Section B | 30 minutes

Developmental Computational Psychiatry lab

How to Develop a Computational Model?

"All models are wrong, but some are useful"
George E. P. Box

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What we will cover:

- An example for how to select the **proper model with respect to a specific task design**
- The **Rescorla Wagner** model
- The concept of **learning rate**
- The concept of **temperature**
- What is a “**softmax**” function

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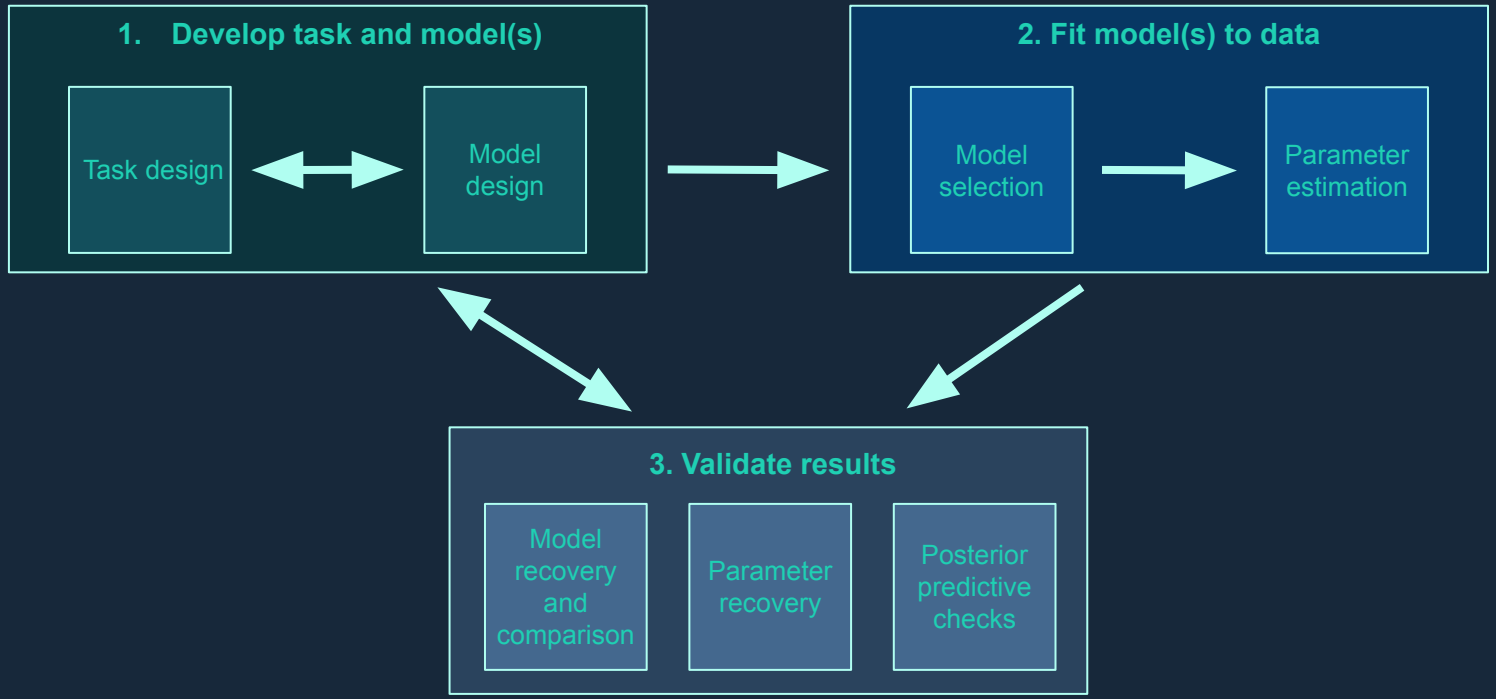
Developing a computational model



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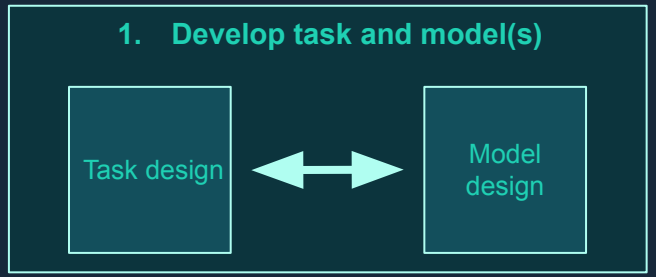
Developing a computational model



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Section B | How to Develop a Computational Model?

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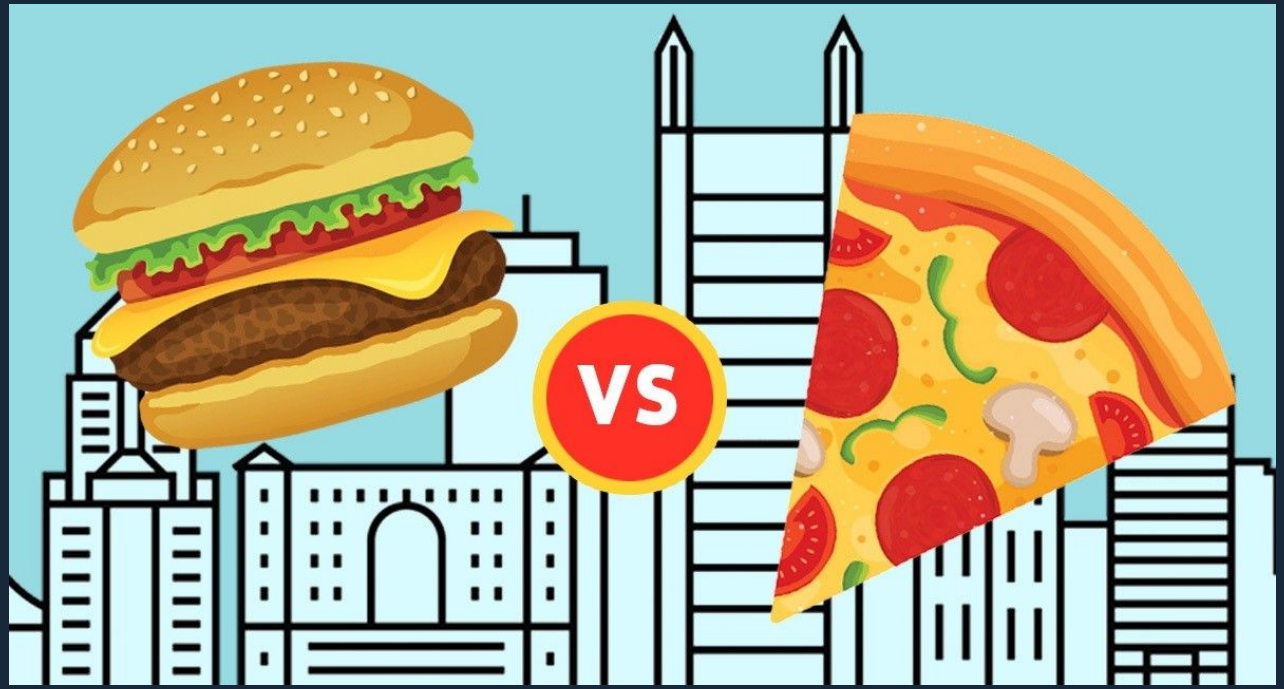

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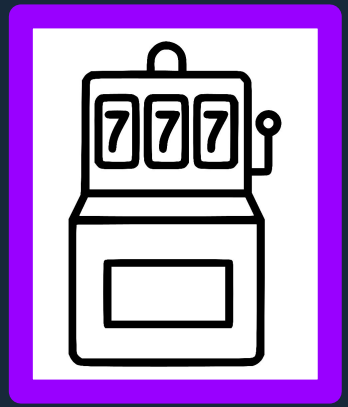
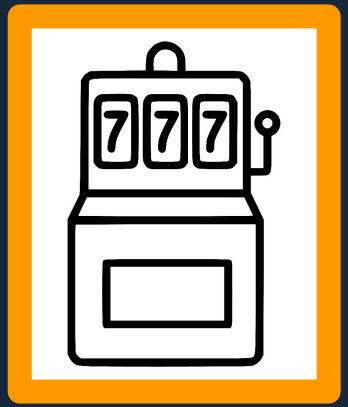
2-arm bandit





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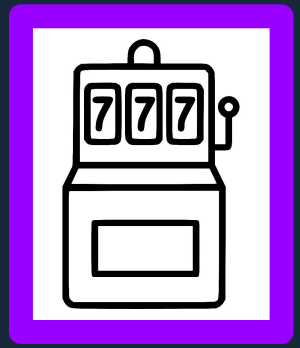
Experimental task -



How do you maximise reward if you do not know which slot machine is better?

