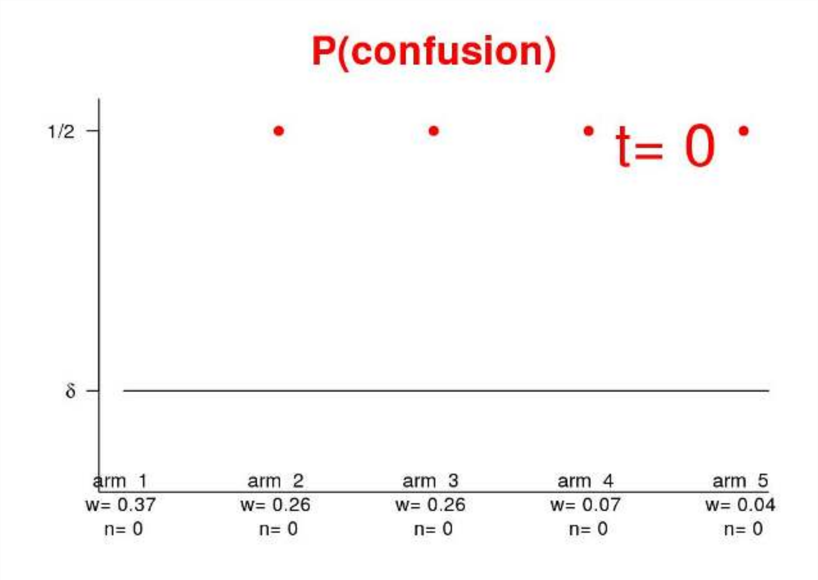


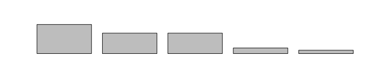

P(confusion)
t= 319
1/2
δ
arm 1
w= 0.30
n= 95
arm 2
w= 0.25
n= 80
arm 3
w= 0.25
n= 80
arm 4
w= 0.10
n= 32
arm 5
w= 0.10
n= 32

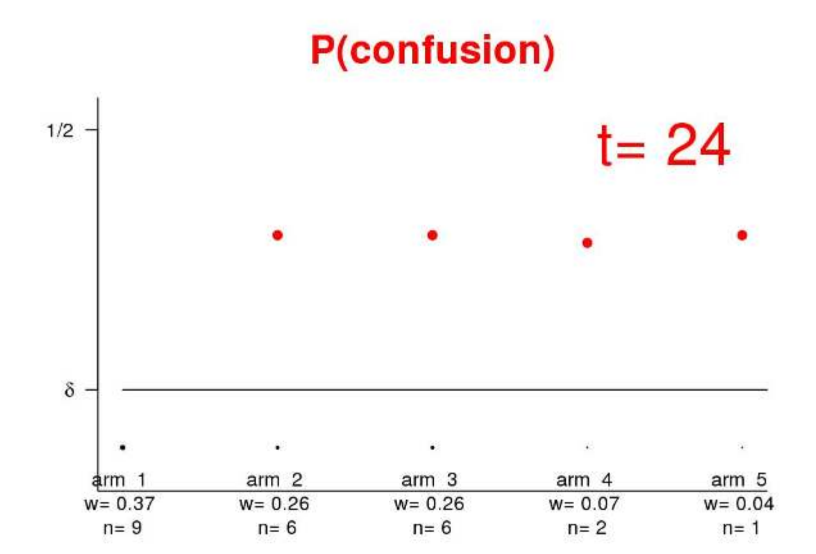
Optimal Proportions



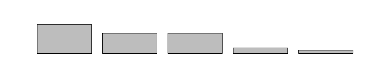


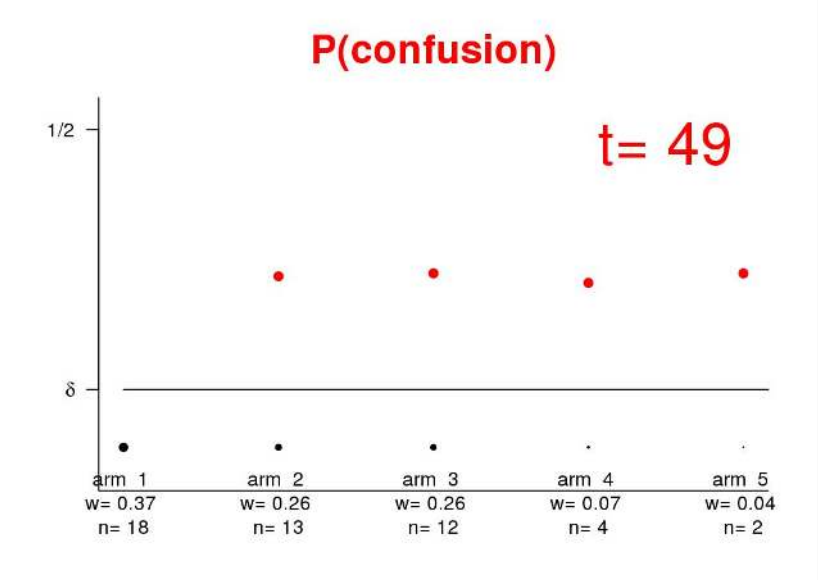
Optimal Proportions



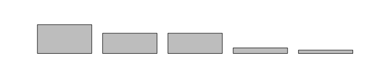


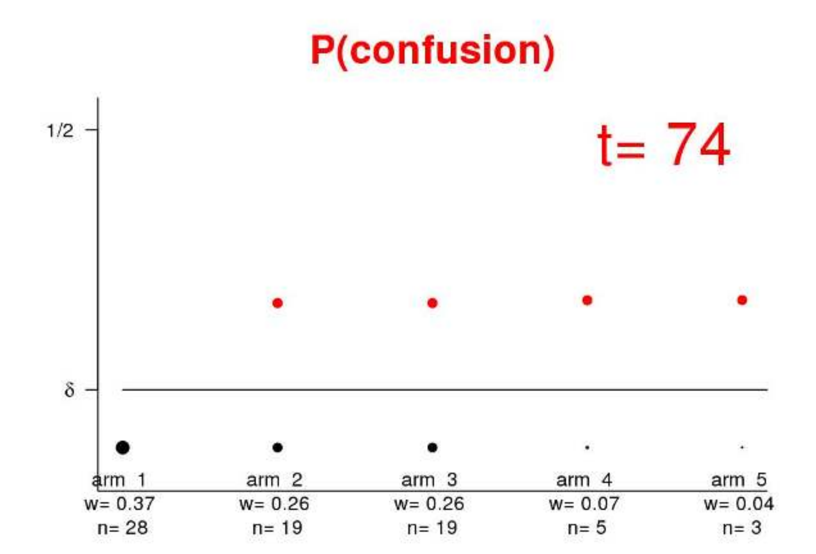
Optimal Proportions



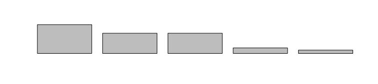


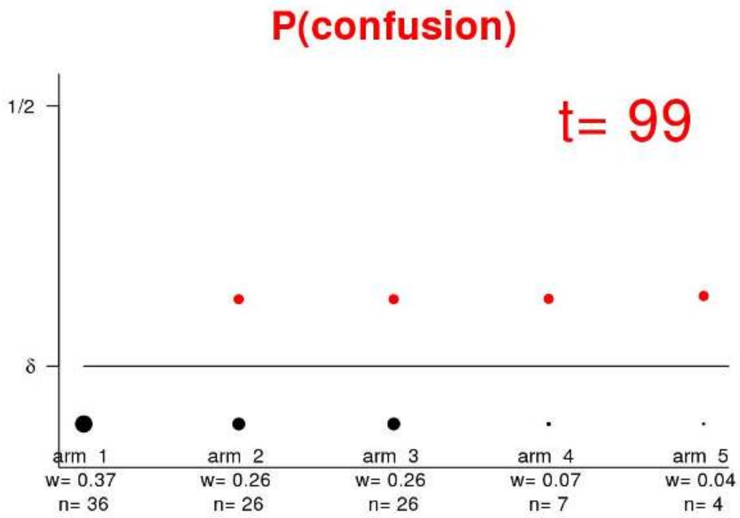
Optimal Proportions

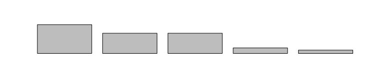


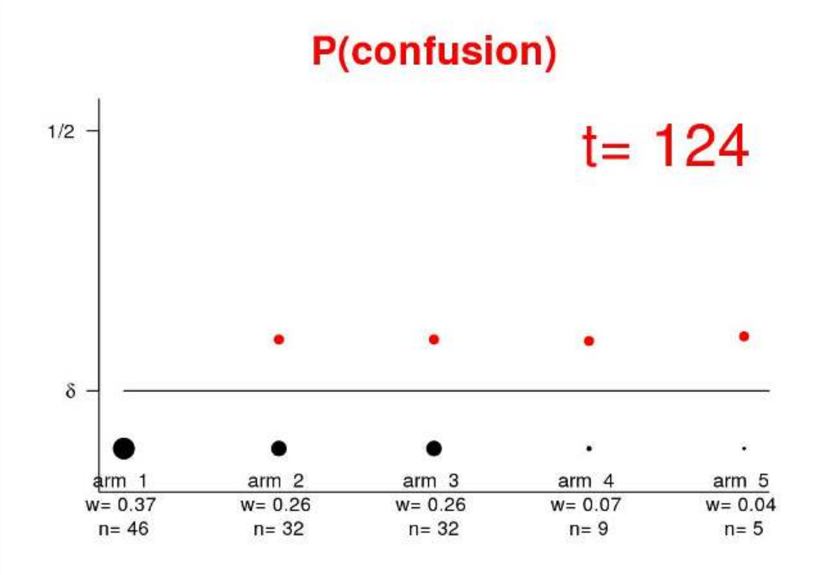


Optimal Proportions

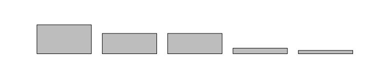


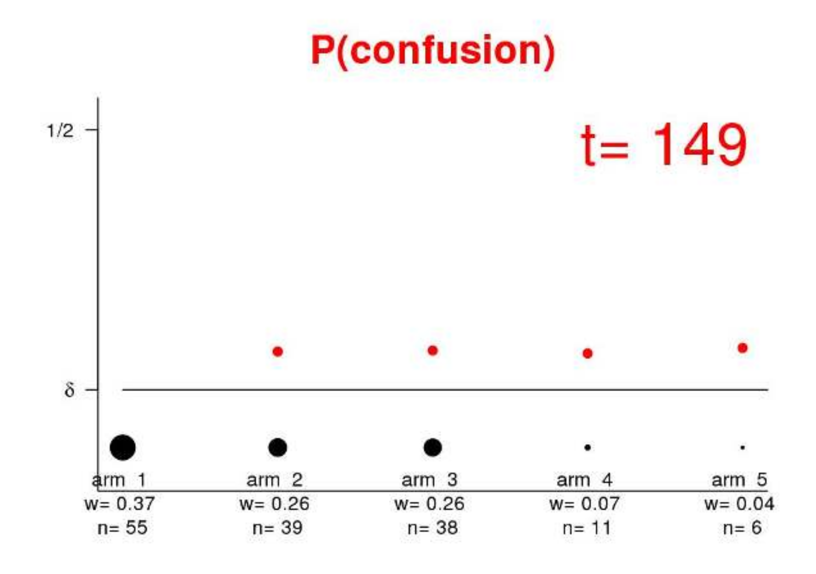




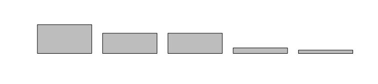

P(confusion)
t= 124
1/2
δ
arm 1
w= 0.37
n= 46
arm 2
w= 0.26
n= 32
arm 3
w= 0.26
n= 32
arm 4
w= 0.07
n= 9
arm 5
w= 0.04
n= 5

