脑启发人工智能导论
Introduction to Brain-Inspired Artificial Intelligence

唐华锦 教授
浙江大学计算机学院
htang@zju.edu.cn
https://person.zju.edu.cn/htang

感知神经信息编码

Sensory Neuronal Coding

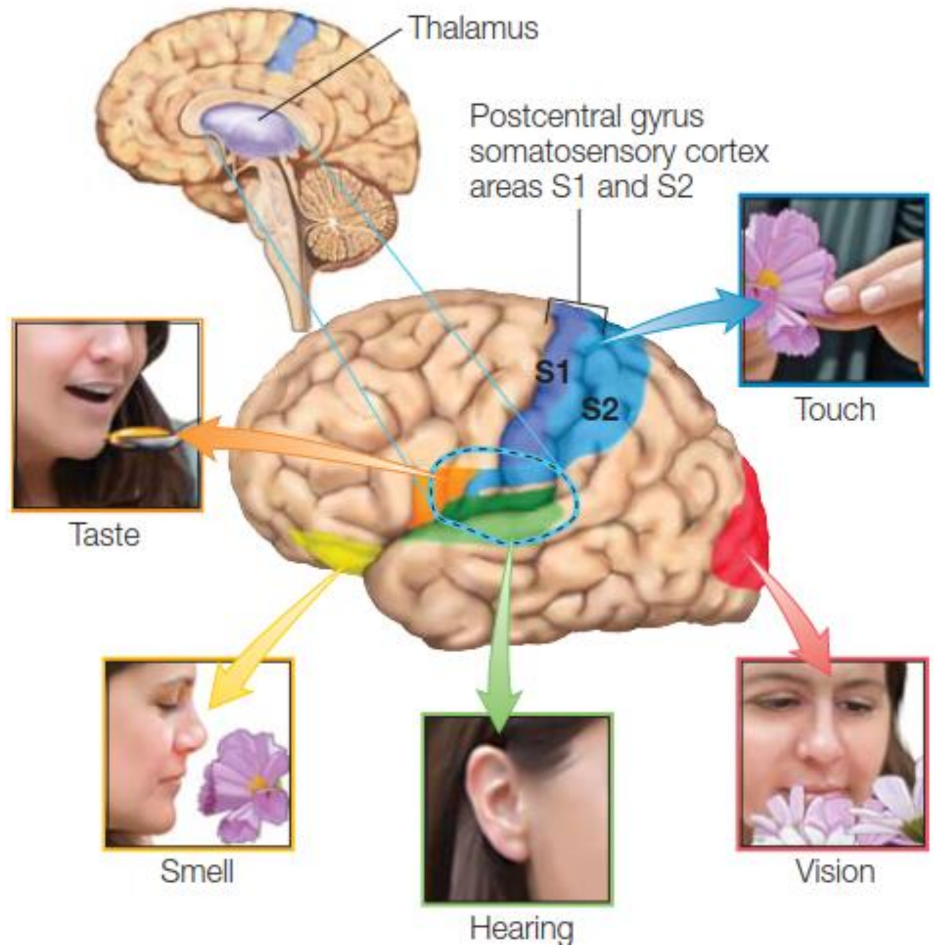
Sensory systems

Five major sensory

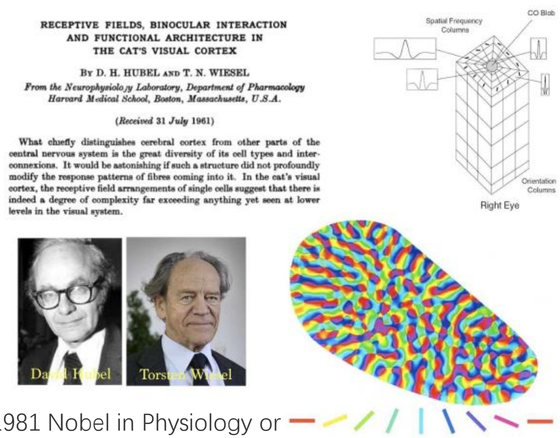
1. **Vision (视)**
2. **Audition (听)**
3. **Somatosensation （触）**
4. **Olfaction （嗅）**
5. **Gustation （味）**

- Sensory inputs about **taste**, **touch**, **smell**, **hearing**, and **seeing** travel to specific regions of the brain for initial processing.

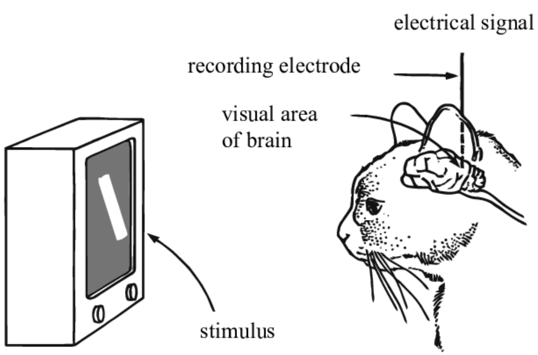
- Neural connections from each of these pathways travel first to what are known as **primary sensory cortex**, and then to **secondary sensory cortex.**



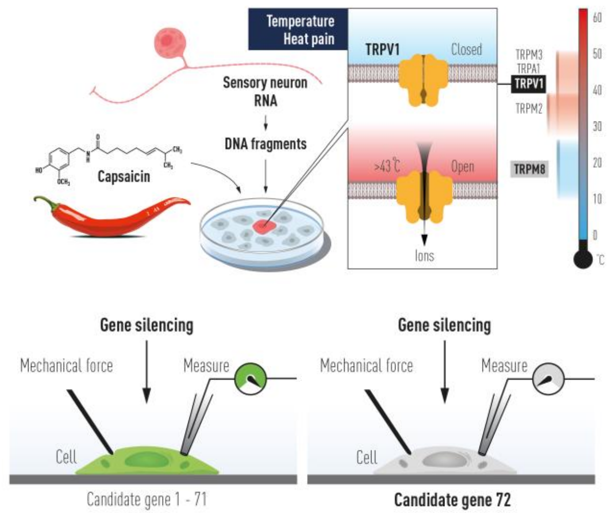
Sensory Neurons

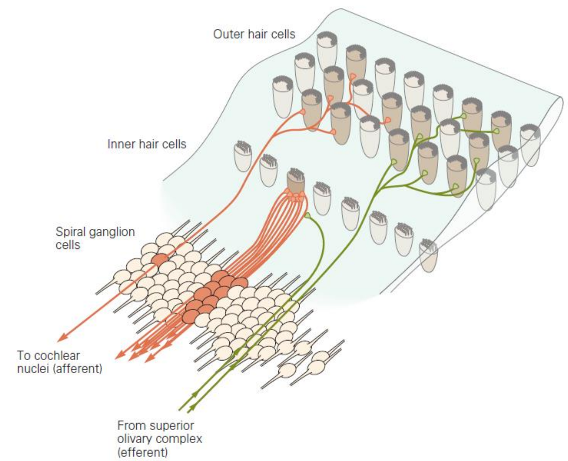


1981 Nobel in Physiology or Medicine



视觉





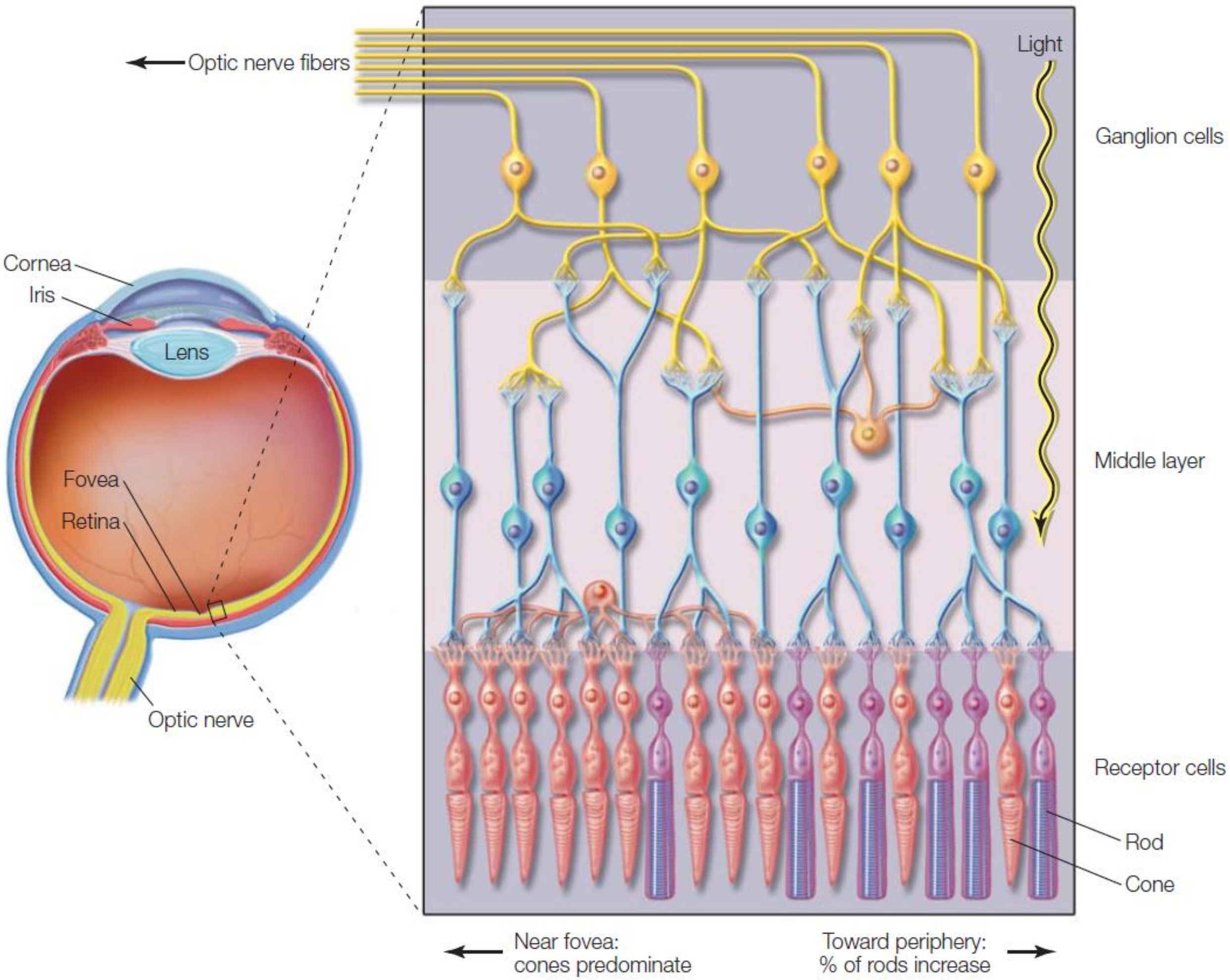
听觉

温度和压力/触觉

How are temperature and mechanical stimuli converted into electrical impulses in the nervous system