- → Learn expected value of each slot machine
- → Make the next choice based on values learnt

Trial	Choice	Outcome
1	Right	0
2	Left new choice	+1
3	Left	+1
4	Right	0
5	Left past experience	+1

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Modelling behaviour with RL

Value function: Rescorla Wagner model

$$V_t = V_{t-1} + \alpha(R_t - V_{t-1})$$

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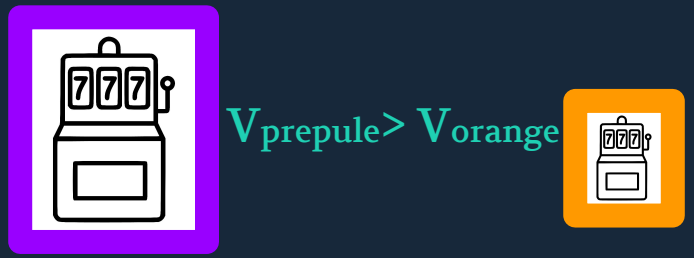
Prediction Error



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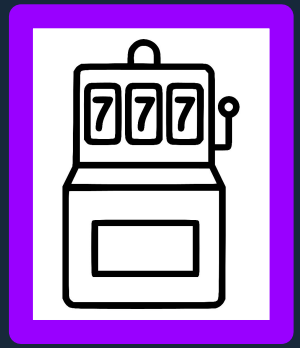
Prediction Error



$$V_t = V_{t-1} + \alpha(R_t - V_{t-1})$$

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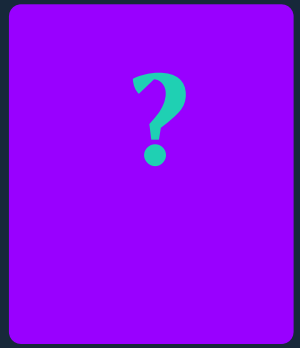
Prediction Error



$$V_t = V_{t-1} + \alpha(R_t - 0.5)$$

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Prediction Error

$$V_t = V_{t-1} + \alpha(1-0.5)$$

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Prediction Error

$$V_t = V_{t-1} + \alpha(1 - 0.5)$$

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Modelling behaviour with RL

Value function: Rescorla Wagner model

$$V_t = V_{t-1} + \alpha (R_t - V_{t-1})$$

Value
(of the slot machine)

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Modelling behaviour with RL

Value function: Rescorla Wagner model

$$V_t = V_{t-1} + \alpha (R_t - V_{t-1})$$

Value (of the slot machine) = Value on previous trial

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Modelling behaviour with RL

Value function: Rescorla Wagner model

$$V_t = V_{t-1} + \alpha (R_t - V_{t-1})$$

Value (of the slot machine) = Value on previous trial + (Reward − Value on previous trial)

Prediction error
what you received - what you expected

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Modelling behaviour with RL

Value function: Rescorla Wagner model

$$V_t = V_{t-1} + \alpha (R_t - V_{t-1})$$

Value (of the slot machine) = Value on previous trial + Learning rate (Reward - Value on previous trial)

Prediction error
what you received - what you expected

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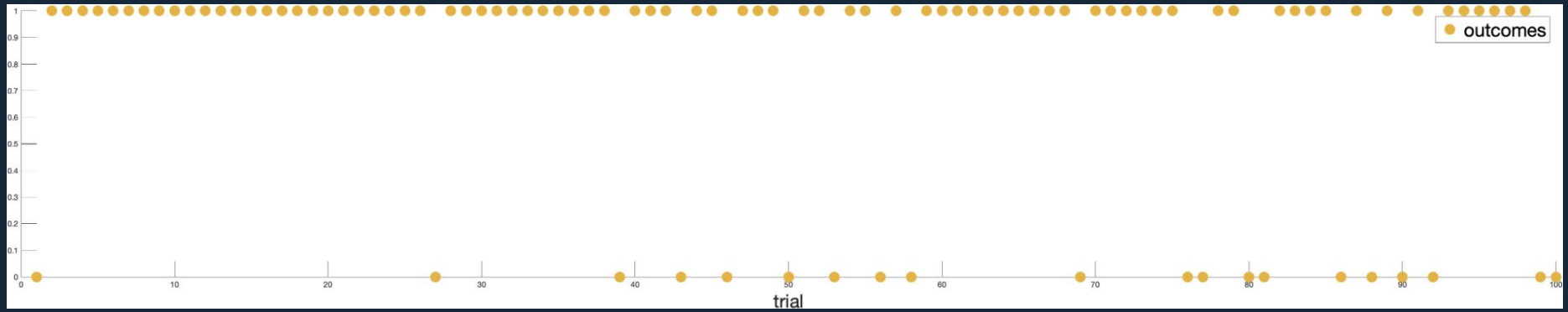
Modelling behaviour with RL

Prediction error
what you received - what you expected

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \times (\text{Reward} - \text{Value on previous trial})$$



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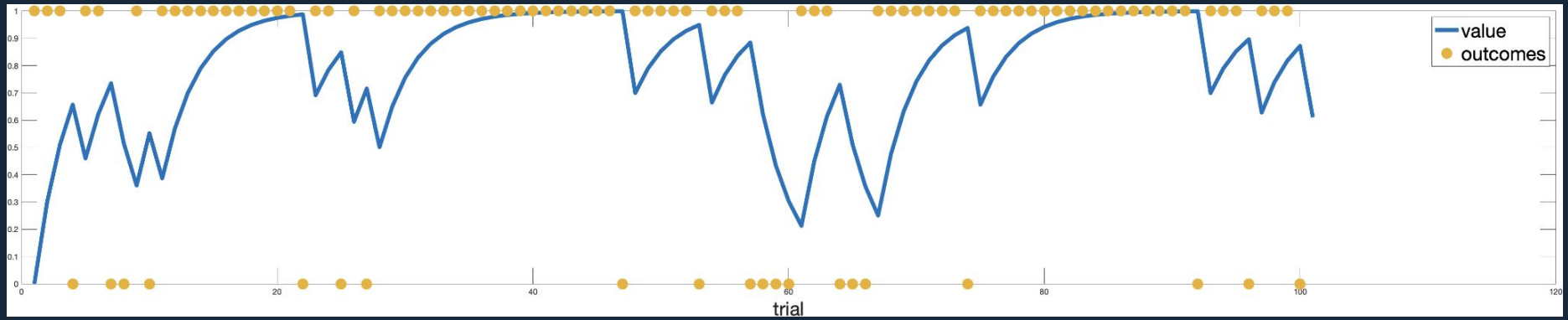
Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (**Reward** - Value on previous trial)



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Modelling behaviour with RL

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \times \underbrace{(\text{Reward} - \text{Value on previous trial})}_{\text{Prediction error: what you received - what you expected}}$$

Trial 1	?				

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward - Value on previous trial)

Trial 1	*?*	*initiation:* 0.5			*initiation:* 0.5

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward - Value on previous trial)

Trial 1	*?*	0.5		*1*	0.5

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward - Value on previous trial)

Trial 1	*?*	0.5	+	*1*	*0.5*

0.5

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Modelling behaviour with RL

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \times \underbrace{(\text{Reward} - \text{Value on previous trial})}_{\text{Prediction error: what you received - what you expected}}$$

Trial 1	***1***	0.5	+	*0.5*

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward − Value on previous trial)

Trial 1	*1*	0.5	+	*0.5*
Trial 2		1	+	1

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward − Value on previous trial)

Trial 1	*1*	0.5	+	*0.5*	
Trial 2		1	+	1	1

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Modelling behaviour with RL

Prediction error
what you received - what you expected

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \left(\text{Reward} - \text{Value on previous trial} \right)$$

Trial 1	*1*	0.5	+	*0.5*
Trial 2		1	+	(1 - 1)

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward - Value on previous trial)

Trial 1	*1*	0.5	+	*0.5*
Trial 2		1	+	*0*

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Modelling behaviour with RL

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \times (\underbrace{\text{Reward} - \text{Value on previous trial}}_{\text{Prediction error: what you received - what you expected}})$$

Trial 1	*1*	0.5	+	*0.5*
Trial 2	***1***	1	+	*0*

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Modelling behaviour with RL

Prediction error
what you received - what you expected

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \left(\text{Reward} - \text{Value on previous trial} \right)$$

Trial 1	*1*	0.5	+	*0.5*
Trial 2	*1*	1	+	*0*

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Modelling behaviour with RL

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Trial 1	*1*	0.5	+	*0.5*
Trial 2	*1*	1	+	*0*
Trial 3		1	+	1