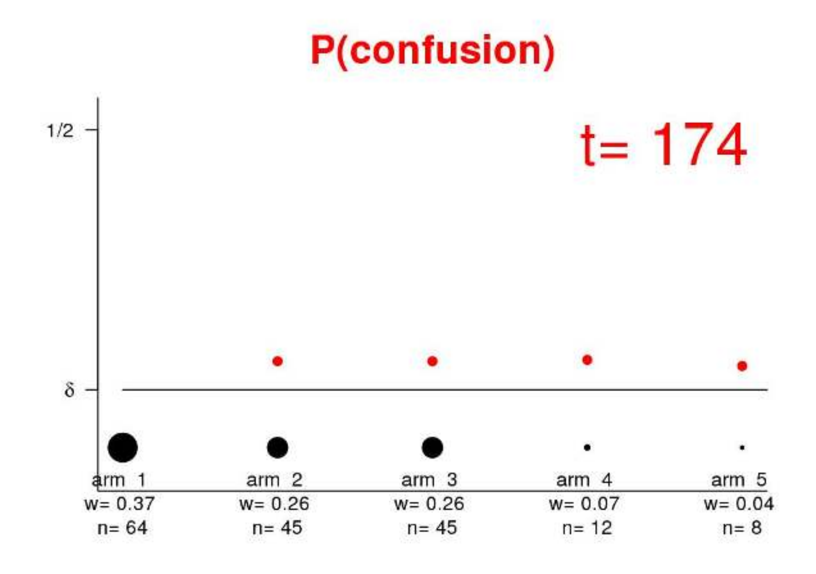
Optimal Proportions



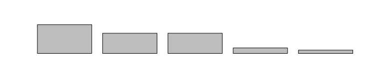


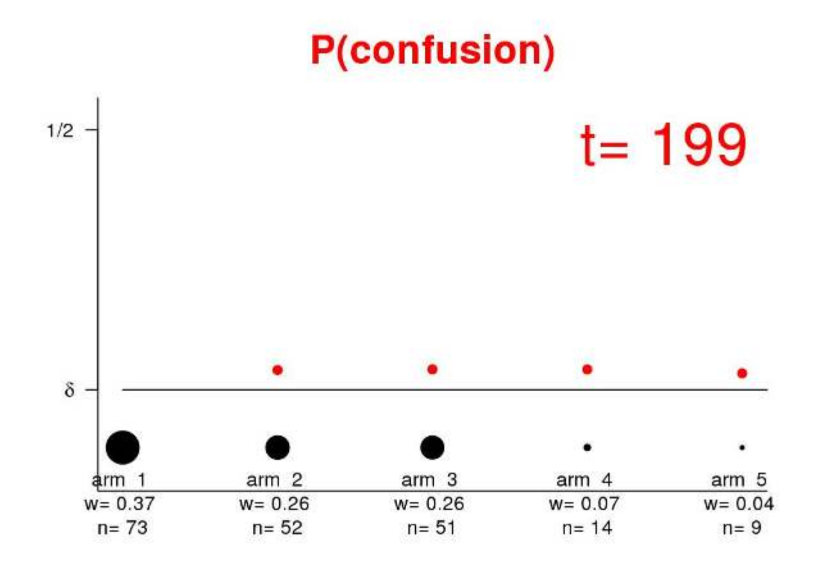
Optimal Proportions



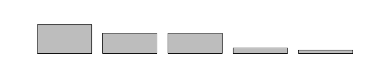


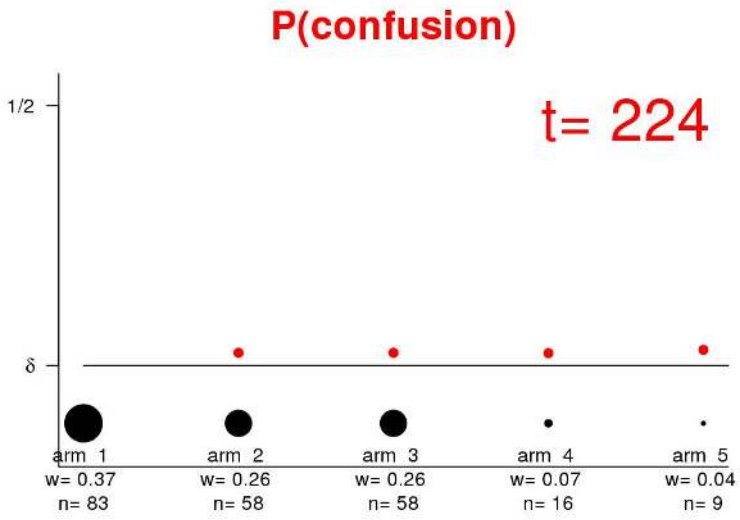
Optimal Proportions

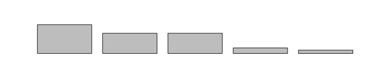


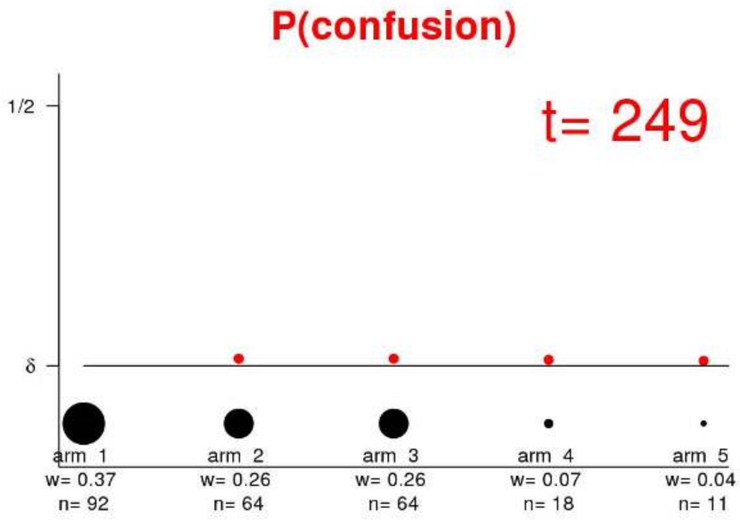


Optimal Proportions

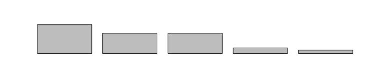


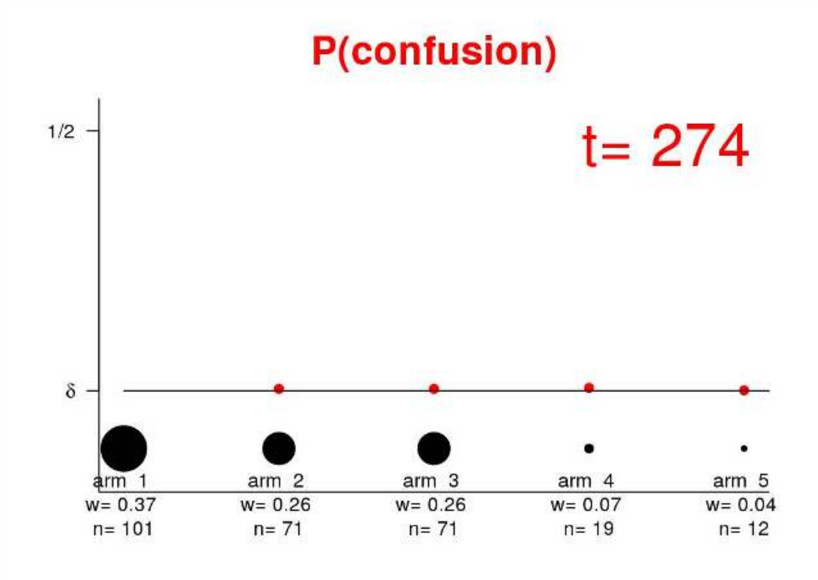




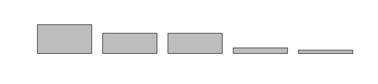

P(confusion)
t= 249
1/2
δ
arm 1
w= 0.37
n= 92
arm 2
w= 0.26
n= 64
arm 3
w= 0.26
n= 64
arm 4
w= 0.07
n= 18
arm 5
w= 0.04
n= 11

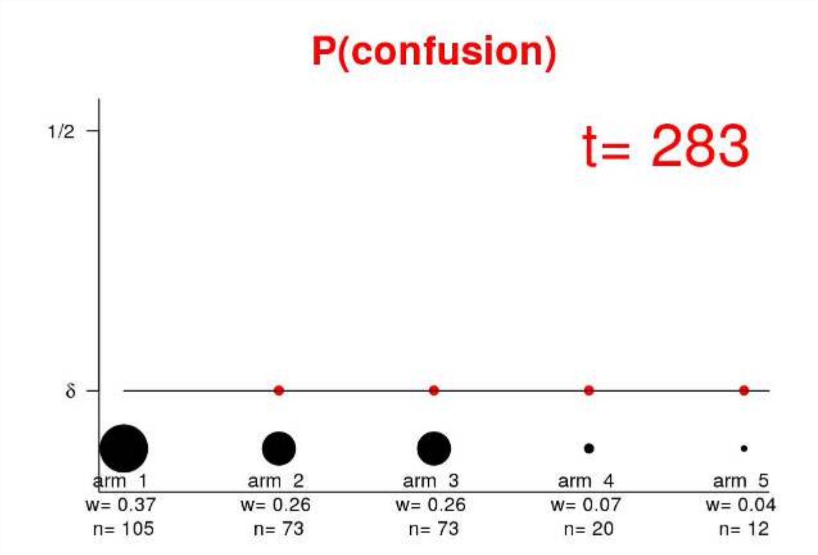
Optimal Proportions



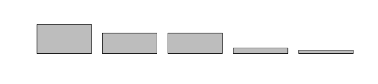


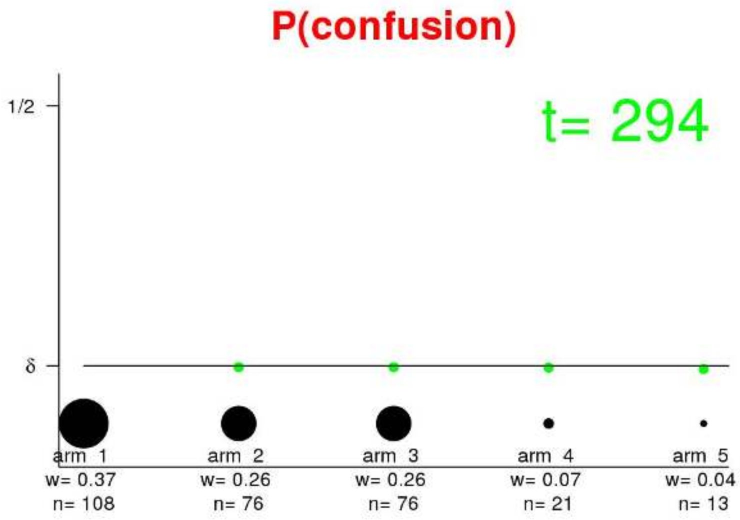
Optimal Proportions





Optimal Proportions





How to Turn this Intuition into a Theorem?