2021 Nobel Prize in Physiology or Medicine

Sensory theory： Vision

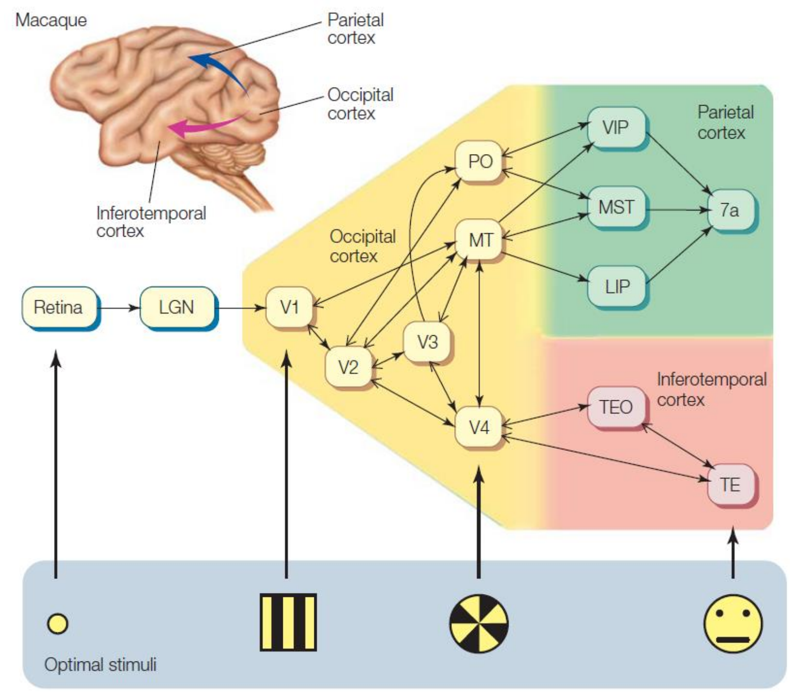


There are two types of receptor cells: rods and cones. The output of the receptor cells is processed in the middle layer of the retina and then relayed to the central nervous system via the optic nerve, the axons of the ganglion cells.

Sensory theory： Vision

Neural Pathways of Vision：

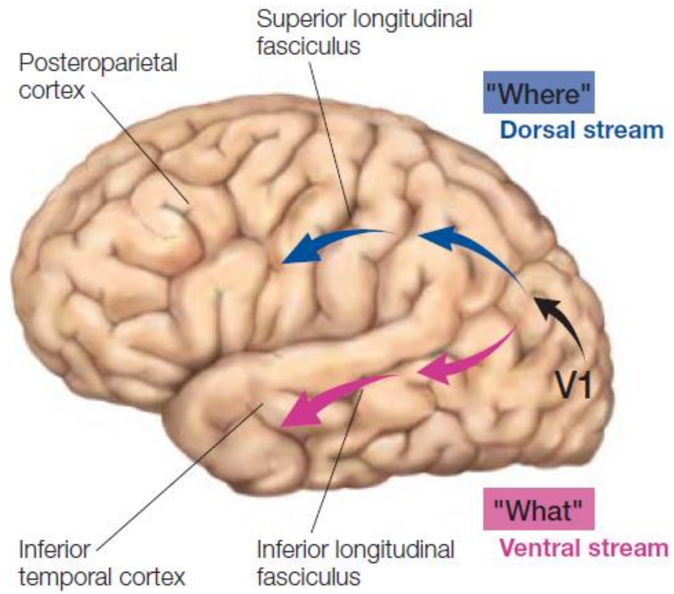
- The *retinogeniculate pathway*, the projection from the retina to the **lateral geniculate nucleus** (LGN) of the thalamus.
- The *geniculocortical* pathway: This bundle of axons exits the LGN and ascends to the cortex, and almost all of the fibers terminate in the **primary visual cortex** (V1) of the occipital lobe.
- The lines connecting these **extrastriate visual areas** demonstrate extensive convergence and divergence across visual areas.



Sensory theory： Vision

Multiple Pathways for Visual Perception：

- Output from V1 is contained primarily in two major fiber bundles, or *fasciculi*: the *superior longitudinal fasciculus* takes a dorsal path from the striate cortex and other visual areas. The *inferior longitudinal fasciculus* follows a ventral route from the occipital striate cortex into the temporal lobe.
- These two pathways are referred to as the **ventral (occipitotemporal) stream** and the **dorsal (occipitoparietal) stream**.
- The ventral “what” pathway terminates in the inferotemporal cortex, and the dorsal “where” pathway terminates in the a–b posteroparietal cortex.



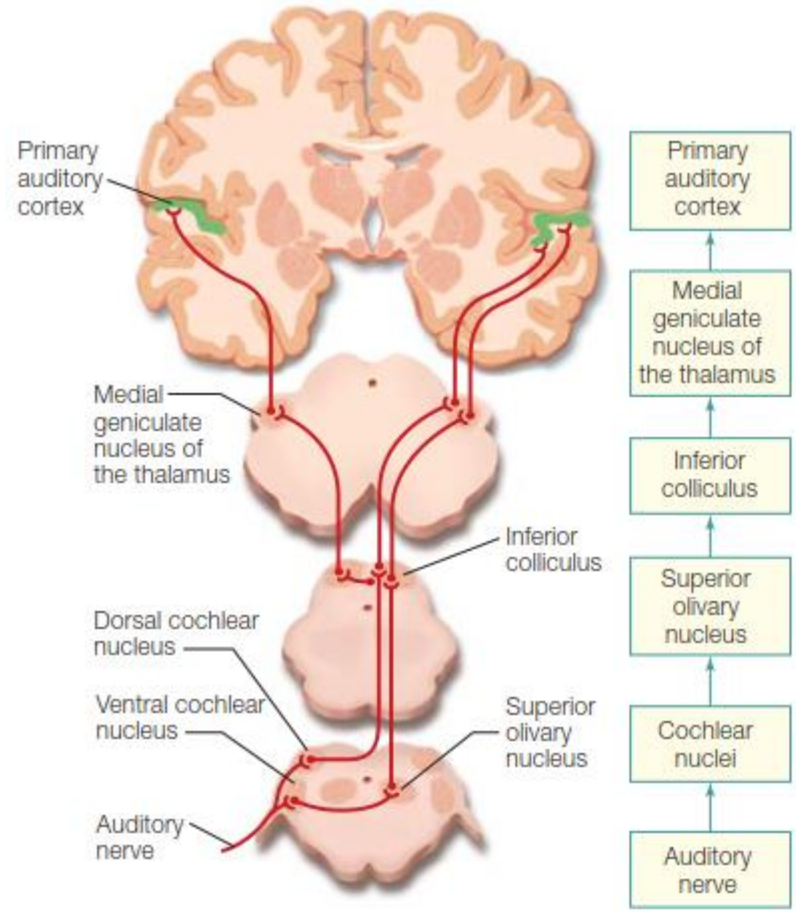
Sensory theory： Audition

Neural Pathways of Audition：

- The **auditory nerve**, projects to the **cochlear nucleus** in the medulla. Axons from this nucleus travel up to the pons and split to innervate the left and right **olivary nucleus.**

- Axons from the cochlear and olivary nuclei project to the **inferior colliculus(下丘)**, higher up in the midbrain.

- From the midbrain, auditory information ascends to the **MGN in the thalamus**, which in turn projects to the **primary auditory cortex (A1)** in the superior part of the temporal lobe.



Sensory theory： Audition

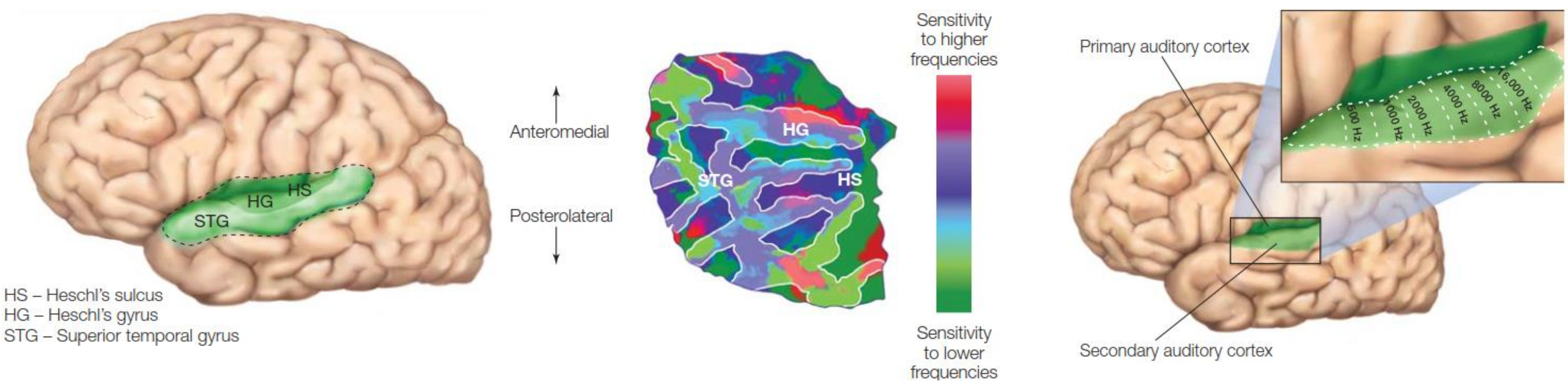
Sound recognition (“what”) :

- **Frequency data are essential for deciphering a sound.** Sound-producing objects have unique resonant properties that provide a characteristic signature.