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward − Value on previous trial)

Trial 1	*1*	0.5	+	*0.5*
Trial 2	*1*	1	+	*0*
Trial 3		1	+	*0* 1

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Modelling behaviour with RL

$$\text{Value (of the slot machine)} = \text{Value on previous trial} + \text{Learning rate} \times \underbrace{(\text{Reward} - \text{Value on previous trial})}_{\text{Prediction error: what you received - what you expected}}$$

Trial 1	*1*	0.5	+	*0.5*
Trial 2	*1*	1	+	*0*
Trial 3		1	+	-1

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Modelling behaviour with RL

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Trial 1	*1*	0.5	+	*0.5*
Trial 2	*1*	1	+	*0*
Trial 3	***0***	1	+	-1

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Modelling behaviour with RL

Prediction error
what you received - what you expected

Value (of the slot machine) = Value on previous trial + Learning rate (Reward - Value on previous trial)

$$V_t = V_{t-1} + \alpha (R_t - V_{t-1})$$

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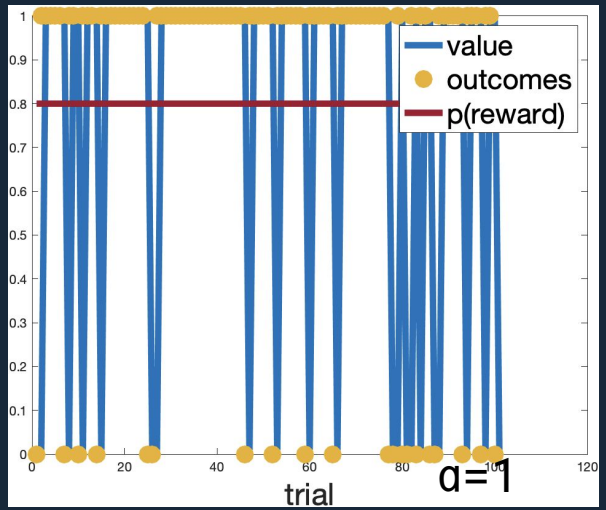
How much should we learn?

What happens if we manipulate learning rate?

$$V_t = V_{t-1} + \alpha(R_t - V_{t-1})$$



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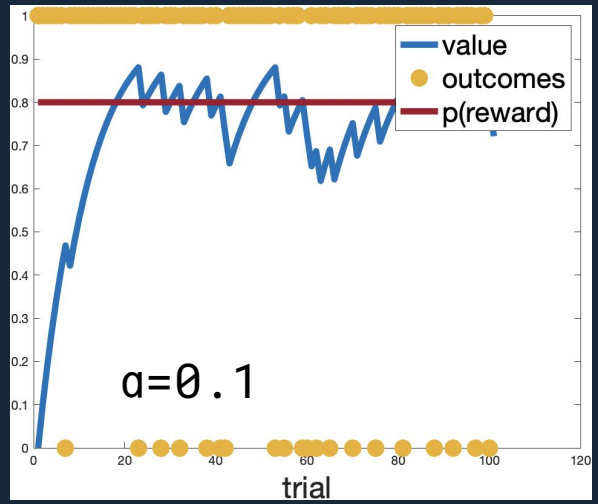

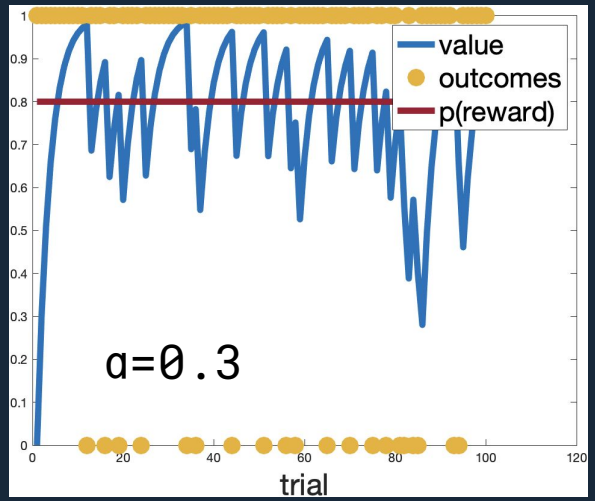

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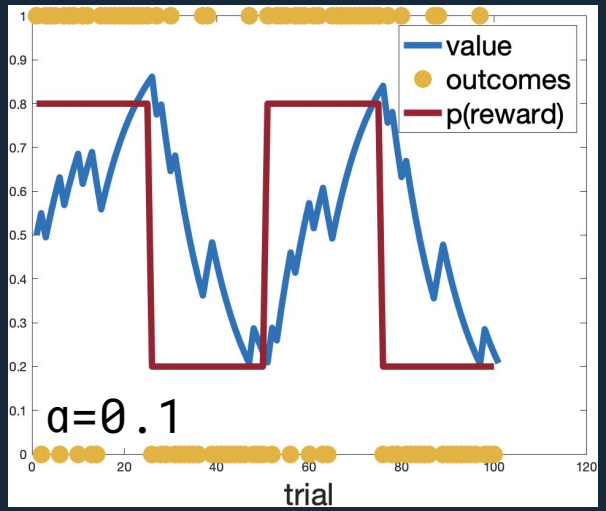
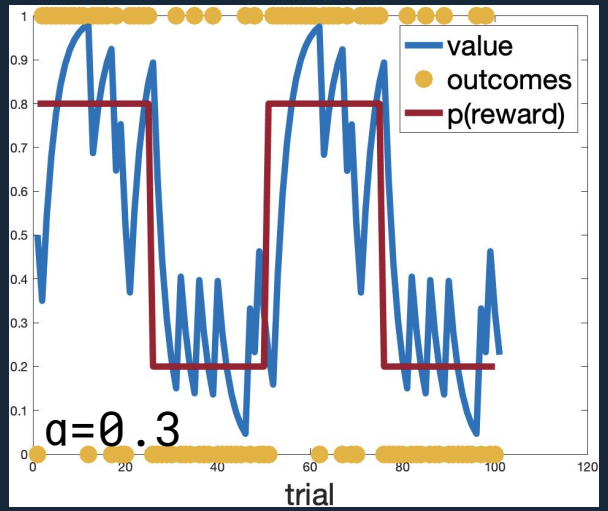
$$V_t = V_{t-1} + \alpha(R_t - V_{t-1})$$





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Is low learning rate always better?

$$V_t = V_{t-1} + \alpha(R_t - V_{t-1})$$

➔ Depend on the statistics of the environment
- Low volatility-> low α is better
- High volatility-> high α is better

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What did we learn so far

- ➔ What are multi arm bandit tasks
- ➔ How RL and, specifically Rescorla Wagner model can help us to ‘solve’ such problems
- ➔ Expected value
- ➔ Prediction error
- ➔ High vs low learning rate

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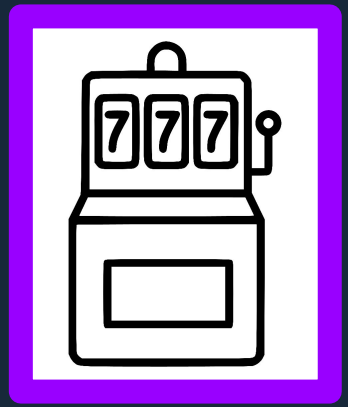
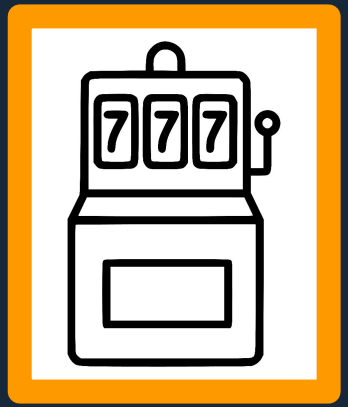
How should we choose?





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How should we choose?

80% reward ← learnt via trial and error (value function) → *20% reward*

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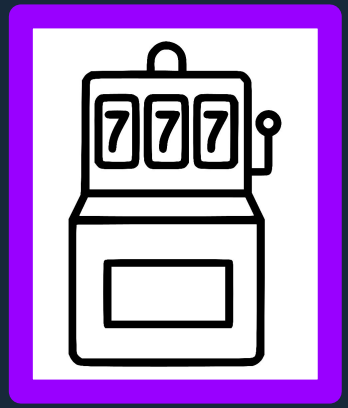
How should we choose?