- The arms are not Gaussian (no formula for probability of confusion)
  $\longrightarrow$ large deviations (Sanov, KL)
- You do not allocate a relative budget at first, but you use sequential sampling
  $\longrightarrow$ no fixed-size samples: *sequential experiment*
  $\longrightarrow$ tracking lemma
- How to compute the optimal proportions?
  $\longrightarrow$ lower bound, game
- The parameters of the distribution are unknown
  $\longrightarrow$ (sequential) estimation
- When should you stop?
  $\longrightarrow$ Chernoff's stopping rule

Exponential Families

$\nu_1, \ldots, \nu_K$ belong to a one-dimensional exponential family

$$\mathbb{P}_{\lambda,\Theta,b} = \left\{\nu_\theta, \theta \in \Theta : \nu_\theta \text{ has density } f_\theta(x) = \exp(\theta x - b(\theta)) \ w.r.t.\ \lambda\right\}$$

Example: Gaussian, Bernoulli, Poisson distributions...

- ν_θ can be parametrized by its mean $\mu = \dot{b}(\theta)$: $\nu^\mu := \nu_{\dot{b}^{-1}(\mu)}$

Notation: Kullback-Leibler divergence

For a given exponential family,

$$d(\mu, \mu') := \mathrm{KL}(\nu^\mu, \nu^{\mu'}) = \mathbb{E}_{X \sim \nu^\mu}\left[\log \frac{d\nu^\mu}{d\nu^{\mu'}}(X)\right]$$

is the KL-divergence between the distributions of mean μ and μ'.

We identify $\nu = (\nu^{\mu_1}, \ldots, \nu^{\mu_K})$ and $\boldsymbol{\mu} = (\mu_1, \ldots, \mu_K)$ and consider

$$\mathcal{S} = \left\{\boldsymbol{\mu} \in (\dot{b}(\Theta))^K : \exists a \in \{1, \ldots, K\} : \mu_a > \max_{i \neq a} \mu_i\right\}$$

Classical strategies

LUCB: Lower-Upper Confidence Bounds

- Build confidence bounds $L_a(t)$ and $U_a(t)$ such that with probability at least $1-\delta$, for all times $t \geq 1$ and all arms $a \in \{1, \dots, K\}$:

$$\mu_a \in [L_a(t), U_a(t)] \ ,$$

- Sample alternately

$$\hat{a}(t) = \underset{a \in \{1,\dots,K\}}{\operatorname{argmax}} \ L_a(t) \qquad \text{and} \qquad \underset{b \neq \hat{a}(t)}{\operatorname{argmax}} \, U_b(t)$$

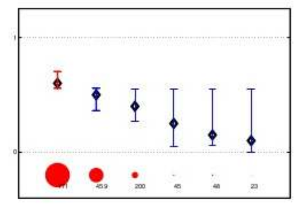
- Stopping time τ_δ = the first time t when

$$\exists \hat{a} \in \{1, \dots, K\} : \forall a \neq \hat{a}, U_a(t) < L_{\hat{a}}(t)$$

Analysis: δ-correct by nature, and with probability at least $1-\delta$:

$$\tau_\delta \leq C \sum_{a \neq a^*} \frac{1}{(\mu^* - \mu_a)^2}$$

for some constant C.

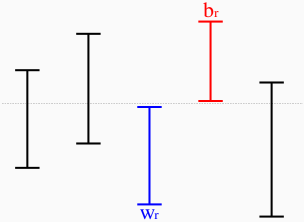


Racing: Successive Eliminations

- Proceed in rounds where, at each round, all active arms are sample once
- Keep a list of active arms = those which have not been eliminated
- At the end of each round, eliminate the arms which are provably suboptimal (with a global risk δ)

Analysis: similarly, one finds a constant C such that

$$\mathbb{E}\left[\tau_\delta\right] \leq C \sum_{a \neq a^*} \frac{1}{(\mu^* - \mu_a)^2} \, .$$



Lower Bound

Information in Bandit Models

Theorem [see Garivier, Ménard and Stoltz, M.O.R. to appear]

For all bandit problems μ and λ, all stopping time τ and $\sigma(\mathcal{F}_\tau)$–measurable random variables Z with values in $[0,1]$,

$$\sum_{a=1}^{K} \mathbb{E}_\mu\big[N_a(\tau)\big]\, d(\mu_a, \lambda_a) \geq \mathrm{kl}\big(\mathbb{E}_\mu[Z], \mathbb{E}_\lambda[Z]\big)\,.$$

Proof: if $I_\tau = (A_1, X_{A_1,1}, \ldots, A_\tau, X_{A_\tau, N_{A_\tau}(\tau)})$,

$$\sum_{a=1}^{K} \mathbb{E}_\mu\big[N_a(\tau)\big]\, d(\mu_a, \lambda_a) = \mathrm{KL}\big(\mathbb{P}_\mu^{I_\tau}, \mathbb{P}_\lambda^{I_\tau}\big) \geq \mathrm{KL}\big(\mathbb{P}_\mu^{Z}, \mathbb{P}_\lambda^{Z}\big) \geq \mathrm{kl}\big(\mathbb{E}_\mu[Z], \mathbb{E}_\lambda[Z]\big)$$

by *tensorization* and *contraction* of entropy (and small lemma).

Lower-Bounding the Sample Complexity

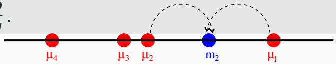
Let $\boldsymbol{\mu} = (\mu_1, \dots, \mu_K)$ and $\boldsymbol{\lambda} = (\lambda_1, \dots, \lambda_K)$ be two elements of $\mathcal{S}$.

Uniform δ-correct Constraint [Kaufmann, Cappé, Garivier '15]

If $a^*(\boldsymbol{\mu}) \neq a^*(\boldsymbol{\lambda})$, any δ-correct algorithm satisfies

$$\sum_{a=1}^{K} \mathbb{E}_{\boldsymbol{\mu}}\left[N_a(\tau_\delta)\right] d(\mu_a, \lambda_a) \geq \mathrm{kl}(\delta, 1-\delta)$$

where $\mathrm{kl}(p,q) = p \log \frac{p}{q} + (1-p) \log \frac{1-p}{1-q}$.



Let $\mathrm{Alt}(\boldsymbol{\mu}) = \{\boldsymbol{\lambda} : a^*(\boldsymbol{\lambda}) \neq a^*(\boldsymbol{\mu})\}$. Take: $\lambda_1 = m_2 - \epsilon \quad \lambda_2 = m_2 + \epsilon$

$$\mathbb{E}_{\boldsymbol{\mu}}[N_1(\tau_\delta)]\, d(\mu_1, m_2 - \epsilon) + \mathbb{E}_{\boldsymbol{\mu}}[N_2(\tau_\delta)]\, d(\mu_2, m_2 + \epsilon) \quad \geq \quad \mathrm{kl}(\delta, 1-\delta)$$

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Let $\boldsymbol{\mu} = (\mu_1, \dots, \mu_K)$ and $\boldsymbol{\lambda} = (\lambda_1, \dots, \lambda_K)$ be two elements of $\mathcal{S}$.

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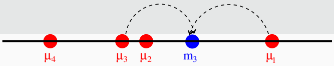

Let $\mathrm{Alt}(\boldsymbol{\mu}) = \{\boldsymbol{\lambda} : a^*(\boldsymbol{\lambda}) \neq a^*(\boldsymbol{\mu})\}$. Take: $\lambda_1 = m_3 - \epsilon \quad \lambda_3 = m_3 + \epsilon$

$$\mathbb{E}_{\boldsymbol{\mu}}[N_1(\tau_\delta)]\, d(\mu_1, m_2 - \epsilon) + \mathbb{E}_{\boldsymbol{\mu}}[N_2(\tau_\delta)]\, d(\mu_2, m_2 + \epsilon) \quad \geq \quad \mathrm{kl}(\delta, 1-\delta)$$
$$\mathbb{E}_{\boldsymbol{\mu}}[N_1(\tau_\delta)]\, d(\mu_1, m_3 - \epsilon) + \mathbb{E}_{\boldsymbol{\mu}}[N_3(\tau_\delta)]\, d(\mu_3, m_3 + \epsilon) \quad \geq \quad \mathrm{kl}(\delta, 1-\delta)$$

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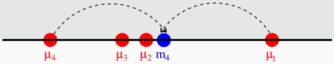
where $\mathrm{kl}(p, q) = p \log \frac{p}{q} + (1-p) \log \frac{1-p}{1-q}$.



Let $\mathrm{Alt}(\boldsymbol{\mu}) = \{\boldsymbol{\lambda} : a^*(\boldsymbol{\lambda}) \neq a^*(\boldsymbol{\mu})\}$. Take: $\lambda_1 = m_4 - \epsilon \quad \lambda_4 = m_4 + \epsilon$

$$\begin{aligned}
\mathbb{E}_{\boldsymbol{\mu}}[N_1(\tau_\delta)]\, d(\mu_1, m_2 - \epsilon) + \mathbb{E}_{\boldsymbol{\mu}}[N_2(\tau_\delta)]\, d(\mu_2, m_2 + \epsilon) &\geq \mathrm{kl}(\delta, 1-\delta) \\
\mathbb{E}_{\boldsymbol{\mu}}[N_1(\tau_\delta)]\, d(\mu_1, m_3 - \epsilon) + \mathbb{E}_{\boldsymbol{\mu}}[N_3(\tau_\delta)]\, d(\mu_3, m_3 + \epsilon) &\geq \mathrm{kl}(\delta, 1-\delta) \\
\mathbb{E}_{\boldsymbol{\mu}}[N_1(\tau_\delta)]\, d(\mu_1, m_4 - \epsilon) + \mathbb{E}_{\boldsymbol{\mu}}[N_4(\tau_\delta)]\, d(\mu_4, m_4 + \epsilon) &\geq \mathrm{kl}(\delta, 1-\delta)
\end{aligned}$$

Lower-Bounding the Sample Complexity

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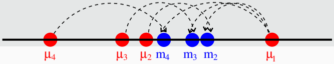
$$\sum_{a=1}^{K} \mathbb{E}_{\boldsymbol{\mu}}\left[N_a(\tau_\delta)\right] d(\mu_a, \lambda_a) \geq \mathrm{kl}(\delta, 1-\delta)$$

where $\mathrm{kl}(p,q) = p \log \frac{p}{q} + (1-p)\log\frac{1-p}{1-q}$.