- E.g., we can identify a “G” from different instruments as the same note. This is because the notes share the same base frequency.

- **Tonotopic map**: An orderly correspondence between the location of the neurons and their **specific frequency tuning**.

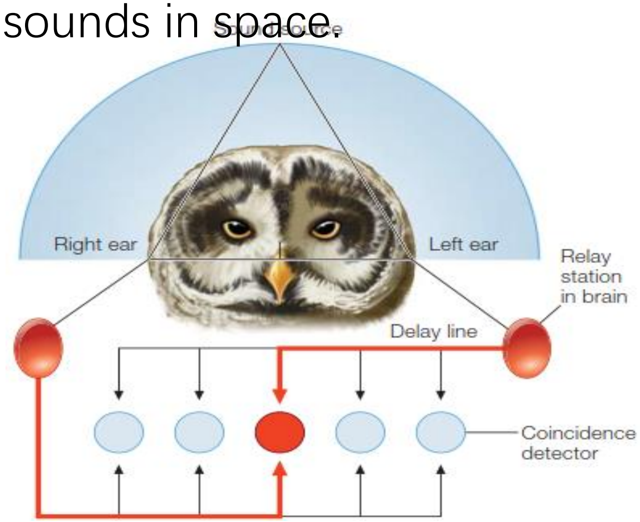
- Cells in the rostral part of A1 tend to be responsive to **low-frequency sounds**; cells in the caudal part of A1 are more responsive to **high-frequency sounds**.



Sensory theory： Audition

Sound Localization (“where”):

- the auditory system relies on integrating information from the two ears to localize sounds in space.



A well-specified neural model of how neurons in the brainstem of the owl **code interaural time differences** by operating as **coincidence detectors**

Left: the sound source is directly in front of the animal. In this situation the coincidence detector in the middle is activated, because the stimulus arrives at each ear at the same time.

Right: When the sound source is located to the left, the sound reaches the left ear first. Now a coincidence detector offset to the opposite side receives simultaneous activation from the two ears.

Sensory theory： Olfaction

The “Read” mechanism of odor molecules：

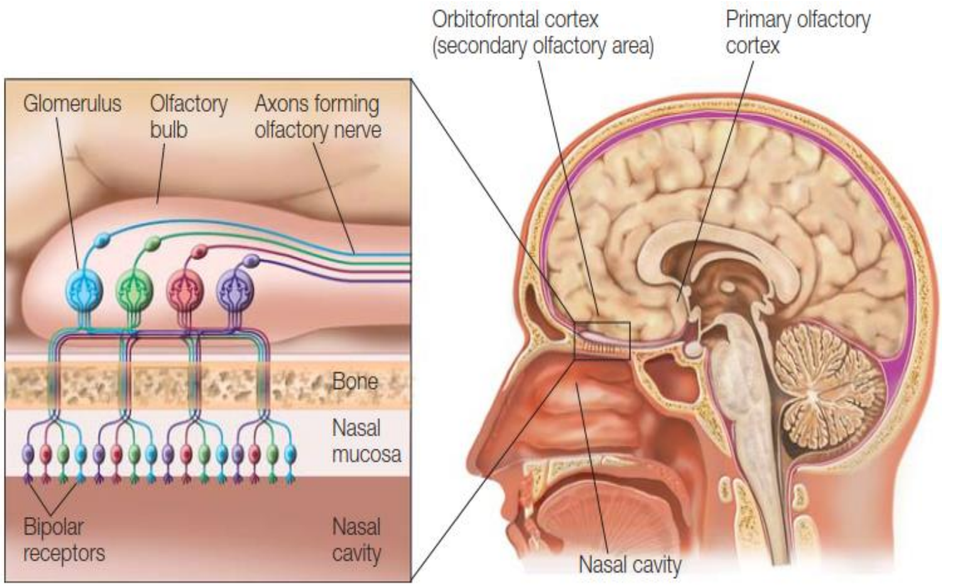
- Hypothesis I: **odor molecules attach to odor receptors**, which are embedded in the mucous membrane of the roof of the nasal cavity, called the olfactory epithelium. There are over 1,000 types of receptors, and most of these respond to only a limited number of odorants, though a single odorant can bind to more than one type of receptor.

- Hypothesis II：**the molecular vibrations of groups of odorant molecules contribute to odor recognition.** This model predicts that odorants with similar vibrational spectra should elicit similar olfactory responses, and it explains why similarly shaped molecules, but with dissimilar vibrations, have very different fragrances. E.g., alcohols and thiols (硫醇) have almost the same structure, but alcohols have a fragrance of, well, alcohol, and thiols smell like rotten eggs

Sensory theory： Olfaction

Neural Pathways of Olfaction：

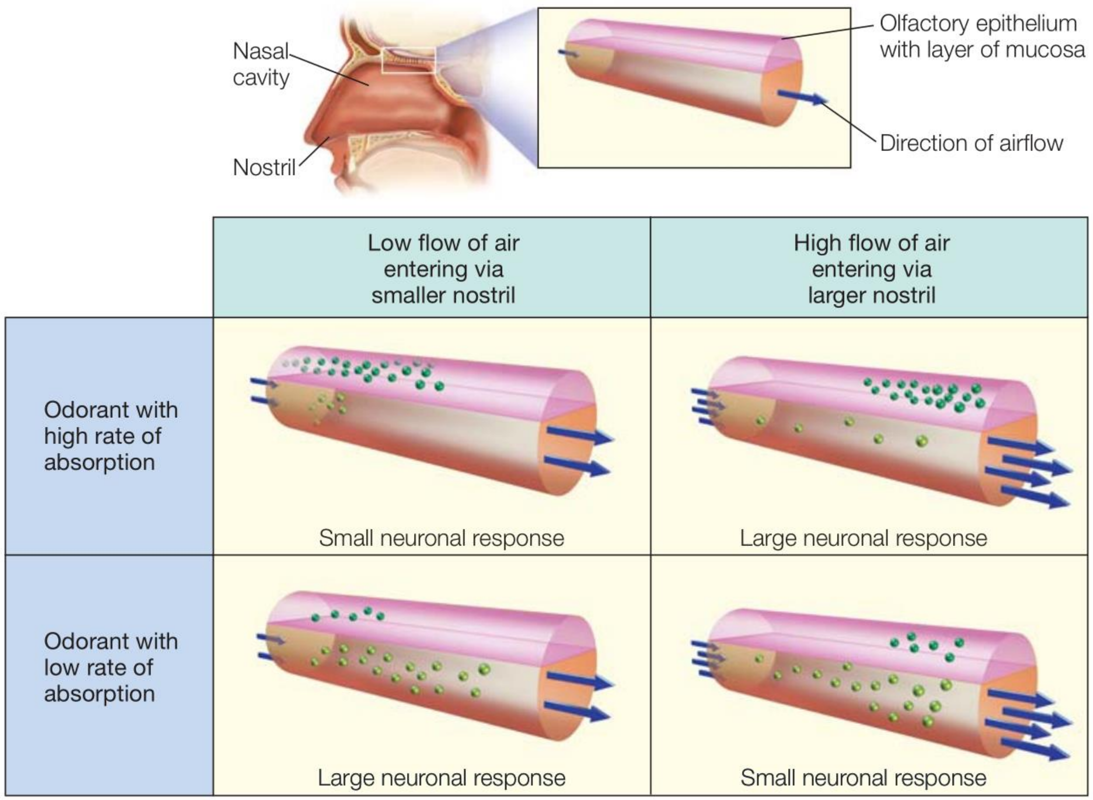
- When an odorant triggers the **bipolar receptor**, whether by shape or vibration, a signal is sent to the **glomeruli neurons** in the **olfactory bulbs.**
- Tremendous convergence and divergence take place in the olfactory bulb. The axons from the glomeruli then exit laterally from the olfactory bulb, forming the olfactory nerve. Their destination is the **primary olfactory cortex**



Two special points

- Most of the axons of the olfactory nerve project to the **ipsilateral cortex**. Only a small number cross over to innervate the contralateral hemisphere.
- The olfactory nerve arrives at the primary olfactory cortex **without going through the thalamus**. The primary olfactory cortex projects to a secondary olfactory area within the orbitofrontal cortex, as well as making connections with other brain regions including the thalamus, hypothalamus, hippocampus, and amygdala.

One Nose, Two Odors



Human nostrils have asymmetric flow rates. Although the same odorants enter each nostril, the response across the epithelium will be different for the two nostrils because of variation in flow rates.