80% reward

Maximise rewards

- ➔ Pick slot machine with largest likelihood of reward
- ➔ Exploit

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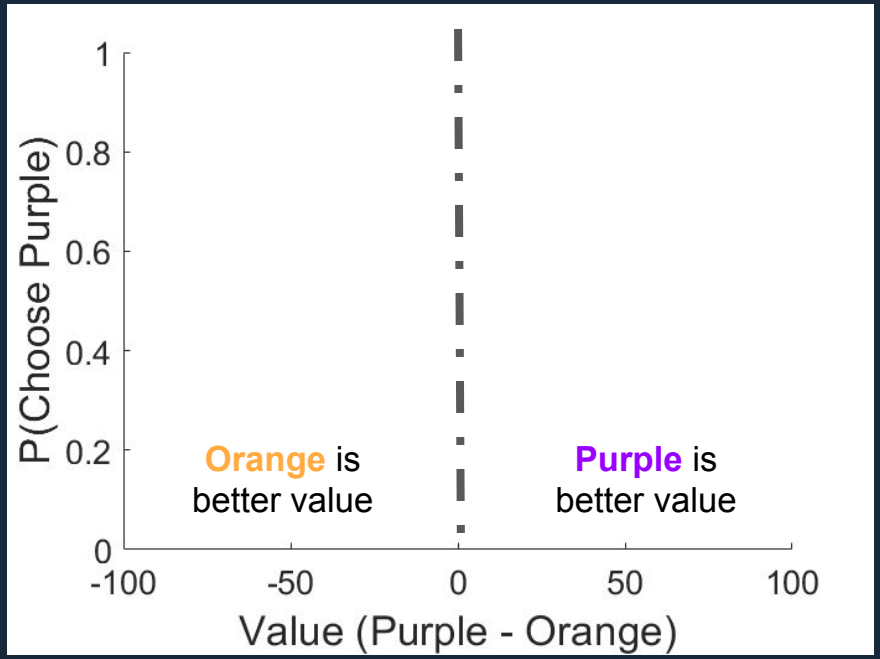
How should we choose?



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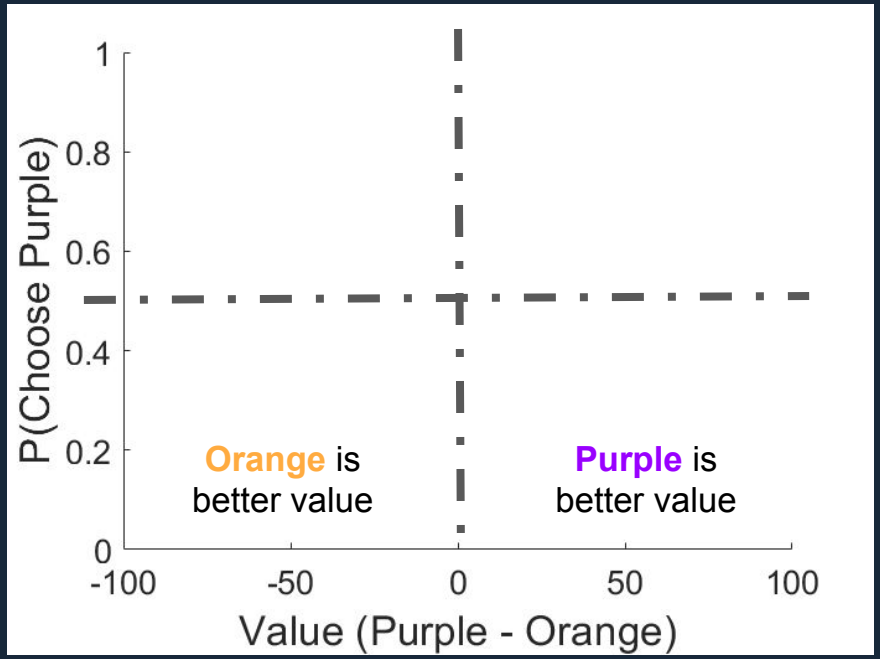
How should we choose?

Choose **purple** is better

Choose **orange** is better



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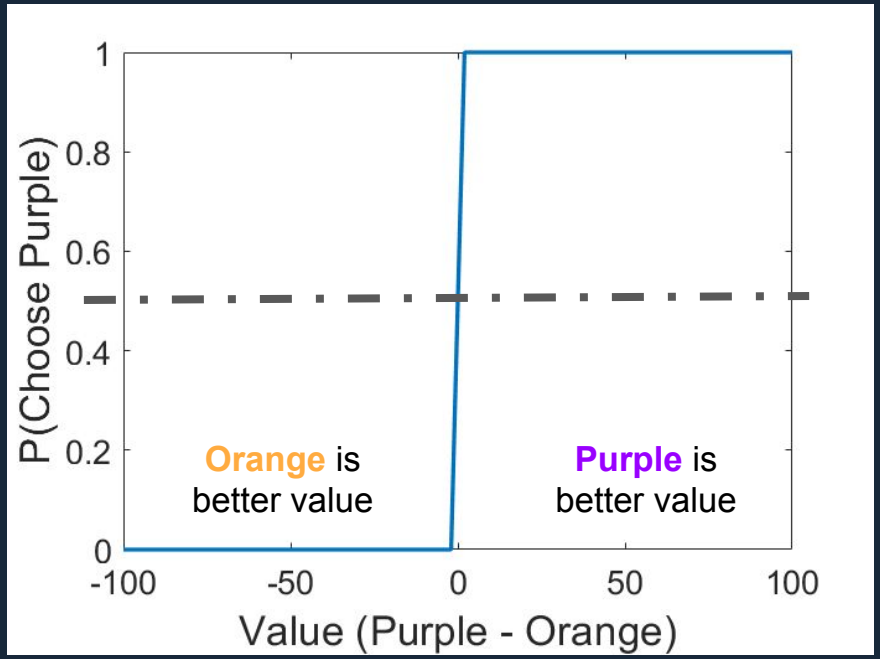
How should we choose?

Choose **purple** is better

Choose **orange** is better



Exploit

➔ Choose slot machine when reward is better than the other

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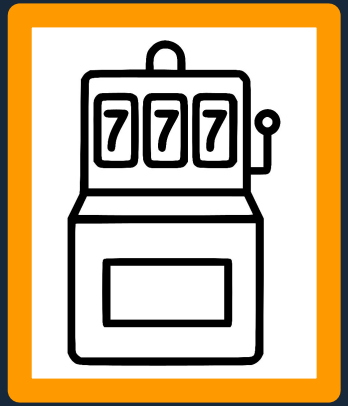
How should we choose?

Try other options

- ➔ Sample the outcomes of the other slot machine
- ➔ Explore



20% reward

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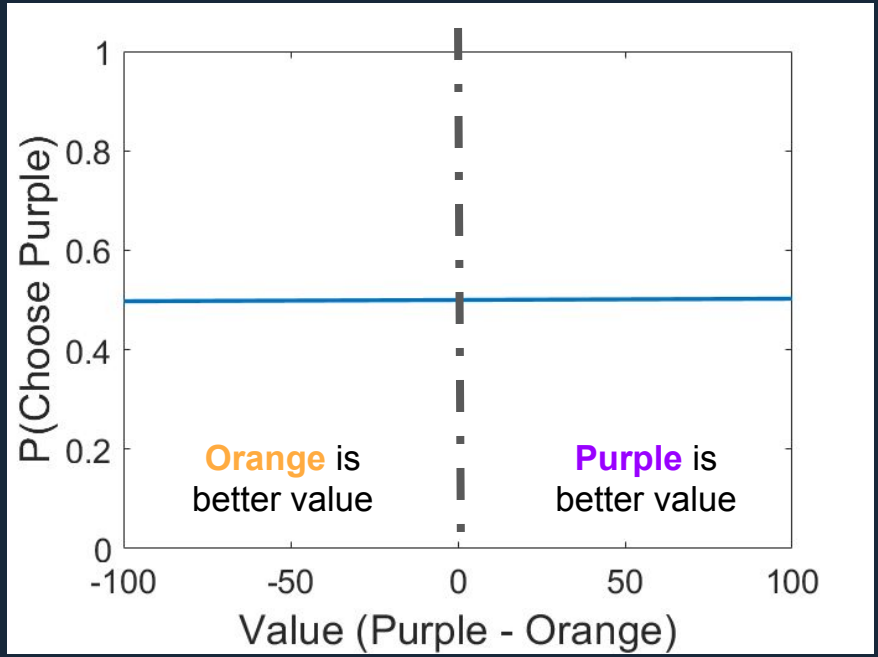
How should we choose?

Choose **purple** is better

Choose **orange** is better



Explore

➔ Choose slot machine equally

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How should we choose?