Let $\mathrm{Alt}(\boldsymbol{\mu}) = \{\boldsymbol{\lambda} : a^*(\boldsymbol{\lambda}) \neq a^*(\boldsymbol{\mu})\}$.

$$\inf_{\boldsymbol{\lambda} \in \mathrm{Alt}(\boldsymbol{\mu})} \sum_{a=1}^{K} \mathbb{E}_{\boldsymbol{\mu}}[N_a(\tau_\delta)]\, d(\mu_a, \lambda_a) \quad \geq \quad \mathrm{kl}(\delta, 1-\delta)$$

$$\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta] \times \inf_{\boldsymbol{\lambda} \in \mathrm{Alt}(\boldsymbol{\mu})} \sum_{a=1}^{K} \frac{\mathbb{E}_{\boldsymbol{\mu}}[N_a(\tau_\delta)]}{\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta]}\, d(\mu_a, \lambda_a) \quad \geq \quad \mathrm{kl}(\delta, 1-\delta)$$

$$\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta] \times \left(\sup_{w \in \Sigma_K} \inf_{\boldsymbol{\lambda} \in \mathrm{Alt}(\boldsymbol{\mu})} \sum_{a=1}^{K} w_a\, d(\mu_a, \lambda_a) \right) \quad \geq \quad \mathrm{kl}(\delta, 1-\delta)$$

Lower Bound: the Complexity of BAI

Theorem [Garivier and Kaufmann 2016]

For any δ-correct algorithm,

$$\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta] \geq T^*(\boldsymbol{\mu})\,\mathrm{kl}(\delta, 1-\delta)\,,$$

where

$$T^*(\boldsymbol{\mu})^{-1} = \sup_{\mathbf{w}\in\Sigma_K} \inf_{\lambda\in\mathrm{Alt}(\boldsymbol{\mu})} \left(\sum_{a=1}^{K} w_a\, d(\mu_a, \lambda_a)\right).$$

- $\mathrm{kl}(\delta, 1-\delta) \sim \log(1/\delta)$ when $\delta \to 0$, $\mathrm{kl}(\delta, 1-\delta) \geq \log\left(1/(2.4\delta)\right)$
- cf. [Graves and Lai 1997, Vaidhyan and Sundaresan, 2015]

➜ the optimal proportions of arm draws are

$$\mathbf{w}^*(\boldsymbol{\mu}) = \underset{\mathbf{w}\in\Sigma_K}{\mathrm{argmax}} \inf_{\lambda\in\mathrm{Alt}(\boldsymbol{\mu})} \left(\sum_{a=1}^{K} w_a d(\mu_a, \lambda_a)\right)$$

➜ they do not depend on δ

PAC-BAI as a Game

Given a parameter $\boldsymbol{\mu} = (\mu_1, \ldots, \mu_K)$:

- the statistician chooses proportions of arm draws $\boldsymbol{w} = (w_a)_a$
- the opponent chooses an alternative model $\boldsymbol{\lambda}$
- the payoff is the minimal number $T = T(\boldsymbol{w}, \boldsymbol{\lambda})$ of draws necessary to ensure that he does not violate the δ-PAC constraint

$$\sum_{a=1}^{K} T w_a \, d(\mu_a, \lambda_a) \geq \mathrm{kl}(\delta, 1-\delta)$$

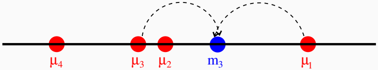
- $T^*(\boldsymbol{\mu}) \, \mathrm{kl}(\delta, 1-\delta) =$ value of the game
  $\boldsymbol{w}^* =$ optimal action for the statistician

PAC-BAI as a Game

Given a parameter $\boldsymbol{\mu} = (\mu_1, \ldots, \mu_K)$ such that $\mu_1 > \mu_2 \geq \cdots \geq \mu_K$:

- the statistician chooses proportions of arm draws $\boldsymbol{w} = (w_a)_a$
- the opponent chooses an arm $a \in \{2, \ldots, K\}$ and

  $\lambda_a = \arg\min_\lambda w_1\, d(\mu_1, \lambda) + w_a\, d(\mu_a, \lambda)$



- the payoff is the minimal number $T = T(\boldsymbol{w}, a, \delta)$ of draws necessary to ensure that

$$T w_1\, d(\mu_1, \lambda_a - \epsilon) + T w_a\, d(\mu_a, \lambda_a + \epsilon) \geq \mathrm{kl}(\delta, 1-\delta)$$

  that is $T(\boldsymbol{w}, a, \delta) = \dfrac{\mathrm{kl}(\delta, 1-\delta)}{w_1\, d(\mu_1, \lambda_a - \epsilon) + w_a\, d(\mu_a, \lambda_a + \epsilon)}$

- $T^*(\boldsymbol{\mu})\, \mathrm{kl}(\delta, 1-\delta) =$ value of the game
  $\boldsymbol{w}^* =$ optimal action for the statistician

Properties of $T^*(\mu)$ and $\mathbf{w}^*(\mu)$

1. Unique solution, solution of scalar equations only
2. For all $\boldsymbol{\mu} \in \mathcal{S}$, for all a, $w_a^*(\boldsymbol{\mu}) > 0$
3. $\mathbf{w}^*$ is continuous in every $\boldsymbol{\mu} \in \mathcal{S}$
4. If $\mu_1 > \mu_2 \geq \cdots \geq \mu_K$, one has $w_2^*(\boldsymbol{\mu}) \geq \cdots \geq w_K^*(\boldsymbol{\mu})$

   (one may have $w_1^*(\boldsymbol{\mu}) < w_2^*(\boldsymbol{\mu})$)
5. Case of two arms [Kaufmann, Cappé, Garivier '14]

$$\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta] \geq \frac{\mathrm{kl}(\delta, 1-\delta)}{d_*(\mu_1, \mu_2)} \ .$$

   where d_* is the 'reversed' Chernoff information

$$d_*(\mu_1, \mu_2) := d(\mu_1, \mu_*) = d(\mu_2, \mu_*) \ .$$

6. Gaussian arms : algebraic equation but no simple formula for $K \geq 3$.

$$\sum_{a=1}^{K} \frac{2\sigma^2}{\Delta_a^2} \leq T^*(\boldsymbol{\mu}) \leq 2 \sum_{a=1}^{K} \frac{2\sigma^2}{\Delta_a^2} \ .$$

The Track-and-Stop Strategy

Outline

Sampling rule: Tracking the optimal proportions

$\hat{\boldsymbol{\mu}}(t) = (\hat{\mu}_1(t), \ldots, \hat{\mu}_K(t))$: vector of empirical means

Introducing

$$U_t = \left\{ a : N_a(t) < \sqrt{t} \right\},$$

the arm sampled at round $t+1$ is

$$A_{t+1} \in \begin{cases} \underset{a \in U_t}{\operatorname{argmin}} \ N_a(t) \quad \text{if } U_t \neq \emptyset & (\textit{forced exploration}) \\ \underset{1 \leq a \leq K}{\operatorname{argmax}} \ t \, w_a^*(\hat{\boldsymbol{\mu}}(t)) - N_a(t) & (\textit{tracking}) \end{cases}$$

Lemma

Under the Tracking sampling rule,

$$\mathbb{P}_{\boldsymbol{\mu}} \left(\lim_{t \to \infty} \frac{N_a(t)}{t} = w_a^*(\boldsymbol{\mu}) \right) = 1.$$

Outline

Sequential Decision Problems

The Simple Bandit Model

Classical strategies

Lower Bound

The Track-and-Stop Strategy

- Sampling Rule
- Stopping Rule
- Optimality

Sequential Generalized Likelihood Test

High values of the Generalized Likelihood Ratio

$$Z_{a,b}(t) := \log \frac{\max_{\{\boldsymbol{\lambda}:\lambda_a \geq \lambda_b\}} dP_{\boldsymbol{\lambda}}(X_1, \dots, X_t)}{\max_{\{\boldsymbol{\lambda}:\lambda_a \leq \lambda_b\}} dP_{\boldsymbol{\lambda}}(X_1, \dots, X_t)}$$

$$= N_a(t)\, d\big(\hat{\mu}_a(t), \hat{\mu}_{a,b}(t)\big) + N_b(t)\, d\big(\hat{\mu}_b(t), \hat{\mu}_{a,b}(t)\big) \quad \text{if } \hat{\mu}_a(t) > \hat{\mu}_b(t)$$

$$-Z_{b,a}(t) \text{ otherwise}$$

reject the hypothesis that $(\mu_a \leq \mu_b)$.

We stop when one arm is assessed to be significantly larger than all other arms, according to a GLR test:

$$\tau_\delta = \inf\left\{t \in \mathbb{N} : \exists a \in \{1, \dots, K\}, \forall b \neq a, Z_{a,b}(t) > \beta(t, \delta)\right\}$$

$$= \inf\left\{t \in \mathbb{N} : \quad Z(t) := \max_{a \in \{1,\dots,K\}} \min_{b \neq a} Z_{a,b}(t) > \beta(t, \delta)\right\}$$

Chernoff stopping rule [Chernoff '59]

Two other possible interpretations of the stopping rule:

➜ MDL:

$$Z_{a,b}(t) = \big(N_a(t) + N_b(t)\big) H\big(\hat{\mu}_{a,b}(t)\big) - \Big[N_a(t) H\big(\hat{\mu}_a(t)\big) + N_b(t) H\big(\hat{\mu}_b(t)\big)\Big]$$

Sequential Generalized Likelihood Test

High values of the Generalized Likelihood Ratio

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Chernoff stopping rule [Chernoff '59]

Two other possible interpretations of the stopping rule:

➜ plug-in complexity estimate: if $F(w, \mu) := \inf_{\boldsymbol{\lambda} \in \mathrm{Alt}(\mu)} \sum_{a=1}^{K} w_a \, d\big(\mu_a, \lambda_a\big)$,

stop when $Z(t) = t\, F\left(\frac{N_a(t)}{t}, \hat{\mu}(t)\right) \geq \beta(t, \delta)$ instead of the lower bound $\frac{t}{T^*(\mu)} = t\, F(\mathbf{w}^*, \mu) \geq \mathrm{kl}(\delta, 1-\delta)$.

Calibration

Theorem

The Chernoff rule is δ-PAC for $\beta(t, \delta) = \log\left(\frac{2(K-1)t}{\delta}\right)$

Lemma

If $\mu_a < \mu_b$, whatever the sampling rule,

$$\mathbb{P}_{\boldsymbol{\mu}}\left(\exists t \in \mathbb{N} : Z_{a,b}(t) > \log\left(\frac{2t}{\delta}\right)\right) \leq \delta$$

The proof uses:

➜ Barron's lemma (change of distribution)

➜ and Krichevsky-Trofimov's universal distribution

(very information-theoretic ideas)

Outline

Asymptotic Optimality of the T&S strategy

Theorem [Garivier and Kaufmann 2016]

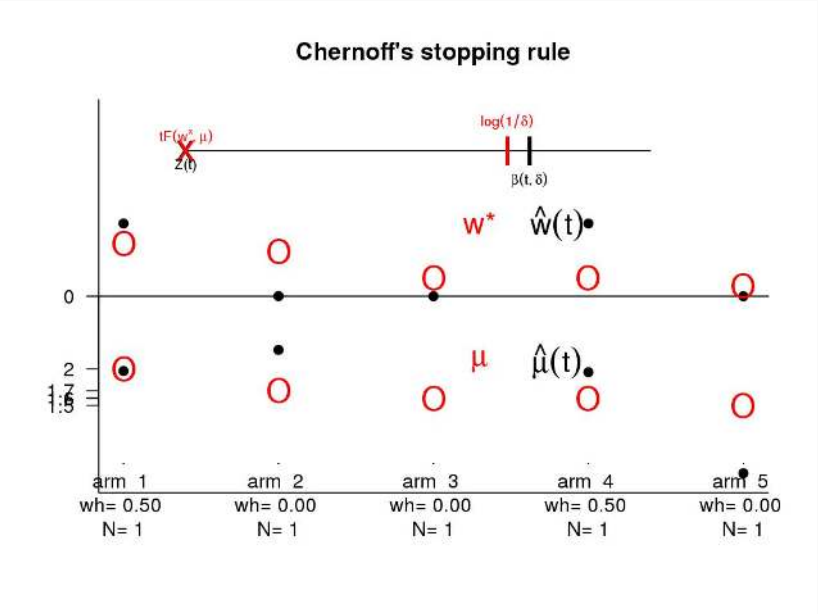
The Track-and-Stop strategy, that uses

- the Tracking sampling rule
- the Chernoff stopping rule with $\beta(t, \delta) = \log\left(\frac{2(K-1)t}{\delta}\right)$
- and recommends $\hat{a}_{\tau_\delta} = \underset{a=1\dots K}{\operatorname{argmax}}\ \hat{\mu}_a(\tau_\delta)$

is δ-PAC for every $\delta \in (0,1)$ and satisfies

$$\limsup_{\delta \to 0} \frac{\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta]}{\log(1/\delta)} = T^*(\boldsymbol{\mu}).$$

Why is the T&S Strategy asymptotically Optimal?