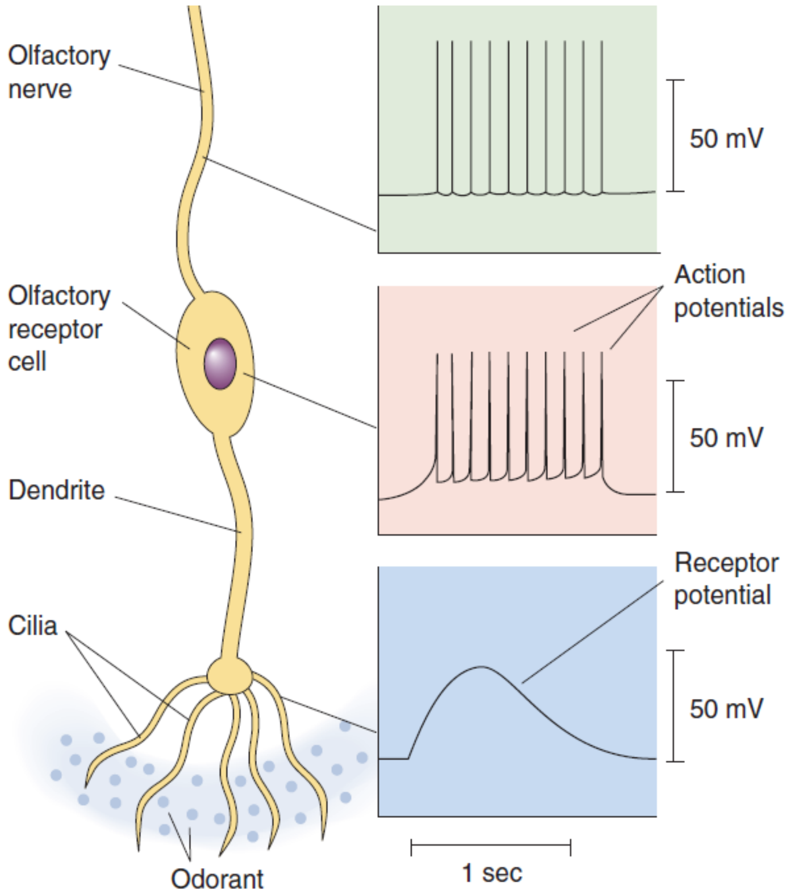
One nostril always has a greater input airflow than the other, and the nostrils switch between the two rates every few hours.

This system of having one low-flow and one high-flow nostril has evolved to give the nose optimal accuracy in perceiving odorants that have both high and low rates of absorption.

Some facts about Olfaction

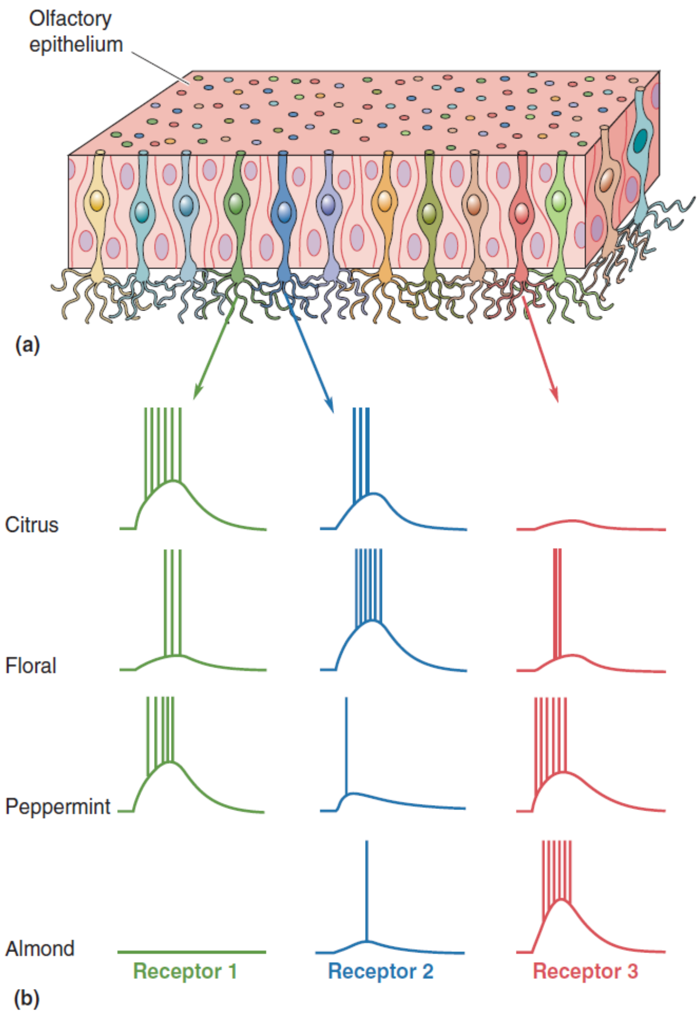
- **Humans are relatively weak smellers**.
- The surface area of the human olfactory epithelium is only about 10 cm^2. The olfactory epithelium of certain dogs may be more than 170 cm^2,
- Dogs have over **100 times more receptors** in each square centimeter than humans.
- By sniffing the aromatic air above the ground, dogs can detect the **few molecules** left by someone walking there hours before. Humans may only be able to smell the dog when he licks their face.

Olfactory Neuron



Voltage recordings from an olfactory receptor cell during stimulation. Odorants generate a slow receptor potential in the cilia; the receptor potential propagates down the dendrite and triggers a series of action potentials within the soma of the olfactory receptor cell. Finally, the action potentials (but not the receptor potential) propagate continuously down the olfactory nerve axon.

Olfactory Neuron Encoding



Broad tuning of single olfactory receptor cells.
(a) Each receptor cell expresses a single olfactory receptor protein (here coded by cell color), and different cells are randomly scattered within a region of the epithelium.
(b) Microelectrode recordings from three different cells show that each one responds to many different odors, but with differing preferences. By measuring responses from all three cells, each of the four odors can be clearly distinguished

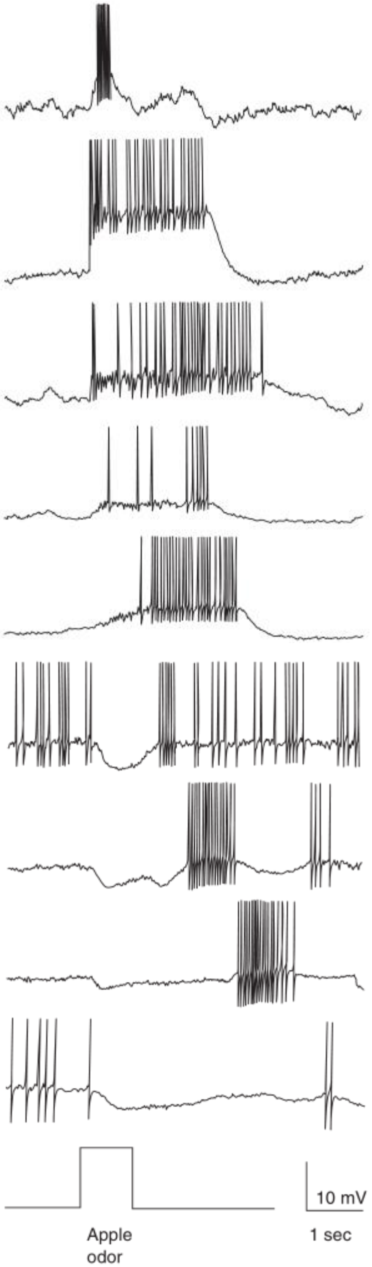
Mixed Representation:

- Neuron responds to multiple features
- Each neuron involves in multiple information representation
- It implies population coding.

Olfactory Neuron Encoding

- The temporal patterns of spiking are essential features of olfactory coding. Compared to many sounds and sights, odors are inherently slow stimuli, so the rapid timing of action potentials does not need to be used to encode the timing of odors. **Temporal coding**, which depends on the timing of spikes, might instead encode the quality of odors

- The loss of synchronous spiking was associated with a loss of the bees' ability to discriminate between similar odors, although not between broad categories of odors. The implication is that the bee analyzes an odor **not only by keeping track of which olfactory neurons fire, but also by when they fire**. It will be very interesting to see whether similar processes occur in a mammalian olfactory system.



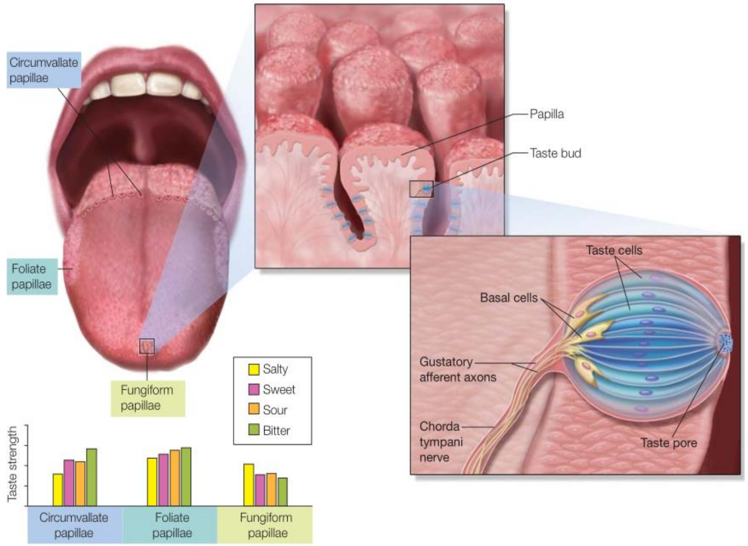
Temporal spiking patterns. The odor of apple produces a range of temporal spiking
patterns in nine olfactory neurons.(These recordings are from neurons in the antenna
lobe of a locust.)

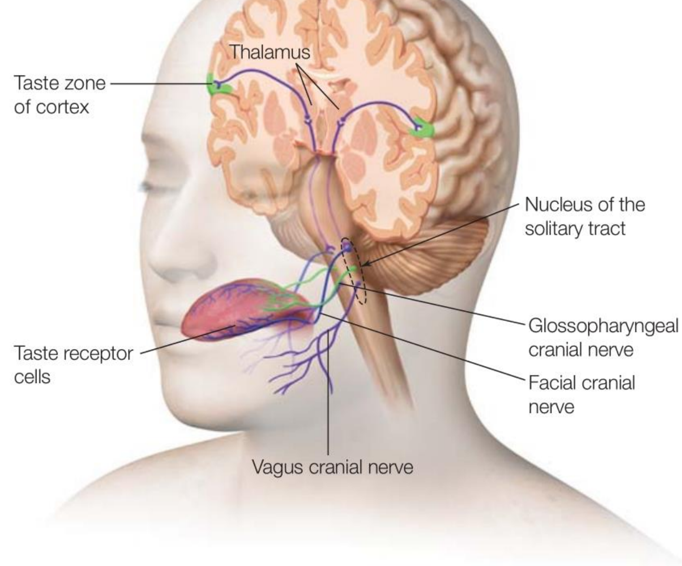
Sensory theory： **Gustation**

Neural Pathways of Gustation：

- Signal transduction is initiated when a taste cell in the mouth responds to a tastant by depolarizing and sends a signal to the gustatory nucleus in the dorsal medulla.
- From there, a signal zips to the ventral posterior medial (VPM) nucleus (腹后核) of the thalamus.
- The VPM synapses with the primary gustatory cortex found in the operculum and insula.
- The primary gustatory cortex connects with the secondary processing areas found in the orbitofrontal cortex.