Exploit ⟶ an individual difference ⟵ *Explore*
we can model as a free parameter

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How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

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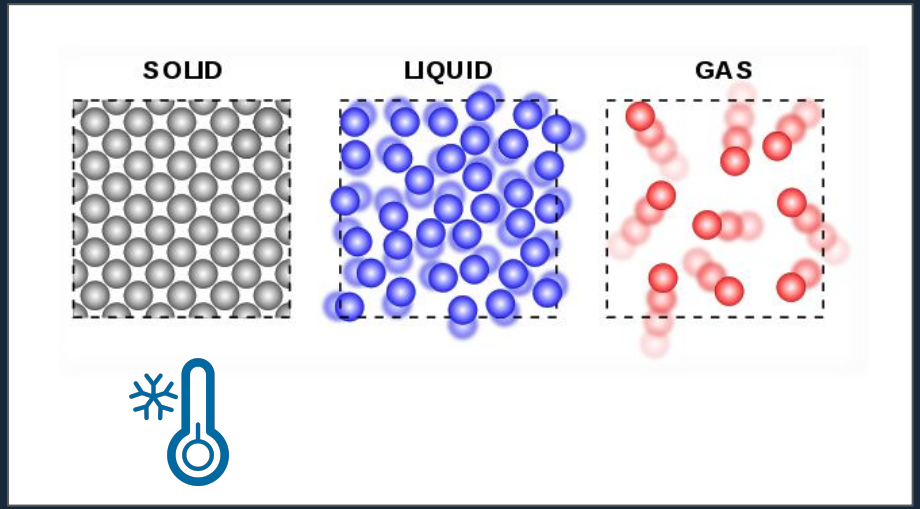
How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

Low temperature
➔ Choices are less noisy



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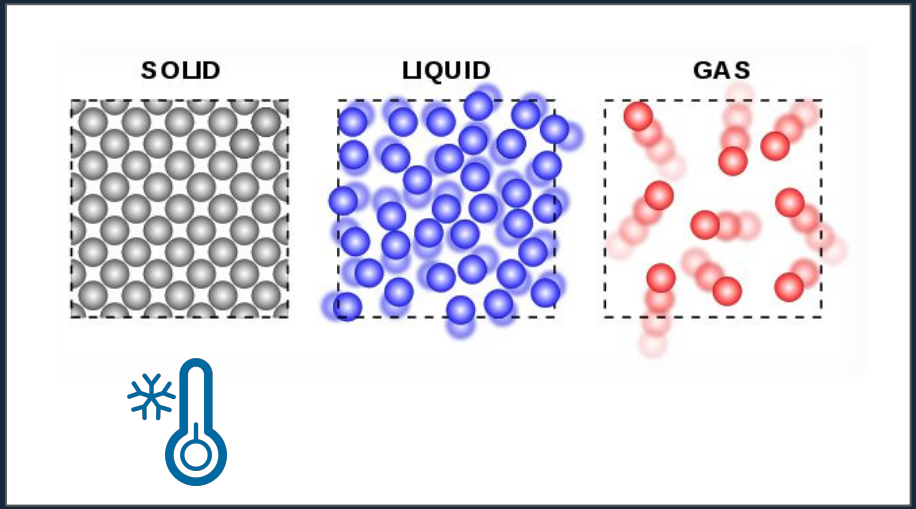
How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

Low temperature

- ➔ Choices are less noisy
- ➔ More affected by value
- ➔ More deterministic



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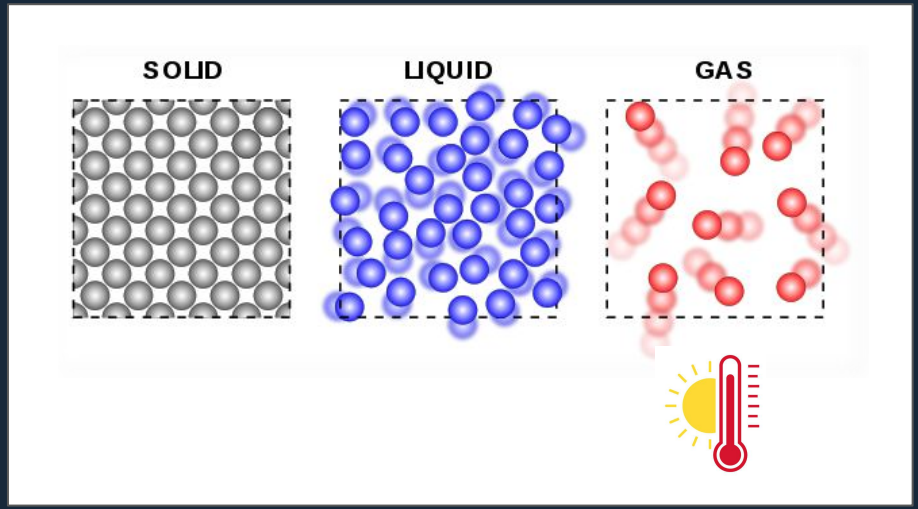
How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

High temperature
- ➔ Choices are more noisy
- ➔ Less affected by value
- ➔ Less deterministic



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How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

➔ Let's assume that if we don't pick purple we will pick orange; and vice versa

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How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

Softmax equation:

$$P(\text{purple}) = \frac{\exp([V_{\text{purple}}]/\tau)}{\text{SUM}[\exp([V_{\text{purple}}, V_{\text{orange}}]/\tau)]}$$

→ Let's assume that if we don't pick purple we will pick orange; and vice versa

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Softmax equation:

$$P(\text{purple}) = \frac{\exp([V_{\text{purple}}]/\tau)}{\text{SUM}[\exp([V_{\text{purple}}, V_{\text{orange}}]/\tau)]}$$

Probability of choosing purple

→ P(orange) = 1 - P(purple)

→ Let's assume that if we don't pick purple we will pick orange; and vice versa

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Value of machines

Probability of choosing purple

→ P(orange) = 1 - P(purple)

→ Let's assume that if we don't pick purple we will pick orange; and vice versa

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How should we choose?

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

Softmax equation:

$$P(\text{purple}) = \frac{\exp([V_{\text{purple}}]/\tau)}{\text{SUM}[\exp([V_{\text{purple}}]/\tau)]}$$

Value of machines

Free parameter temperature

Probability of choosing purple

➔ P(orange) = 1 - P(purple)

➔ Let's assume that if we don't pick purple we will pick orange; and vice versa

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$

$$V_{\text{orange}}$$

Exploit

➔ Choose slot machine when reward is better than the other

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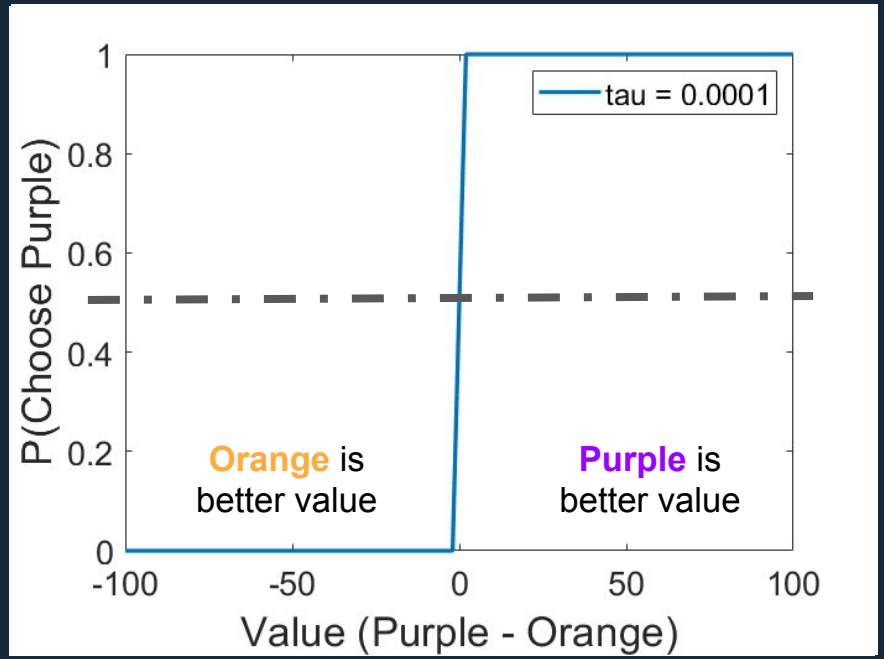
How should we choose?