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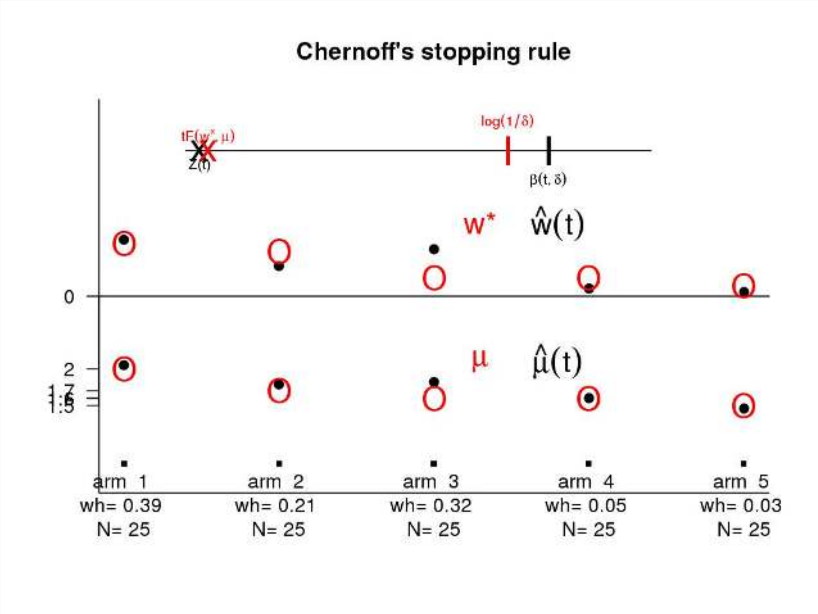

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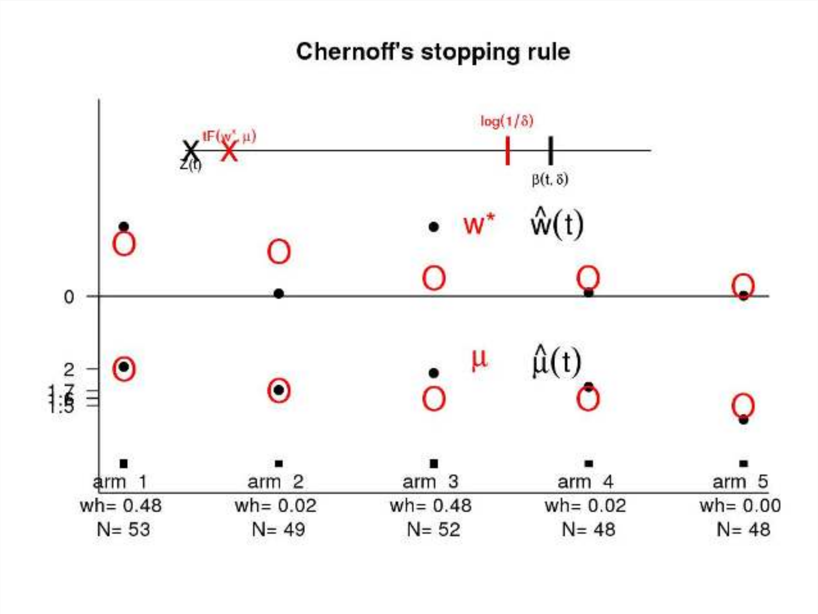

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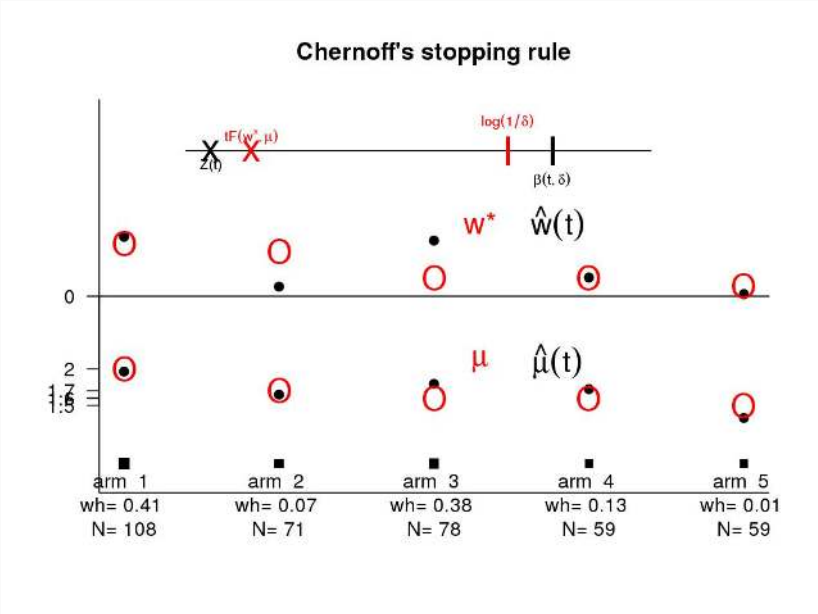

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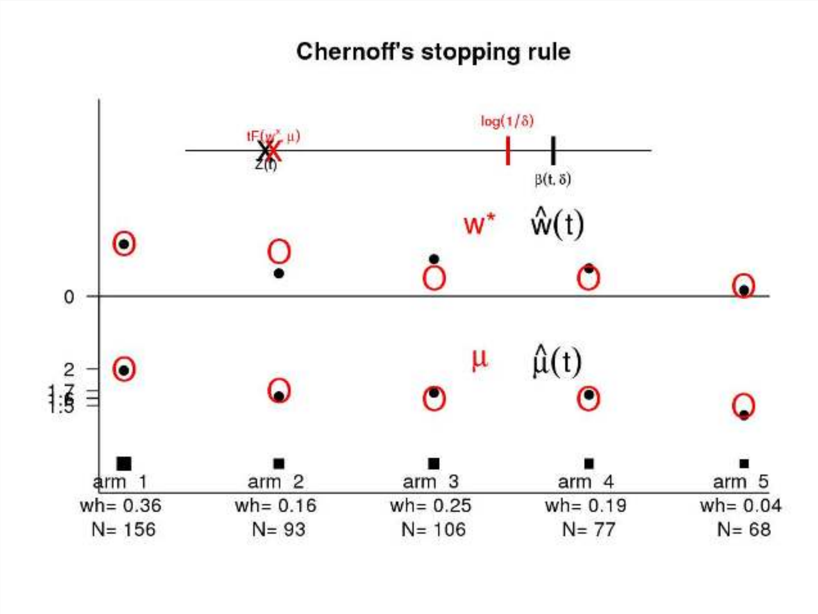

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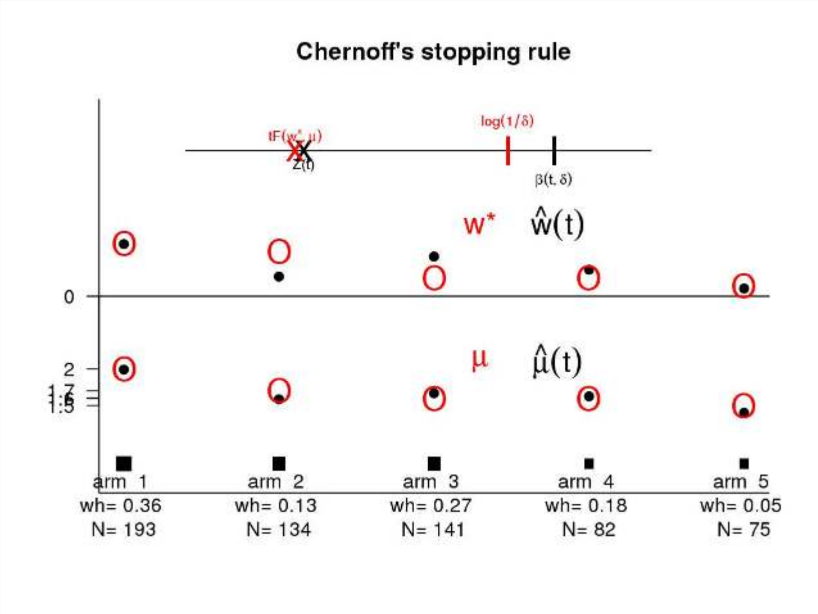

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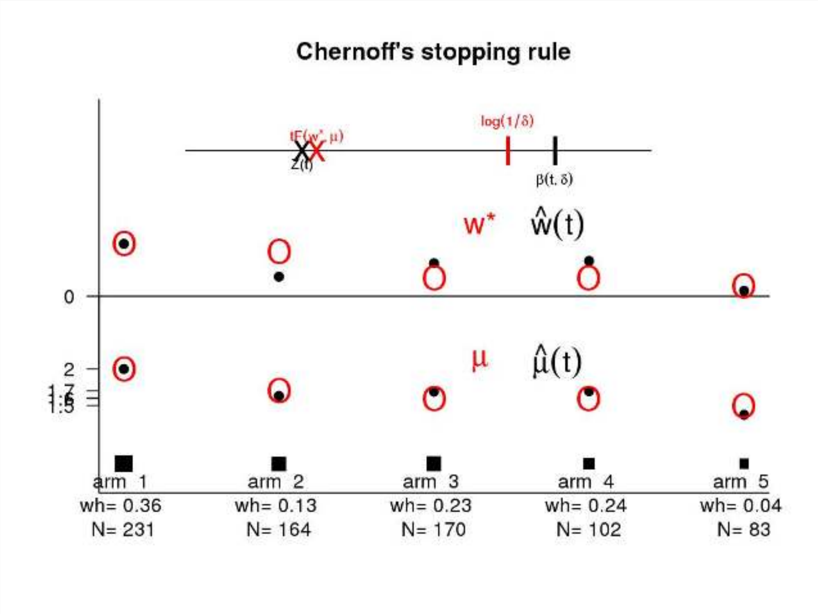