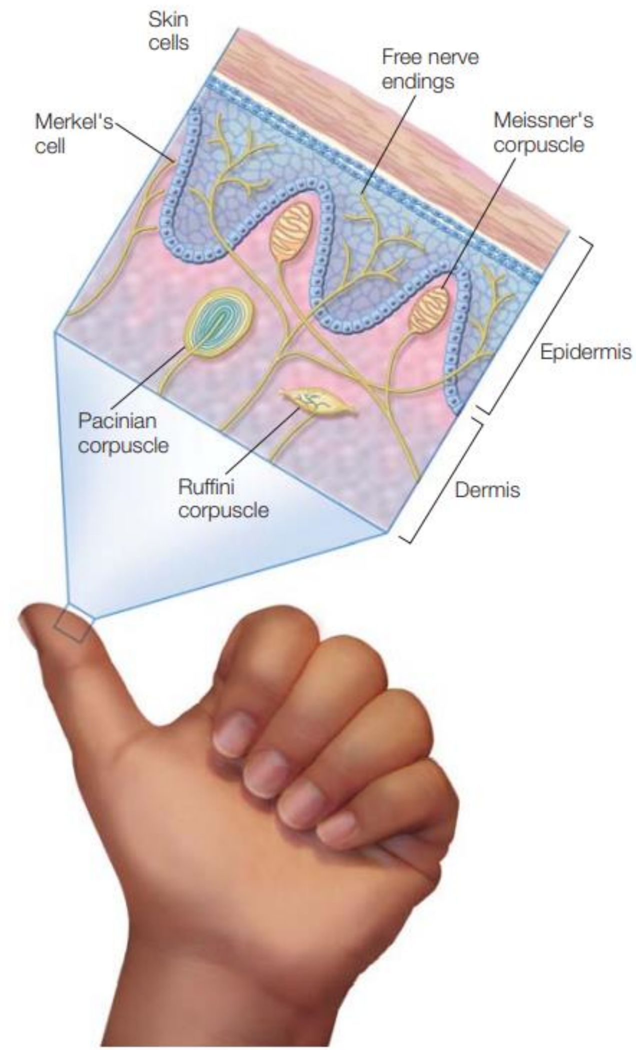
★ *Gustation and Olfaction are referred to as the chemical senses*





Sensory theory： Somatosensation

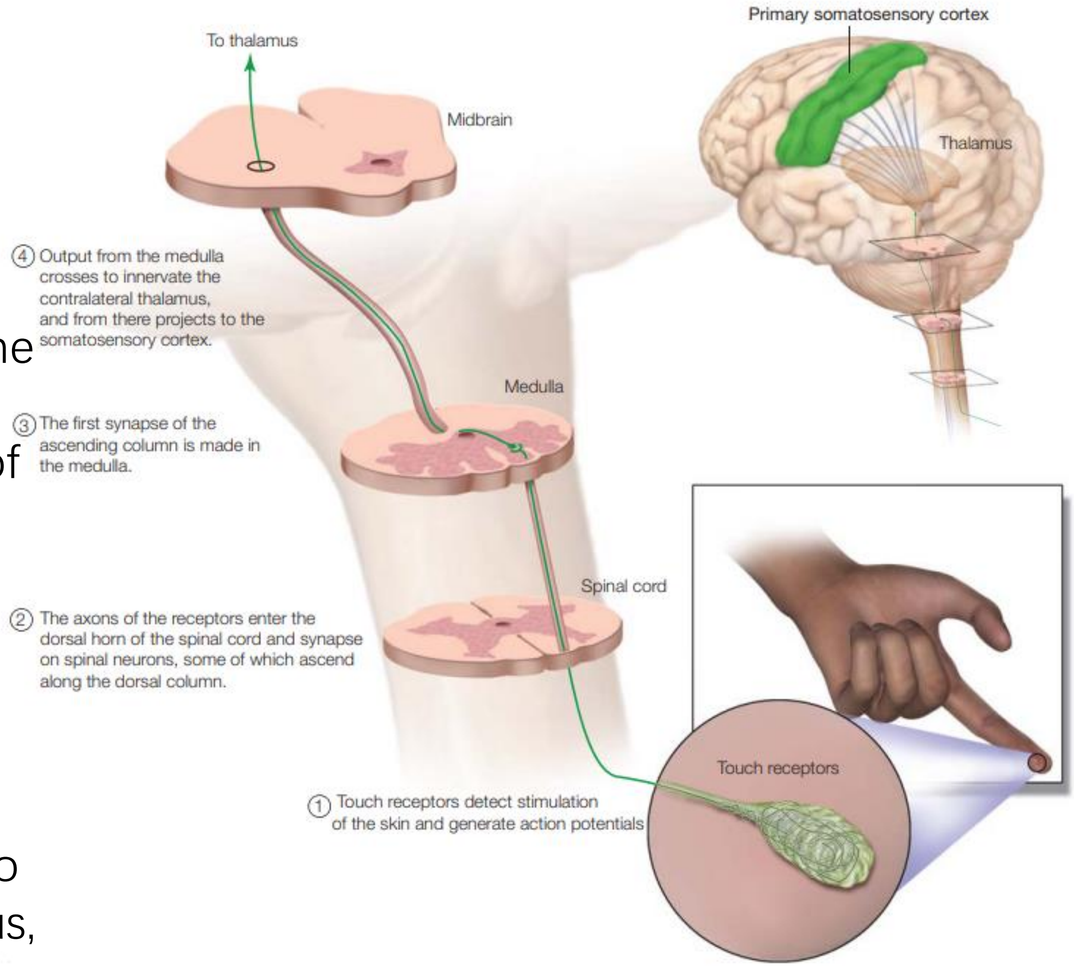
- Somatosensory receptors lie under the skin and at the musculoskeletal junctions (关节).
- Touch is signaled by specialized receptors in the skin, including Meissner’s corpuscles , Merkel’s cells, Pacinian corpuscles, and Ruffini corpuscles.
- These receptors differ in how quickly they adapt and in their sensitivity to various types of touch, such as deep pressure or vibration.
- Pain is signaled by nociceptors, the least differentiated of the skin’s sensory receptors.
- Specialized nerve cells provide information about the body’s position, or what is called proprioception. Proprioception allows the sensory and motor systems to represent information about the state of the muscles and limbs.



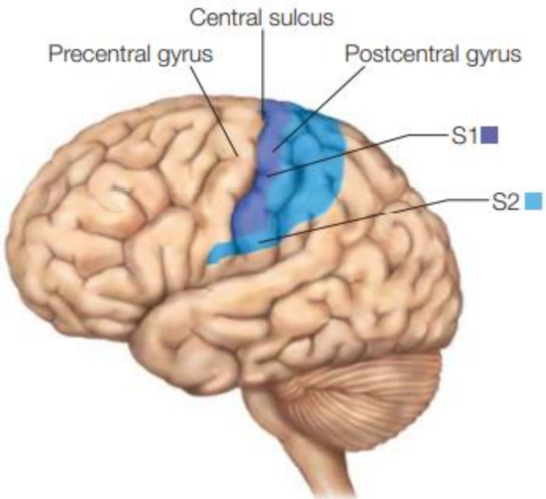
Sensory theory： Somatosensation

Neural Pathways of Somatosensation：

- Touch receptors detect stimulation of the skin and generate action potentials.
- The axons of the receptors enter the dorsal horn of the spinal cord and synapse on spinal neurons, some of which ascend along the dorsal column.
- The first synapse of the ascending column is made in the medulla.
- Output from the medulla crosses to innervate the contralateral thalamus, and from there projects to the somatosensory cortex.

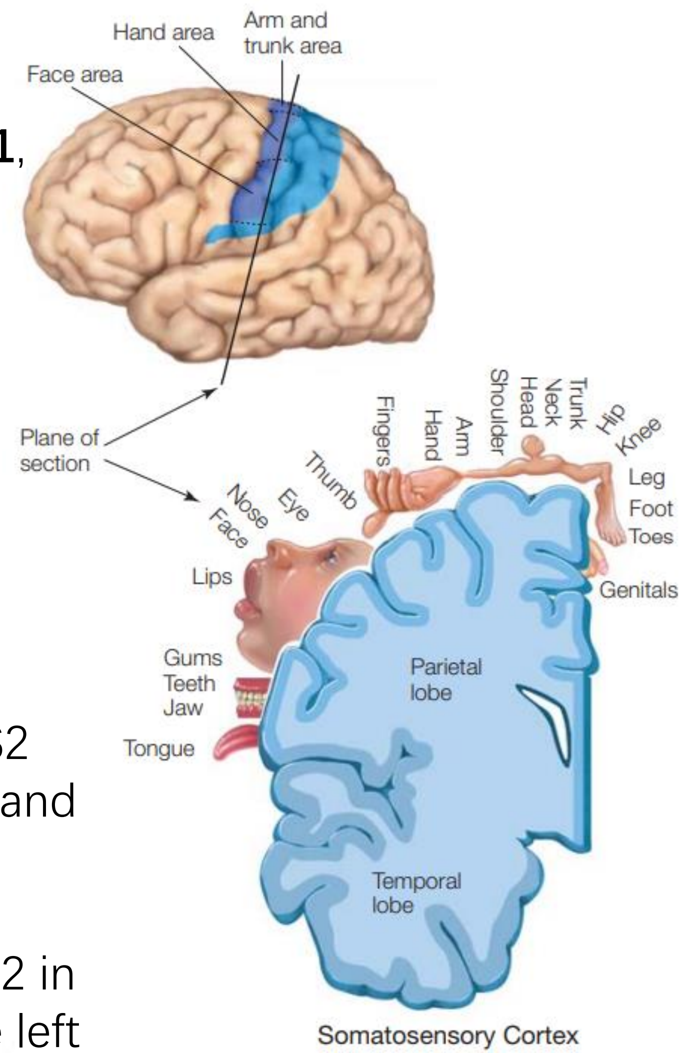


Sensory theory： Somatosensation



- The initial cortical receiving area is called **primary somatosensory cortex** or **S1**, which includes Brodmann areas 1, 2, and 3.