Choose **purple** is better

Choose **orange** is better



$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$
$$V_{\text{orange}}$$

Exploit

➔ Choose slot machine when reward is better than the other

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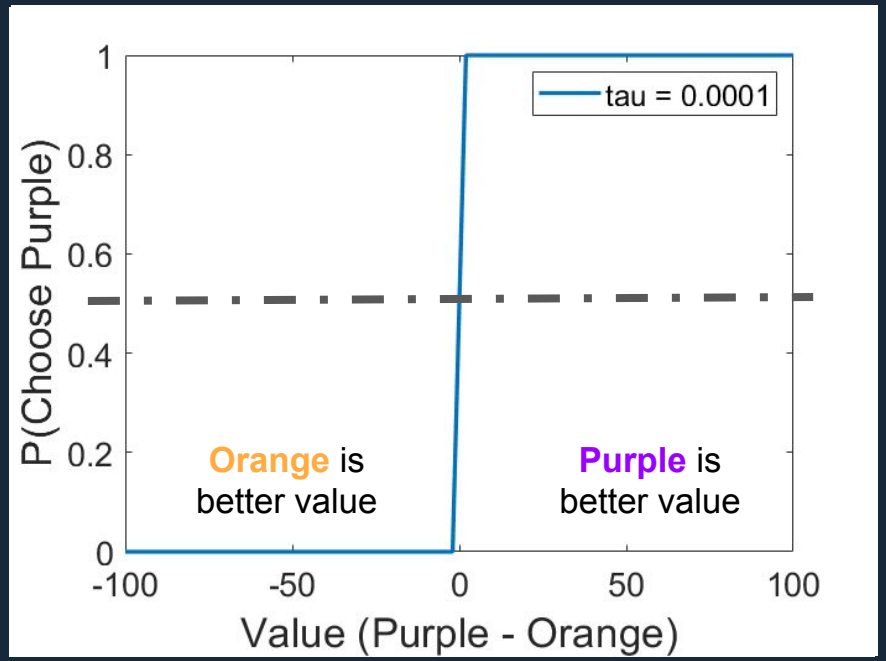
How should we choose?

Choose **purple** is better

Choose **orange** is better



$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$
$$V_{\text{orange}}$$

Exploit

➔ Choose slot machine when reward is better than the other

Temperature is low

➔ Choices are less noisy

➔ More affected by value

➔ More deterministic

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]_{V_{\text{orange}}}}$$

Explore

➔ Random choice

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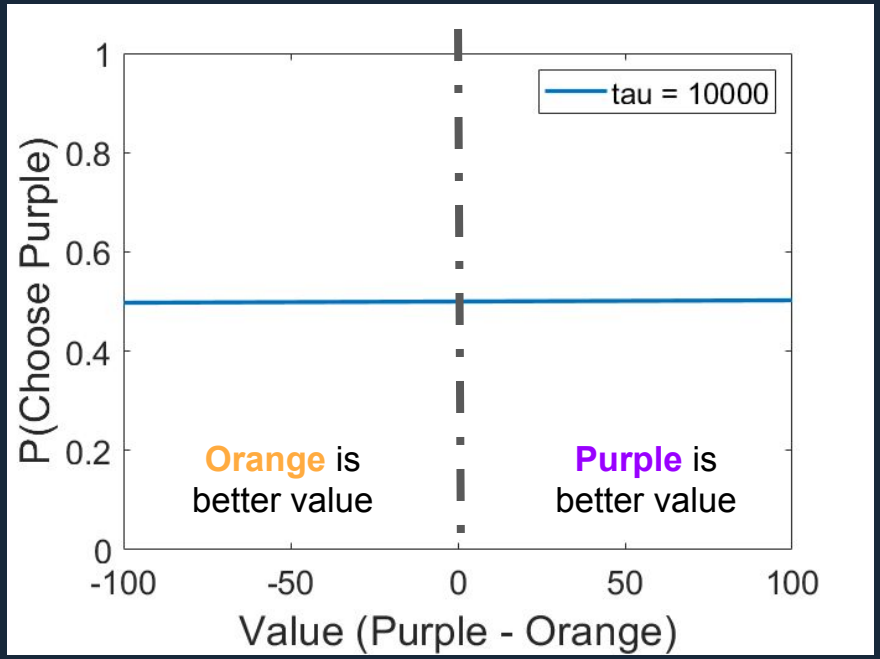
How should we choose?

Choose **purple** is better

Choose **orange** is better



$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$
$$V_{\text{orange}}$$

Explore

➔ Random choice

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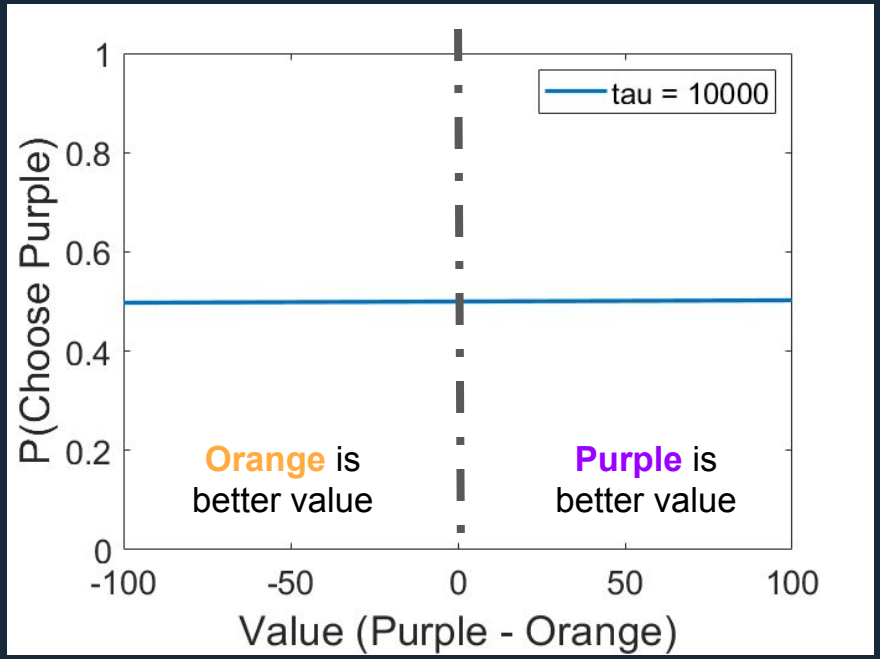
How should we choose?

Choose **purple** is better

Choose **orange** is better



$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$
$$V_{\text{orange}}$$

Explore

➔ Random choice

Temperature is high

➔ Choices are more noisy

➔ Less affected by value

➔ More random

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$

$$V_{\text{orange}}$$

Temperature is low

- ➔ Choices are less noisy
- ➔ More affected by value
- ➔ More deterministic

Temperature is high

- ➔ Choices are more noisy
- ➔ Less affected by value
- ➔ Less deterministic

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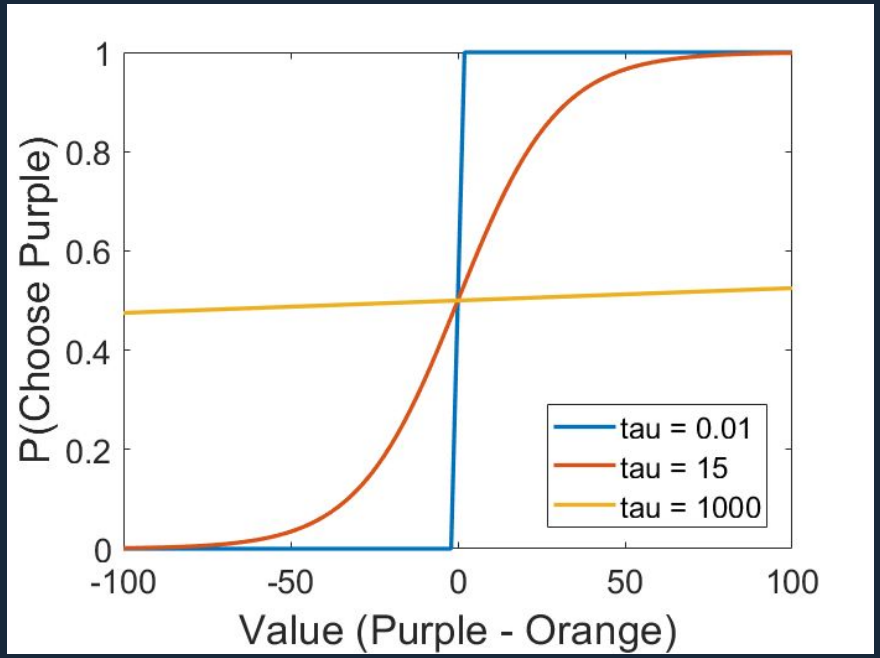
How should we choose?

Choose **purple** is better

Choose **orange** is better



$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}} \quad V_{\text{orange}}\ ]/\tau)]}$$

Temperature is low

- ➔ Choices are less noisy
- ➔ More affected by value
- ➔ More deterministic

Temperature is high

- ➔ Choices are more noisy
- ➔ Less affected by value
- ➔ Less deterministic

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How should we choose?