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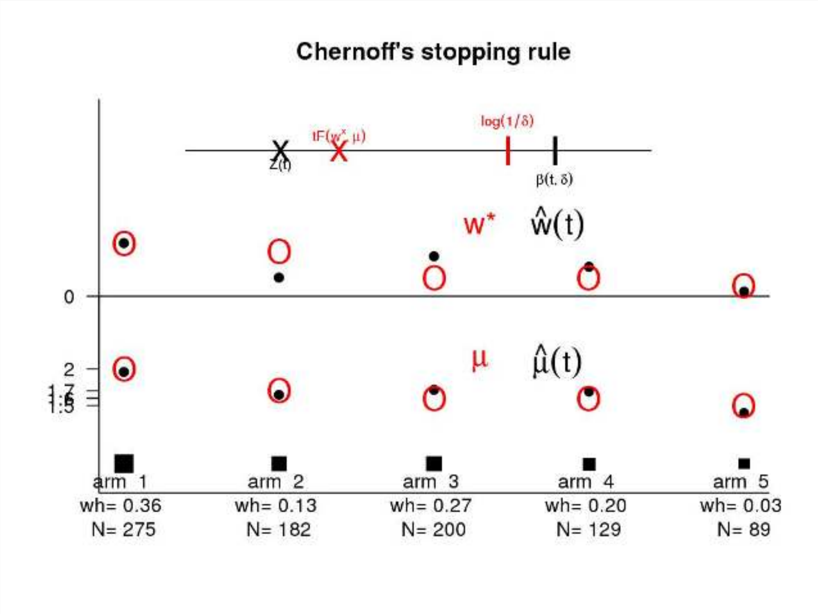

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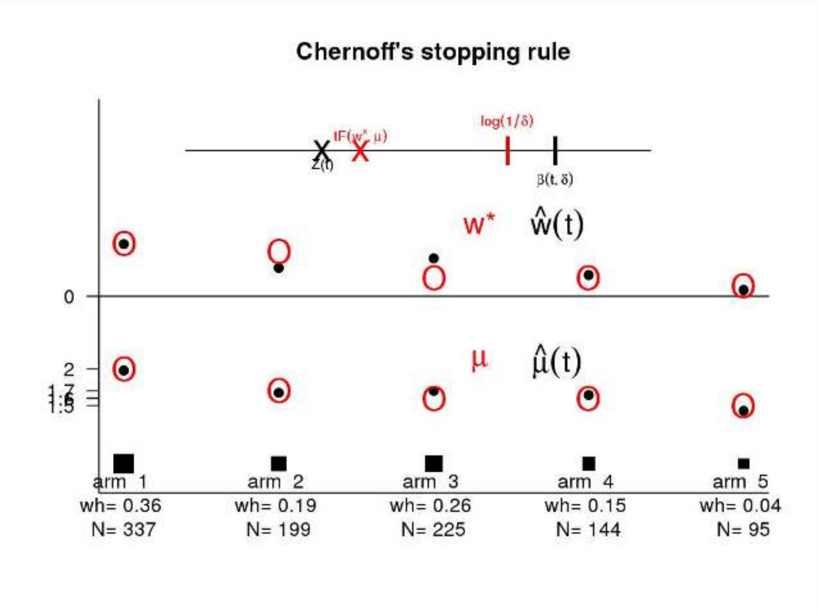

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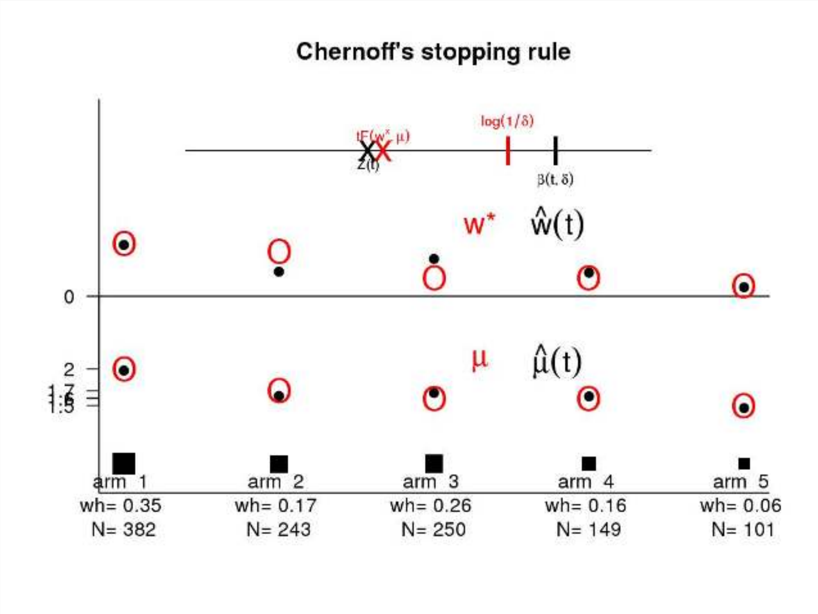

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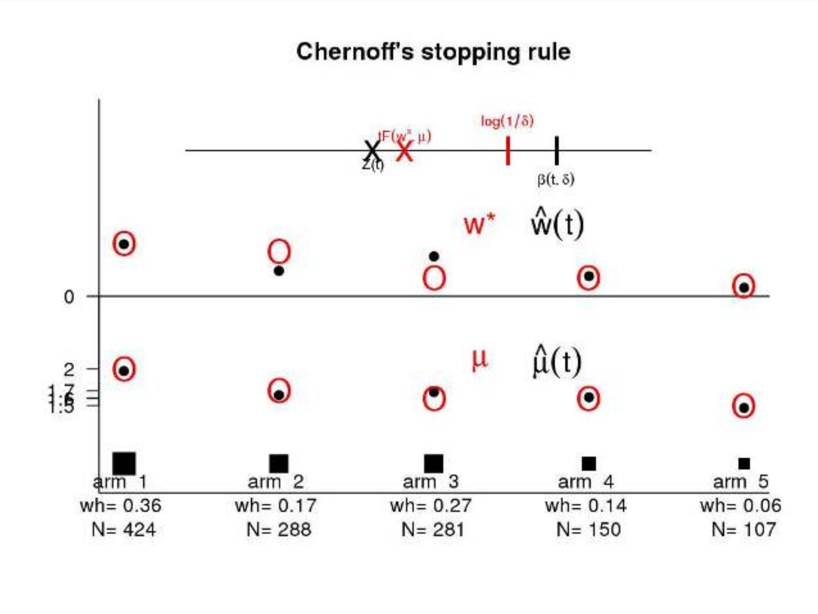

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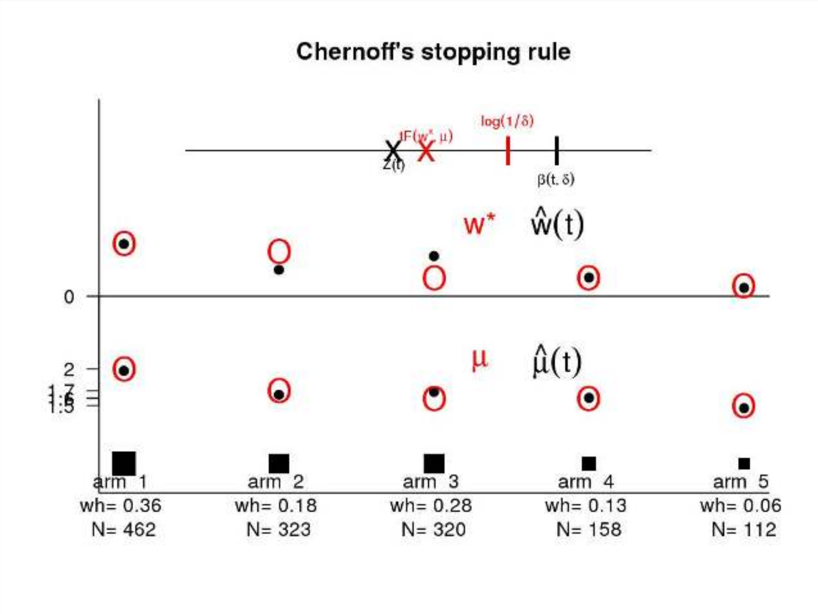

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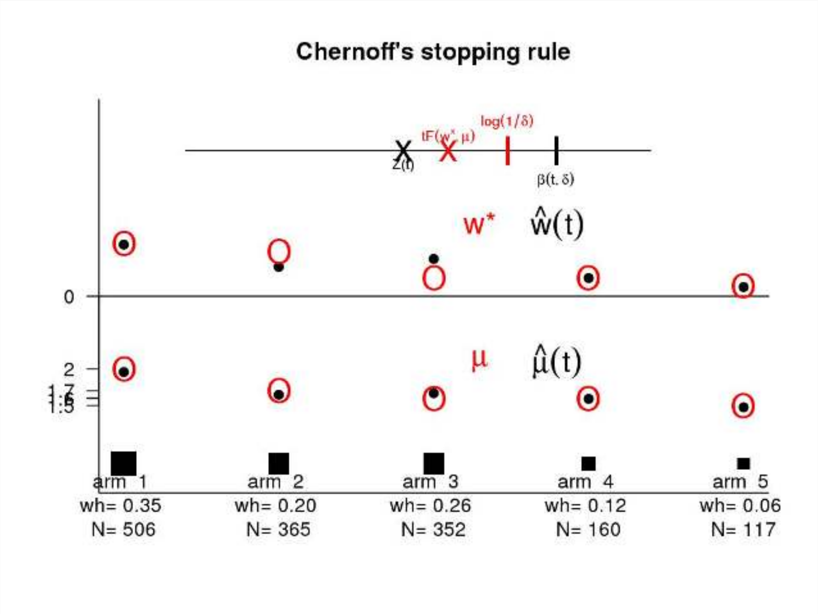

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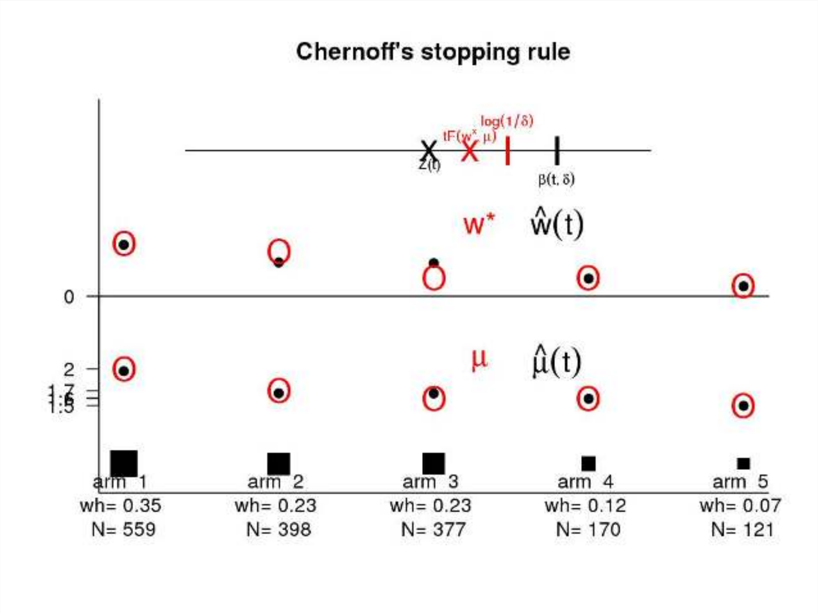