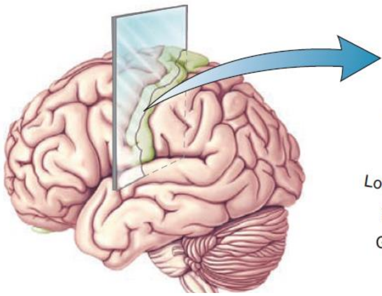
- S1 contains a somatotopic representation of the body, called the sensory homunculus.

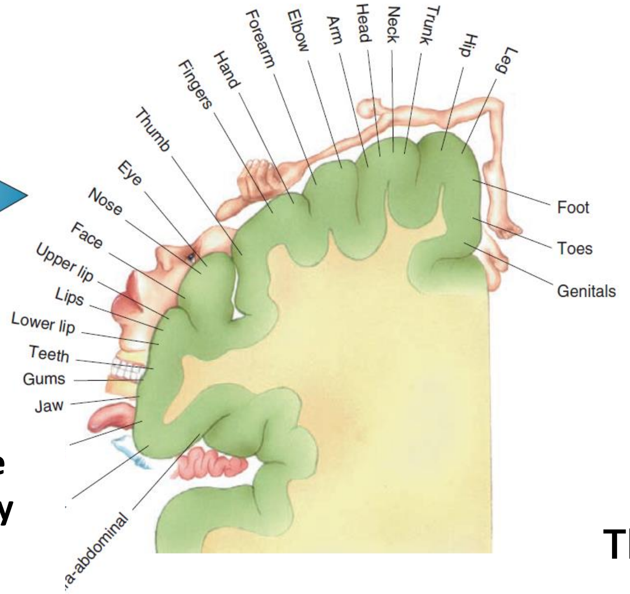


- Secondary somatosensory cortex (S2) builds more complex representations. From touch, for example, S2 neurons may code information about object texture and size.

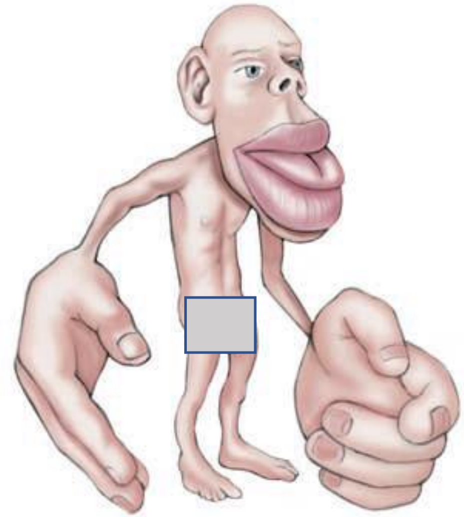
- Because of projections across the corpus callosum, S2 in each hemisphere receives information from both the left and the right sides of the body.

Sensory theory





A somatotopic map of the body surface onto primary somatosensory cortex. This map is a cross section through the postcentral gyrus (shown at top). Neurons in each area are most responsive to the parts of the body illustrated above them.



The homunculus（感觉侏儒/感觉拓扑模型）

① The mouth, tongue, and fingers are absurdly large, while the trunk, arms, and legs are tiny.

② The relative size of cortex devoted to each body part is correlated with the *density* of sensory input received from that part. Size on the map is also related to the *importance* of the sensory input from that part of the body; information from your index finger is more useful than that from your elbow.

③ The importance of touch information from our hands and fingers is obvious, but why throw so much cortical computing power at the mouth? Two likely reasons are that tactile sensations are important in the production of speech and that your lips and tongue (feeling, as well as tasting) are the last line of defense when deciding if a morsel is delicious, nutritious food, or something that could choke you, break your tooth, or bite back.

④ The importance of an input, and the size of its representation in cortex, are also reflections of how often it is used.

Sensory theory: Gustation

Taste Aversion Learning

- Rats were fed with a sweet liquid, and in some cases, they were fed a drug that made them briefly feel ill. After even one such trial, rats that had received the drug **avoided the sweet stimulus for ever**! The rats' aversion was specific for the taste stimulus; they did not avoid sound or light stimuli under the same conditions.

- Extensive research has shown that **flavor aversion learning** results in a particularly robust form of associative memory. It is most effective for food stimuli (taste and smell both contribute), it requires remarkably little experience (as little as one trial), and it can last a very long time—more than 50 years in some people! And learning occurs even when there is a very long delay between the food and the nausea.

- This is obviously a useful form of learning in the wild. An animal can't afford to be a slow learner when new foods might be poisonous.

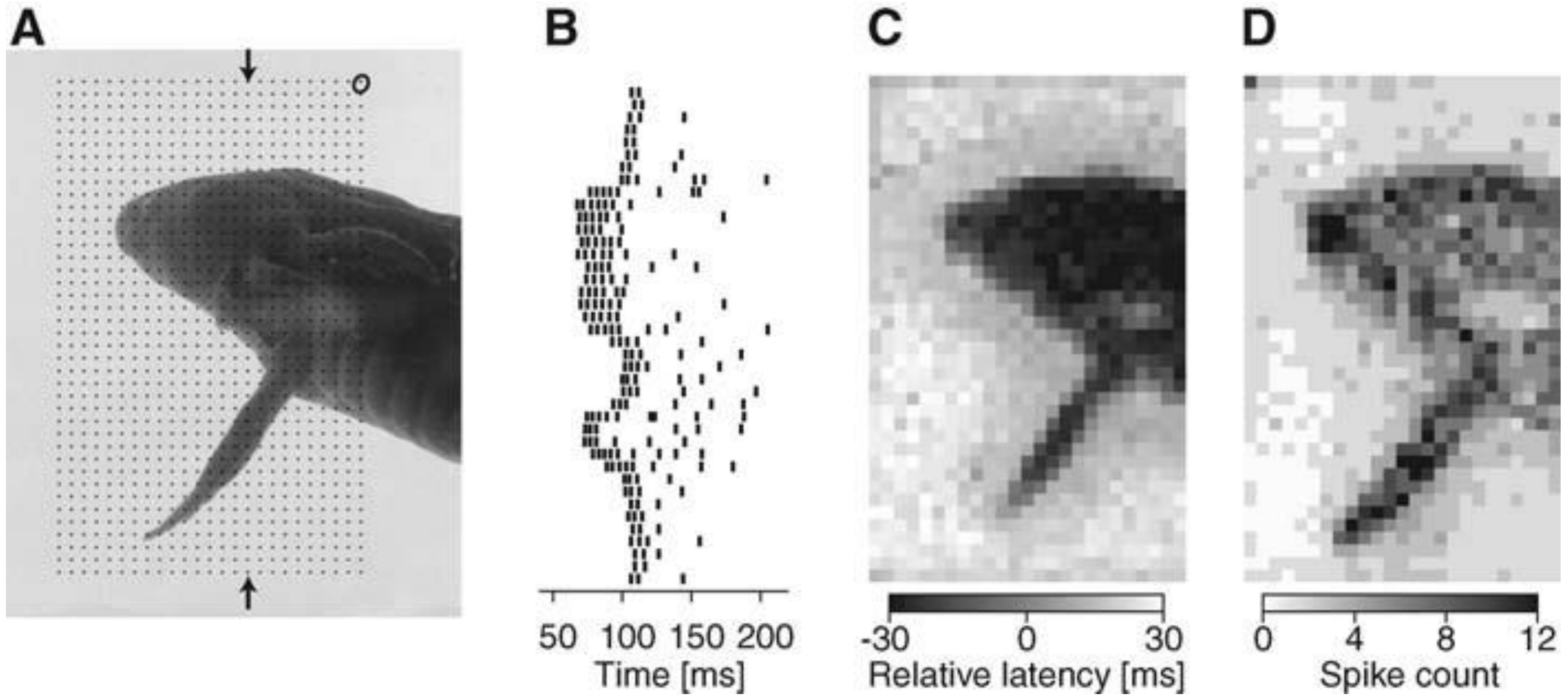
One shot learning, lasts for ever!

Neural Information Spike Encoding

神经信息的脉冲编码

- Rate-based Encoding: Rate Coding
- Timing-based Encoding: Temporal Coding

Neural Encoding

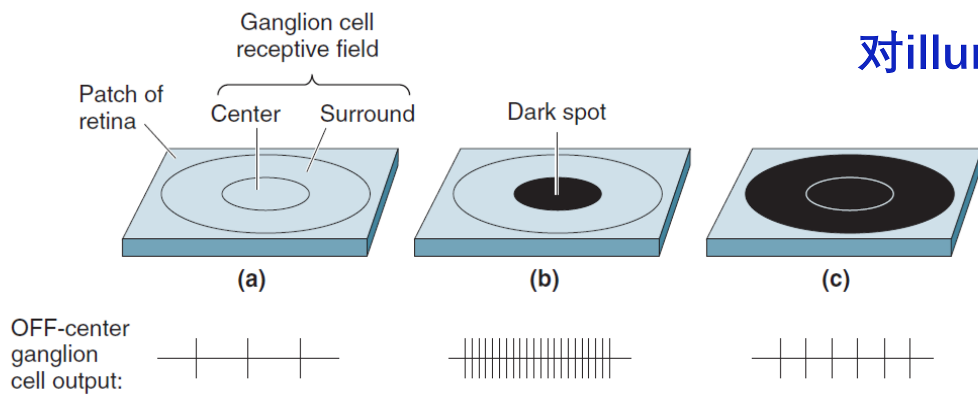


Responses of a fast OFF ganglion cell to a flashed natural image.(A) Photograph of a swimming salamander larva projected on the retina. (B) Spike trains of the ganglion cell for receptive-field locations along the column marked by the arrows in (A). (C) Gray-scale plot of the differential spike latency. (D) Corresponding gray-scale plot of the spike counts.
(Gollishc et al, Science, 2008)