Softmax

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]}$$
$$V_{\text{orange}}$$

What does the exponential (exp) do?

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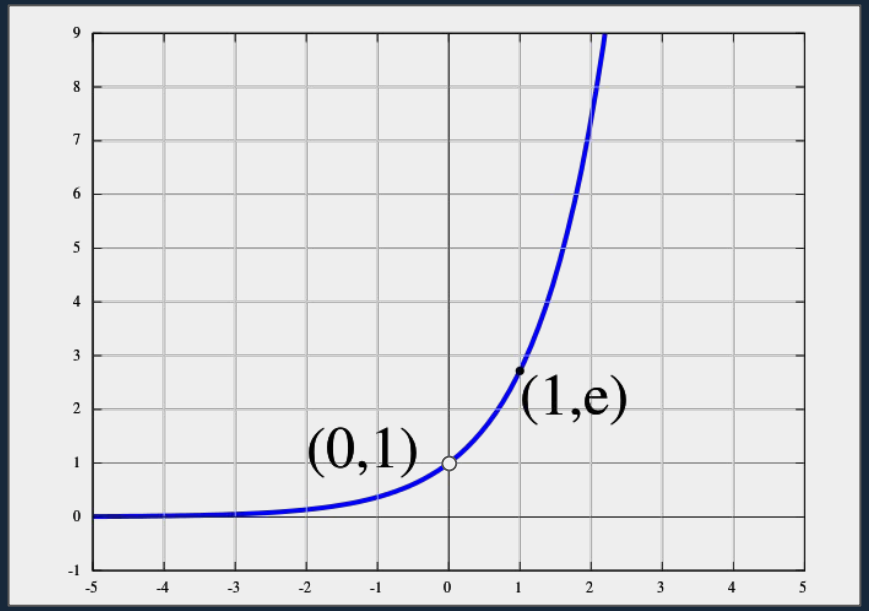
How should we choose?

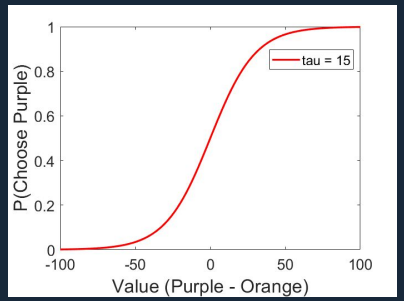


Softmax

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\tau)]_{V_{\text{orange}}}}$$

What does the exponential (exp) do?

- ➔ Deals with negative values
- ➔ Non-linear transformation of value



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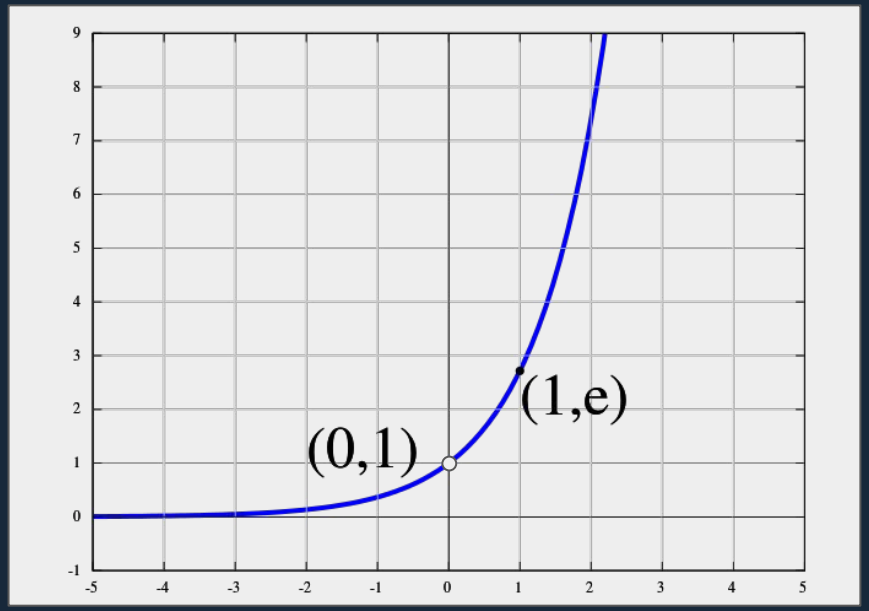

Softmax

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ]/\tau)]}$$

What does the exponential (exp) do?

- ➔ Deals with negative values
- ➔ Non-linear transformation of value

What does the division by SUM do?

- ➔ Normalizes values to between 0 to 1

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ])]}$$

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{purple}\ ])}{SUM[\exp([\ V_{purple}\ V_{orange}\ ])]}$$

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

For my next slot machine play...

$V_{purple} = [\ 60\ ]$ $V_{orange} = [\ 40\ ]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}} \\ V_{\text{orange}}\ ])]}$$

$$= \frac{\exp([\ 60\ ])}{\text{SUM}[\exp([\ 60 \\ 40\ ])]}$$

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

For my next slot machine play...

$V_{\text{purple}} = [\ 60\ ]$ $V_{\text{orange}} = [\ 40\ ]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ])]}$$

$$= \frac{\exp([\ 60\ ])}{\text{SUM}[\exp([\ 60\ 40\ ])]}$$

$$= \frac{e^{60}}{e^{60}+e^{40}}$$

$$= 1$$

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

For my next slot machine play...

$V_{\text{purple}} = [\ 60\ ]$ $V_{\text{orange}} = [\ 40\ ]$

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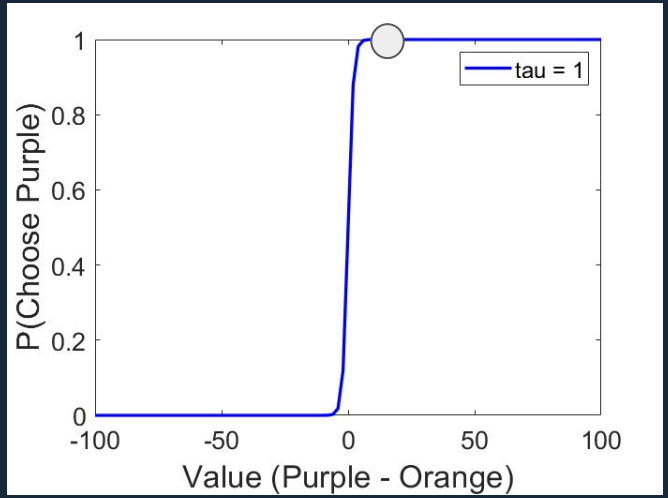
$$= \frac{e^{60}}{e^{60}+e^{40}}$$

$$= 1$$

Softmax

➔ Transforms value input into values between 0 to 1



$V_{\text{purple}} = [\ 60\ ]$ $V_{\text{orange}} = [\ 40\ ]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ])]}$$

$$= \frac{\exp([\ 60\ ])}{\text{SUM}[\exp([\ 60\ 40\ ])]}$$

$$= \frac{e^{60}}{e^{60}+e^{40}}$$

$$= 1$$

$$P(\text{orange}) = \frac{\exp([\ V_{\text{orange}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ])]}$$

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

$V_{\text{purple}} = [\ 60\ ]$ $V_{\text{orange}} = [\ 40\ ]$

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$$= \frac{\exp([\ 60\ ])}{\text{SUM}[\exp([\ 60\ 40\ ])]}$$

$$= \frac{e^{60}}{e^{60}+e^{40}}$$

$$= 1$$

$$P(\text{orange}) = \frac{\exp([\ V_{\text{orange}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ])]}$$

$$= \frac{e^{40}}{e^{60}+e^{40}}$$

$$= 0$$

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

$V_{\text{purple}} = [\ 60\ ]$ $V_{\text{orange}} = [\ 40\ ]$

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$$= \frac{\exp([\ 60\ ])}{\text{SUM}[\exp([\ 60\ 40\ ])]}$$

$$= \frac{e^{60}}{e^{60}+e^{40}}$$

$$= 1$$

$$P(\text{orange}) = \frac{\exp([\ V_{\text{orange}}\ ])}{\text{SUM}[\exp([\ V_{\text{purple}}\ V_{\text{orange}}\ ])]}$$

$$= \frac{e^{40}}{e^{60}+e^{40}}$$

$$= 0$$

probability equals to 1

Softmax

➔ Transforms value input into values between 0 to 1

Assume temperature = 1

$V_{\text{purple}} = [\ 60\ ]$ $V_{\text{orange}} = [\ 40\ ]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([V_{\text{purple}}]/\tau)}{\text{SUM}[\exp([V_{\text{purple}}, V_{\text{orange}}]/\tau)]}$$