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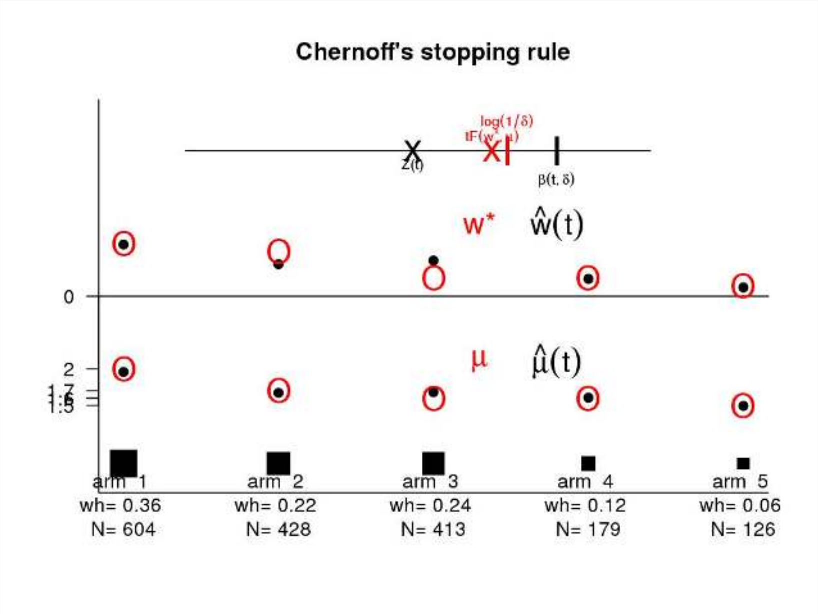

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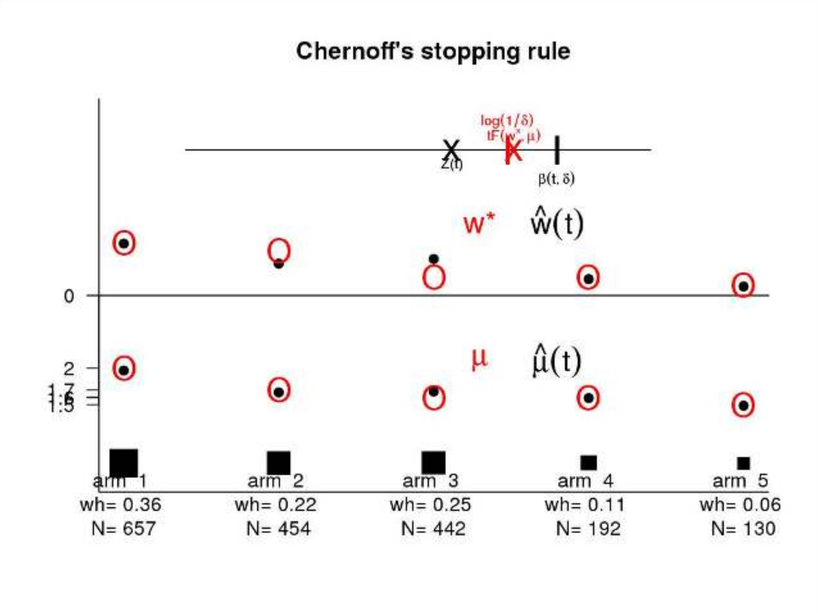

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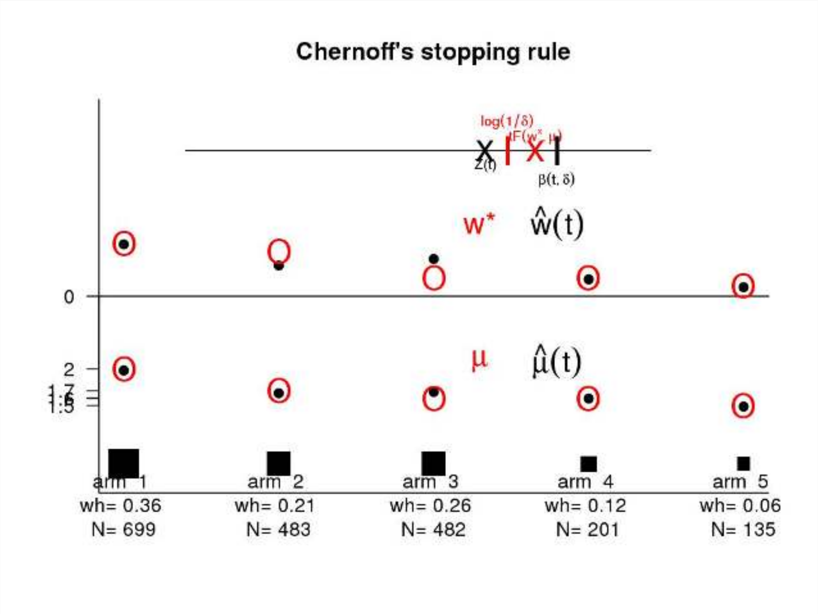

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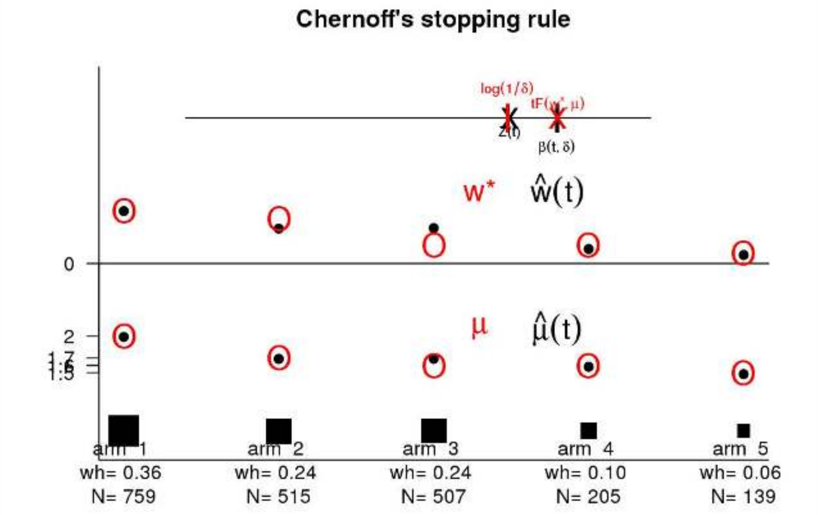

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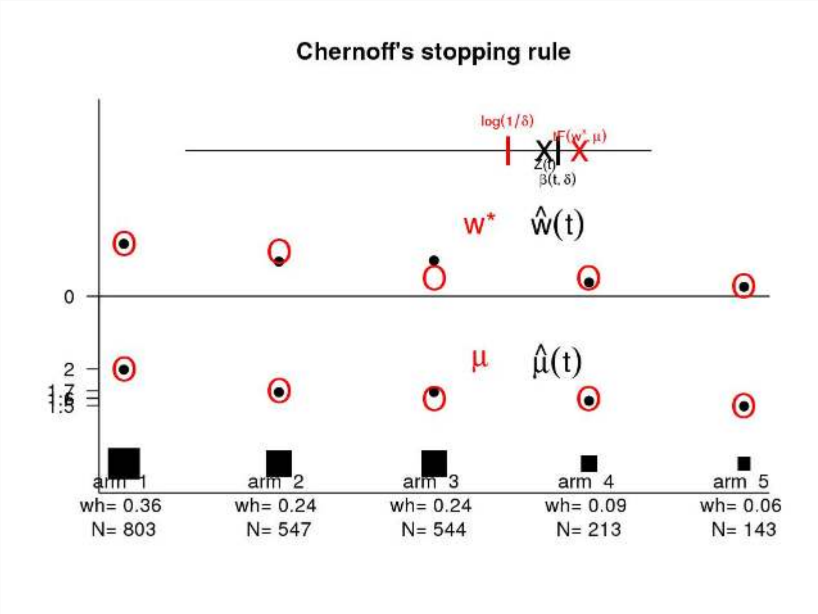

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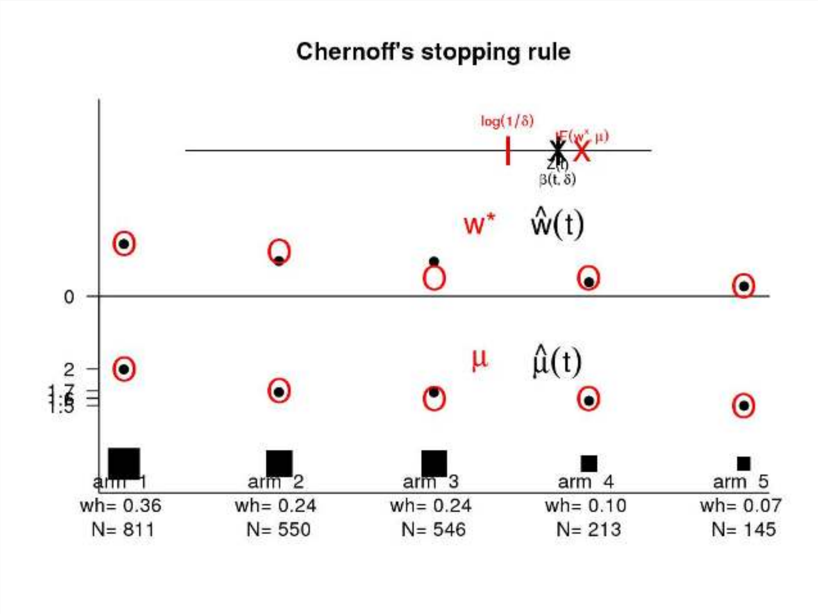


Sketch of proof (almost-sure convergence only)

- forced exploration $\implies$ $N_a(t) \to \infty$ a.s. for all $a \in \{1, \ldots, K\}$

➜ $\hat{\boldsymbol{\mu}}(t) \to \boldsymbol{\mu}$ a.s.

➜ $\boldsymbol{w}^*\big(\hat{\boldsymbol{\mu}}(t)\big) \to \boldsymbol{w}^*$ a.s.

➜ tracking rule: $\dfrac{N_a(t)}{t} \underset{t\to\infty}{\to} w_a^*$ a.s.

- but the mapping $F : (\boldsymbol{\mu}', w) \mapsto \inf_{\boldsymbol{\lambda}\in\mathrm{Alt}(\boldsymbol{\mu}')} \sum_{a=1}^{K} w_a d(\mu'_a, \lambda_a)$ is continuous at $(\boldsymbol{\mu}, w^*(\boldsymbol{\mu}))$:

➜ $Z(t) = t \times F\Big(\hat{\boldsymbol{\mu}}(t), (N_a(t)/t)_{a=1}^K\Big) \sim t \times F(\mu, \mathbf{w}^*) = t \times T^*(\mu)^{-1}$

and for every $\epsilon > 0$ there exists t_0 such that

$$t \geq t_0 \;\Rightarrow\; Z(t) \geq t \times (1+\epsilon)^{-1} T^*(\boldsymbol{\mu})^{-1}$$

$\implies$ Thus $\tau_\delta \leq t_0 \wedge \inf\Big\{t \in \mathbb{N} : (1+\epsilon)^{-1} T^*(\boldsymbol{\mu})^{-1} t \geq \log(2(K-1)t/\delta)\Big\}$

and $\limsup_{\delta\to 0} \dfrac{\tau_\delta}{\log(1/\delta)} \leq (1+\epsilon) T^*(\boldsymbol{\mu})$ *a.s.*

Numerical Experiments

- $\boldsymbol{\mu}_1 = [0.5\ 0.45\ 0.43\ 0.4] \quad ➜ \quad w^*(\boldsymbol{\mu}_1) = [0.42\ 0.39\ 0.14\ 0.06]$
- $\boldsymbol{\mu}_2 = [0.3\ 0.21\ 0.2\ 0.19\ 0.18]$ ➜ $w^*(\boldsymbol{\mu}_2) = [0.34\ 0.25\ 0.18\ 0.13\ 0.10]$

In practice, set the threshold to $\beta(t,\delta) = \log\left(\frac{\log(t)+1}{\delta}\right)$ (δ-PAC OK)

	Track-and-Stop	Chernoff-Racing	KL-LUCB	KL-Racing
$\boldsymbol{\mu}_1$	4052	4516	8437	9590
$\boldsymbol{\mu}_2$	1406	3078	2716	3334

Table 1: Expected number of draws $\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta]$ for $\delta = 0.1$, averaged over $N = 3000$ experiments.