视觉信息的脉冲编码

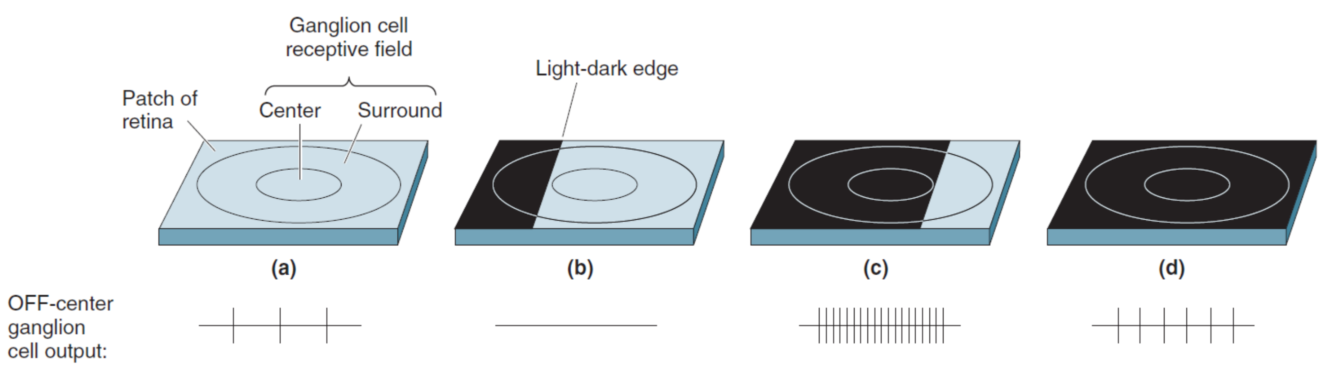
对illumination的反应

视网膜包含2种中心环绕型神经节细胞，分别是on-center, off-center



OFF-center ganglion cell

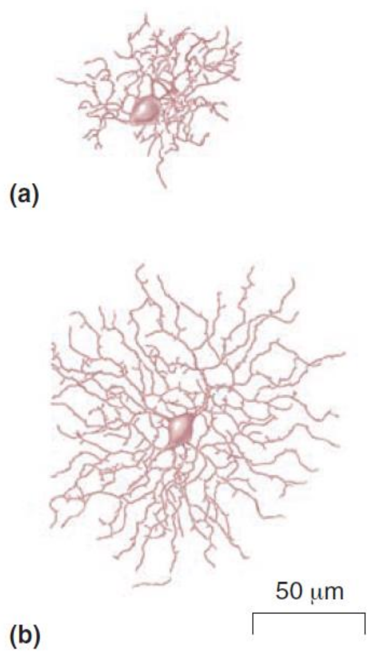
A center-surround ganglion cell receptive field. (a, b) An OFF-center ganglion cell responds with a barrage of action potentials when a dark spot is imaged on its receptive field center. (c) If the spot is enlarged to include the receptive field surround, the response is greatly reduced.



OFF-center ganglion cell

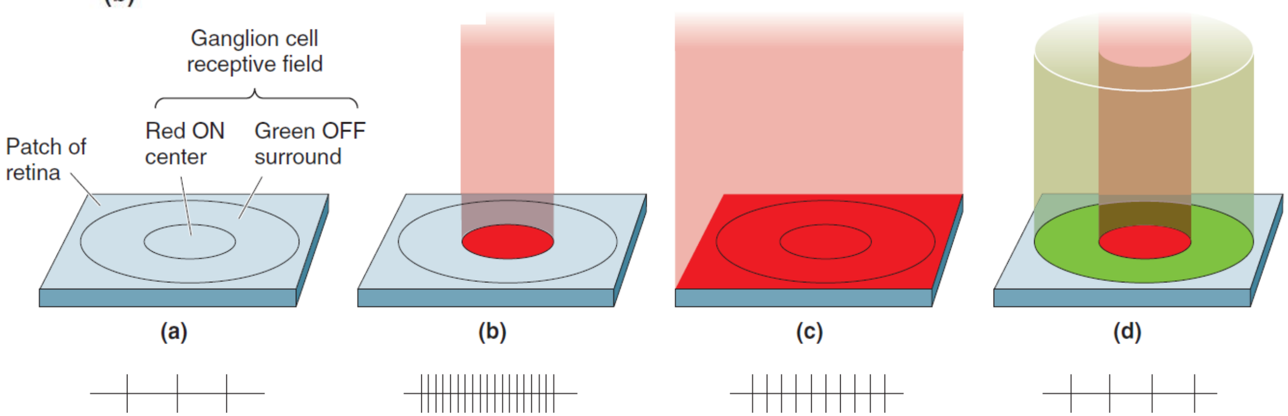
Responses to a light-dark edge crossing an OFF-center ganglion cell receptive field. The response of the neuron is determined by the fraction of the center and surround that are filled by light and dark.

视觉信息的脉冲编码



颜色敏感神经节细胞

M-type and P-type ganglion cells in the macaque monkey retina. (a) A small P cell from the peripheral retina. (b) An M cell from a similar retinal location is significantly larger.



A color-opponent center-surround receptive field of a P-type ganglion cell.

思考：对不同颜色敏感，实际是对？？的反应？

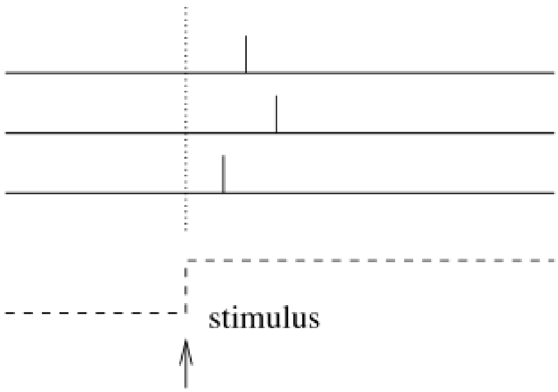
时间编码

生物能够对快速变化的刺激进行迅速响应(如视觉皮层、视网膜感光细胞、外侧膝状核)，其响应精准度达到毫秒级。因此提出时间编码理论。

首次脉冲发放时间编码

Time-to-First-Spike

- **定义：**
  - 信息被编码在刺激开始和第一个脉冲的延迟内
- **生物依据：**
  - 一个新刺激的大部分信息在神经元响应的前20或50毫秒内传达
- **编码特点：**
  - 在眼睛飞快扫视后，视网膜上的光受体会收到新的视觉输入
  - 对每个神经元来说，第一个脉冲的时间包含了关于新刺激的所有信息
  - 每个神经元对每个刺激传输一个脉冲



用脉冲时间传递信息，而不是脉冲数量

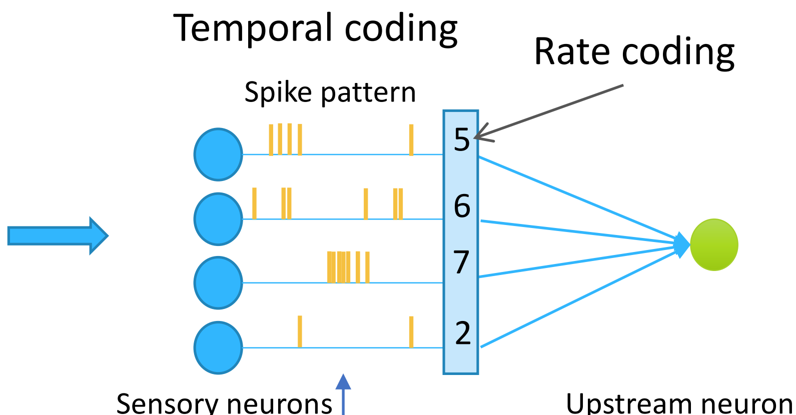
What is Neuromorphic Encoding?

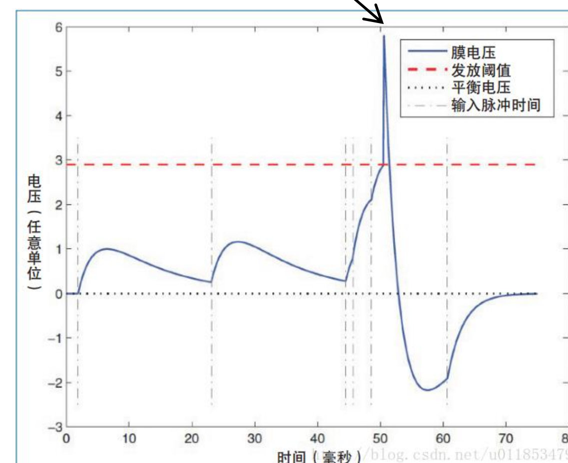
External information of sensory neurons will be encoded into the spatio-temporal attribute of a spike pattern:

- **Temporal:** each spike has a precise firing time;
- **Spatio:** different regions of information are encoded by different neurons.