Temperature (τ)

➔ how much value affects choices

Assume temperature = 15

$V_{\text{purple}} = [60]$ $V_{\text{orange}} = [40]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\,V_{\text{purple}}\,]/\,\tau)}{\text{SUM}[\exp([\,V_{\text{purple}}\;V_{\text{orange}}\,]/\,\tau)]}$$

$$= \frac{\exp([\,60\,]/\,15)}{\text{SUM}[\exp([\,60\;40\,]/\,15)]}$$

Temperature (τ)

➔ how much value affects choices

Assume temperature = 15

$V_{\text{purple}} = [\,60\,]$ $V_{\text{orange}} = [\,40\,]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\,V_{\text{purple}}\,]/\,\tau)}{\text{SUM}[\exp([\,V_{\text{purple}}\;V_{\text{orange}}\,]/\,\tau)]}$$

$$= \frac{\exp([\,60\,]/\,15)}{\text{SUM}[\exp([\,60\;40\,]/\,15)]}$$

$$= \frac{e^{60/15}}{e^{60/15}+e^{40/15}}$$

$$= 0.79$$

Temperature (τ)

➔ how much value affects choices

Assume temperature = 15

$V_{\text{purple}} = [\,60\,]$ $V_{\text{orange}} = [\,40\,]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([\,V_{\text{purple}}\,]/\,\tau)}{\text{SUM}[\exp([\,V_{\text{purple}}\;V_{\text{orange}}\,]/\,\tau)]}$$

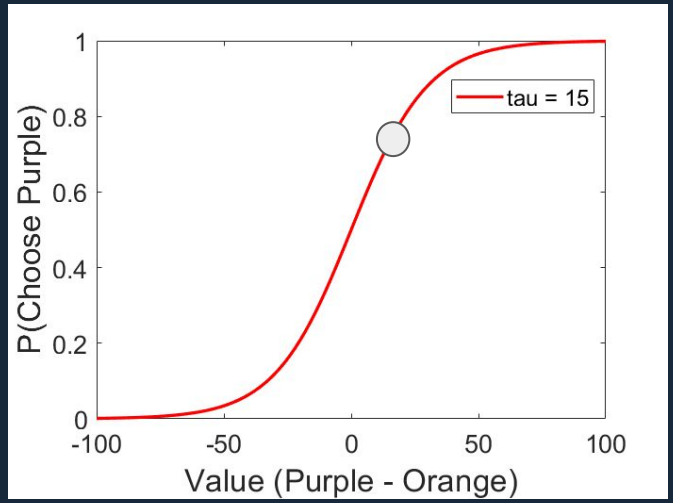
$$= \frac{\exp([\,60\,]/\,15)}{\text{SUM}[\exp([\,60\;40\,]/\,15)]}$$

$$= \frac{e^{60/15}}{e^{60/15}+e^{40/15}}$$

$$= 0.79$$

Temperature (τ)

➔ how much value affects choices



$V_{\text{purple}} = [\,60\,]$ $V_{\text{orange}} = [\,40\,]$

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How should we choose?

$$P(\text{purple}) = \frac{\exp([V_{\text{purple}}]/\tau)}{\text{SUM}[\exp([V_{\text{purple}}, V_{\text{orange}}]/\tau)]}$$

$$= \frac{\exp([60]/15)}{\text{SUM}[\exp([60, 40]/15)]}$$

$$= \frac{e^{60/15}}{e^{60/15}+e^{40/15}}$$

$$= 0.79$$

$$P(\text{orange}) = \frac{\exp([V_{\text{orange}}]/\tau)}{\text{SUM}[\exp([V_{\text{purple}}, V_{\text{orange}}]/\tau)]}$$

$$= \frac{e^{40/15}}{e^{60/15}+e^{40/15}}$$

$$= 0.21$$

probability equals to 1

Temperature (τ)

→ how much value affects choices

Assume temperature = 15

$V_{\text{purple}} = [60]$ $V_{\text{orange}} = [40]$

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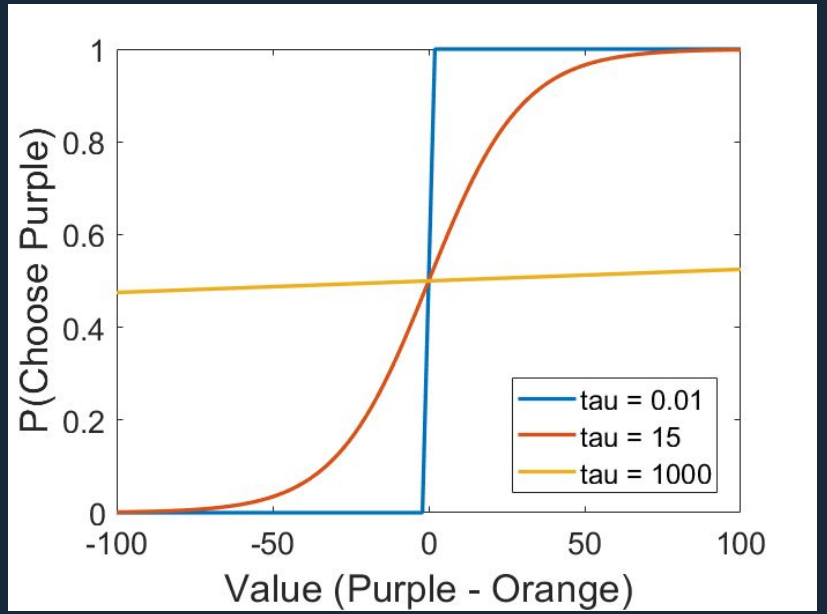
What have we learnt about choice?

Softmax equation:

$$P(\text{purple}) = \frac{\exp([\ V_{\text{purple}}\ ]/\ \tau)}{\text{SUM}[\exp([\ V_{\text{purple}}\ ]/\ \tau)]}$$
$$V_{\text{orange}}$$

Temperature (τ): parameter that determines the extent to which value estimates influence choice behaviour

Exploit or Explore



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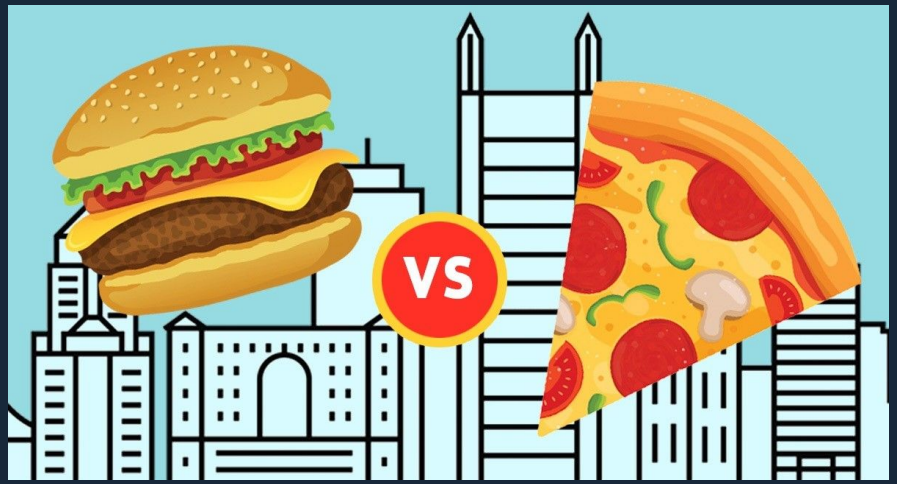
What have we learnt about choice?

Exploit versus Explore:

- ➔ Discover “what works” by alternating between exploration and exploitation
- ➔ In uncertain environments, more exploration could be useful



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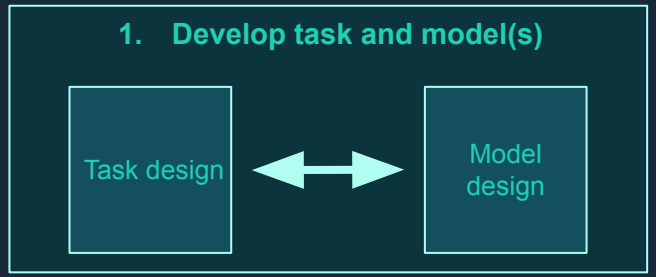
Developmental Computational Psychiatry lab

HARTLEY LAB

Summary



Task	**Trial and error learning**	**Reinforcement Learning**
Value Function	**Subjective value from objective outcomes**	**Rescorla-Wagner**
Choice Function	**Choice probabilities from value**	**Softmax**

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