➜ Empirically good even for ‘large’ values of the risk δ

➜ Racing is sub-optimal in general, because it plays $w_1 = w_2$

➜ LUCB is sub-optimal in general, because it plays $w_1 = 1/2$

Perspectives

For best arm identification, we showed that

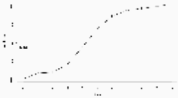
$$\limsup_{\delta \to 0} \inf_{\delta\text{-correct strategy}} \frac{\mathbb{E}_{\boldsymbol{\mu}}[\tau_\delta]}{\log(1/\delta)} = \left(\sup_{w \in \Sigma_K} \inf_{\boldsymbol{\lambda} \in \mathrm{Alt}(\boldsymbol{\mu})} \left(\sum_{a=1}^{K} w_a d(\mu_a, \lambda_a) \right) \right)^{-1}$$

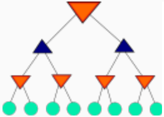
and provided an efficient strategy asymptotically matching this bound.

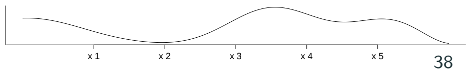
Future work:

- * anytime stopping ➜ gives a confidence level
- ** find an ϵ-optimal arm (PAC-setting)
- * find the m-best arms
- *** design and analyze more stable algorithm (hint: optimism)
- *** give a simple algorithm with a finite-time analysis

  candidate: play action maximizing the expected increase of $Z(t)$
- *** extend to structured (dose, MCTS) and continuous settings







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Thank you for your attention!

Back to: Equalizing the Probabilities of Confusion

Most simple setting: for all $a \in \{1, \dots, K\}$, $\nu_a = \mathcal{N}(\mu_a, 1)$.

For example: $\mu = [2, 1.75, 1.75, 1.6, 1.5]$.

You allocate a relative budget w_a to option a, with $w_1 + \cdots + w_K = 1$.

At time t, you have sampled $n_a \approx w_a\, t$ times option a and the empirical average is $\bar{X}_{a,n_a}$.

$\longrightarrow$ if you stop at time t, your probability of prefering arm $a \geq 2$ to arm $a^* = 1$ is:

$$\begin{aligned}
\mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right) &= \mathbb{P}\left(\frac{\bar{X}_{a,n_a} - \mu_a - \left(\bar{X}_{1,n_1} - \mu_1\right)}{\sqrt{1/n_1 + 1/n_a}} > \frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right) \\
&= \bar{\Phi}\left(\frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right) \\
&\leq e^{-\frac{(\mu_1 - \mu_a)^2}{2\left(1/n_1 + 1/n_a\right)}} \qquad \text{Chernoff's bound}
\end{aligned}$$

Back to: Equalizing the Probabilities of Confusion

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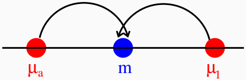
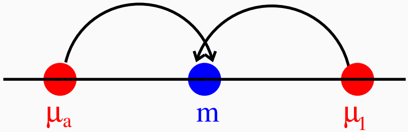
&= \bar{\Phi}\left(\frac{\mu_1 - \mu_a}{\sqrt{1/n_1 + 1/n_a}}\right) \\
&\approx e^{-\frac{(\mu_1 - \mu_a)^2}{2\left(1/n_1 + 1/n_a\right)}} \qquad \text{Large Deviation Principle} \\
&= e^{-\frac{n_1(\mu_1 - m)^2}{2}} \times e^{-\frac{n_a(\mu_a - m)^2}{2}} \qquad \text{with} \quad m = \frac{n_1\mu_1 + n_1\mu_a}{n_1 + n_a} \\
&\approx \mathbb{P}\big(\bar{X}_{1,n_1} < m\big) \times \mathbb{P}\big(\bar{X}_{a,n_a} \geq m\big) \\
&= \max_{\mu_a < m < \mu_1} \mathbb{P}\big(\bar{X}_{1,n_1} < m\big) \times \mathbb{P}\big(\bar{X}_{a,n_a} \geq m\big) \qquad \text{cf. Sanov}
\end{aligned}$$



Entropic Method for Large Deviations Lower Bounds

Let $d(\mu, \mu') = \mathrm{KL}\big(\mathcal{N}(\mu, 1), \mathcal{N}(\mu', 1)\big) = \frac{(x-y)^2}{2}$,
$\mathcal{KL}(Y, Z) = \mathrm{KL}\big(\mathcal{L}(Y), \mathcal{L}(Z)\big)$, $\quad \epsilon > 0$, $\quad \mu_a \leq m \leq \mu_1$ and

- $X_{1,1}, \ldots, X_{1,n_1} \overset{iid}{\sim} \mathcal{N}(\mu_1, 1)$
- $X_{a,1}, \ldots, X_{a,n_a} \overset{iid}{\sim} \mathcal{N}(\mu_a, 1)$
- $X'_{1,1}, \ldots, X'_{1,n_1} \overset{iid}{\sim} \mathcal{N}(m - \epsilon, 1)$
- $X'_{a,1}, \ldots, X'_{a,n_a} \overset{iid}{\sim} \mathcal{N}(m + \epsilon, 1)$



$$n_1\, d(m - \epsilon, \mu_1) + n_a\, d(m + \epsilon, \mu_a) = \mathcal{KL}\big((X'_{a,i})_{a,i}, (X_{a,i})_{a,i}\big)$$

$\mathrm{KL}(P \otimes P', Q \otimes Q') = \mathrm{KL}(P, Q) + \mathrm{KL}(P', Q')$

$$\geq \mathcal{KL}\left(\mathbb{1}\left\{\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1}\right\}, \mathbb{1}\left\{\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right\}\right)$$

contraction of entropy
= data-processing inequality

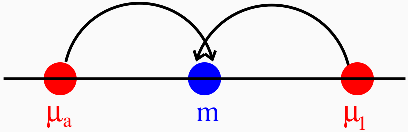
$$= \mathrm{kl}\left(\mathbb{P}\left(\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1}\right), \mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right)\right)$$

$$\mathrm{kl}(p, q) = p \log \frac{p}{q} + (1 - p) \log \frac{1 - p}{1 - q}$$

$$\geq \mathbb{P}\left(\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1}\right) \log \frac{1}{\mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right)} - \log(2)$$

$$\mathrm{kl}(p, q) \geq p \log \frac{1}{q} - \log 2$$

Entropic Method for Large Deviations Lower Bounds



$$n_1\, d(m-\epsilon, \mu_1) + n_a\, d(m+\epsilon, \mu_a) = \mathcal{KL}\Big((X'_{a,i})_{a,i}, (X_{a,i})_{a,i} \Big)$$

$$\mathrm{KL}(P \otimes P', Q \otimes Q') = \mathrm{KL}(P, Q) + \mathrm{KL}(P', Q')$$

$$\geq \mathcal{KL}\Big(\mathbb{1}\left\{ \bar{X}'_{a,n_a} > \bar{X}'_{1,n_1} \right\}, \mathbb{1}\left\{ \bar{X}_{a,n_a} > \bar{X}_{1,n_1} \right\} \Big)$$

contraction of entropy
= data-processing inequality

$$= \mathrm{kl}\Big(\mathbb{P}\left(\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1} \right), \mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1} \right) \Big)$$

$$\mathrm{kl}(p, q) = p \log \frac{p}{q} + (1-p) \log \frac{1-p}{1-q}$$

$$\geq \mathbb{P}\left(\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1} \right) \log \frac{1}{\mathbb{P}\Big(\bar{X}_{a,n_a} > \bar{X}_{1,n_1} \Big)} - \log(2)$$

$$\mathrm{kl}(p, q) \geq p \log \frac{1}{q} - \log 2$$

$$\mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1} \right) \geq \max_{\mu_1 \leq m \leq \mu_a} \exp\left(- \frac{n_1\, d(m-\epsilon, \mu_1) + n_a\, d(m+\epsilon, \mu_a) + \log(2)}{1 - e^{-(n_1+n_a)\epsilon^2/2}} \right)$$

$$= \exp\left(- \frac{\frac{(\mu_1 - \mu_a + \epsilon)^2}{1/n_1 + 1/n_a} + \log(2)}{2\left(1 - e^{-(n_1+n_a)\epsilon^2/2}\right)} \right)$$

$$m = \frac{n_1 \mu_1 + n_a \mu_a}{n_1 + n_a}$$

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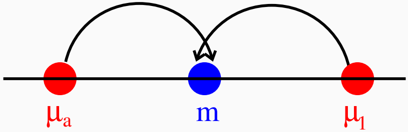

$$n_1\, d(m-\epsilon,\mu_1) + n_a\, d(m+\epsilon,\mu_a) = \mathcal{KL}\Big((X'_{a,i})_{a,i}, (X_{a,i})_{a,i}\Big)$$

$\mathrm{KL}(P\otimes P', Q\otimes Q') = \mathrm{KL}(P,Q) + \mathrm{KL}(P',Q')$

$$\geq \mathcal{KL}\left(\mathbb{1}\left\{\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1}\right\}, \mathbb{1}\left\{\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right\}\right)$$

contraction of entropy
= data-processing inequality

$$= \mathrm{kl}\Big(\mathbb{P}\left(\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1}\right), \mathbb{P}\left(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\right)\Big)$$

$\mathrm{kl}(p,q) = p\log\frac{p}{q} + (1-p)\log\frac{1-p}{1-q}$

$$\geq \mathbb{P}\left(\bar{X}'_{a,n_a} > \bar{X}'_{1,n_1}\right)\log\frac{1}{\mathbb{P}\Big(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\Big)} - \log(2)$$

$\mathrm{kl}(p,q) \geq p\log\frac{1}{q} - \log 2$

$$\Longrightarrow \quad T\Big(w_1\, d(m-\epsilon,\mu_1) + w_a\, d(m+\epsilon,\mu_a)\Big) \gtrsim \log\frac{1}{\mathbb{P}\Big(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\Big)}$$

➜ if you want to have $\mathbb{P}\Big(\bar{X}_{a,n_a} > \bar{X}_{1,n_1}\Big) \leq \delta$ then you need

$$T \gtrsim \frac{\log(1/\delta)}{w_1 d(m,\mu_1) + w_a\, d(m,\mu_a)}$$