When the membrane potential crosses a certain threshold value, the neuron will elicit a **spike.**

External stimuli





Neural Information Encoding

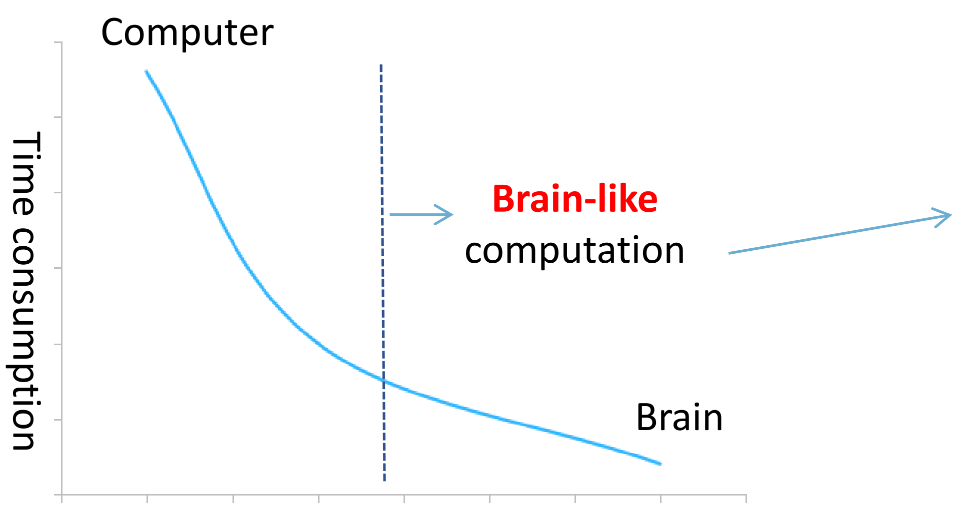
Action potential (Spike)

为什么脉冲编码？

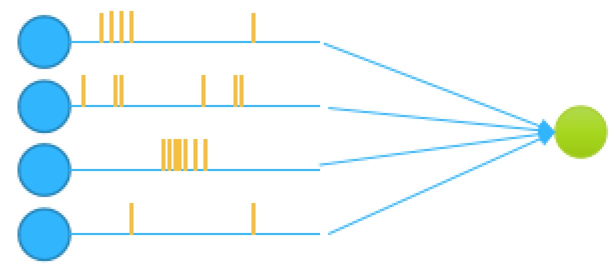
	频率编码	**时序编码**
适用模型	传统神经网络	脉冲神经网络
生物依据	神经元会根据外界刺激的不同调整自己的**脉冲发放速率**。	神经元发放脉冲的精确时间包含丰富的信息。
编码方法	忽视脉冲序列中的时间结构，只记录编码窗口内的脉冲个数。	保留脉冲的时间特征。
优点	简单，有一定抗噪能力	信息量更丰富，**事件驱动**
缺点	丢失了部分信息	计算复杂，不适用于当前的计算机体系结构
适用硬件	GPU、CPU	**神经形态硬件**
能耗	2400000瓦（阿尔法狗）	**20瓦**（大脑）

Why Spike-based Coding?

- Brain-like computation aims to simulate the information processing ability of the brain to **improve** performance and **reduce** energy consumption.
- SNN is a key model for developing brain-like computation.



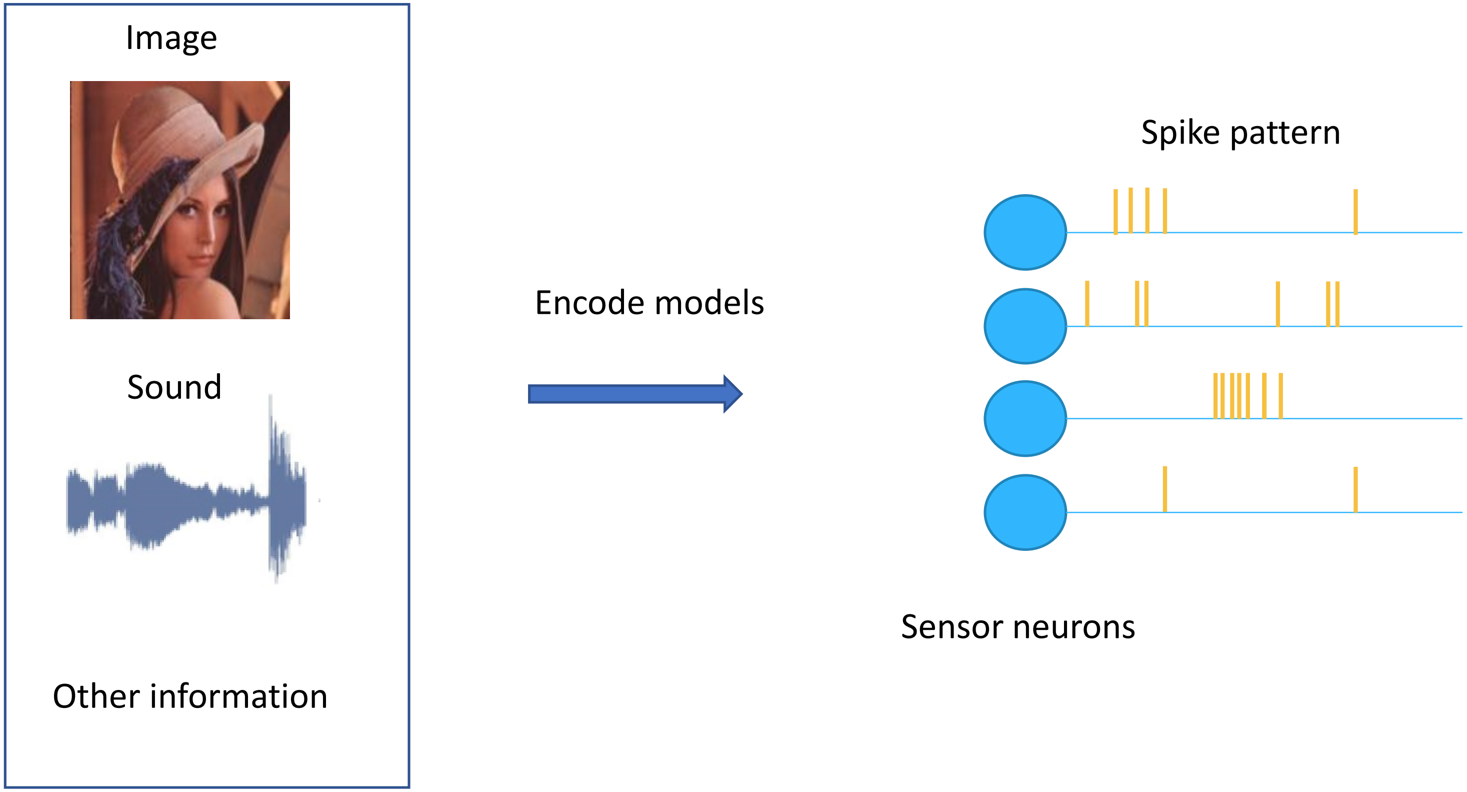
Structure's complexity



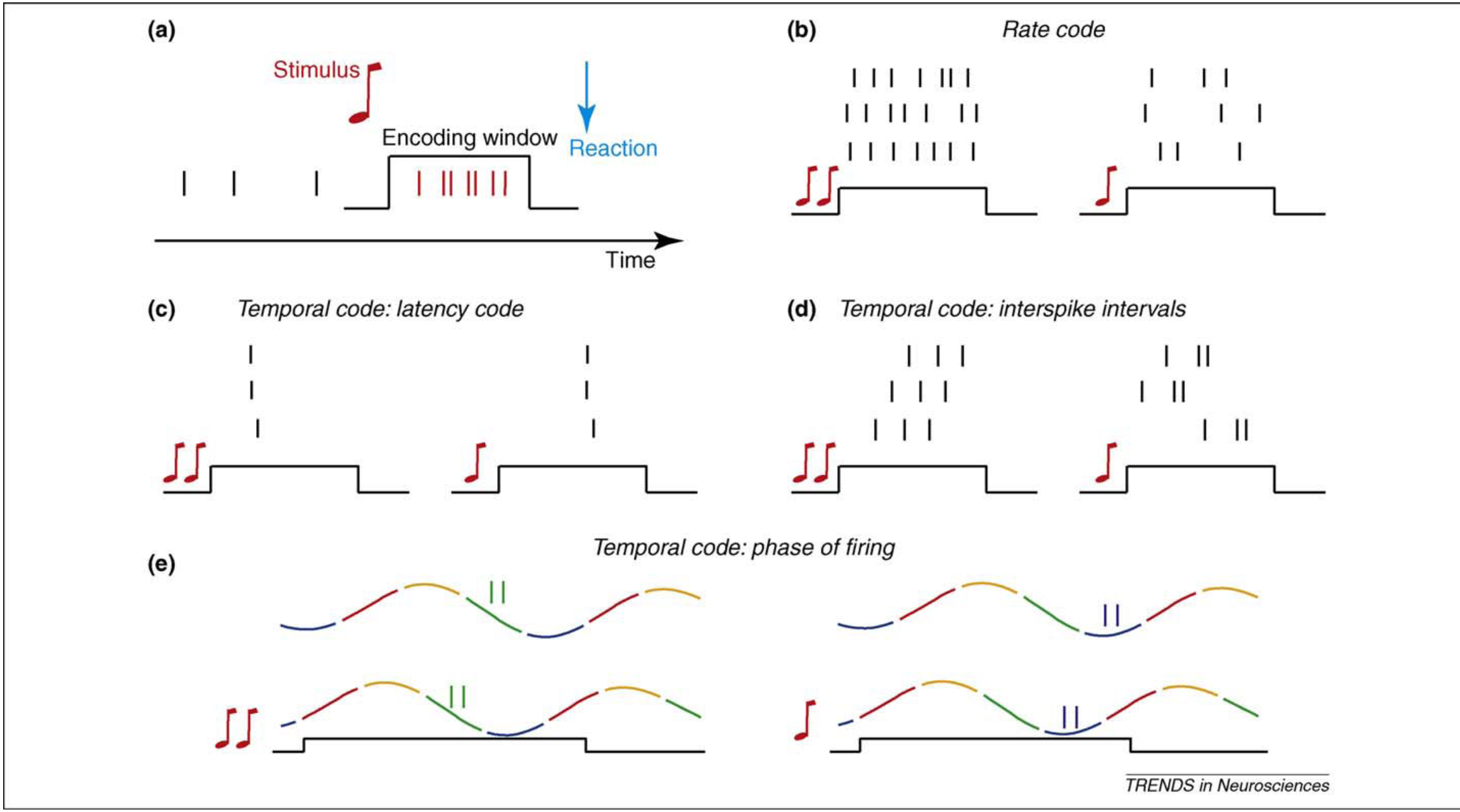
Spiking Neural Network (SNN)

How to Encode?

- By designing **biological models**
- Directly deriving from **mathematical models** such as statistics or probability



Spike Based Encoding

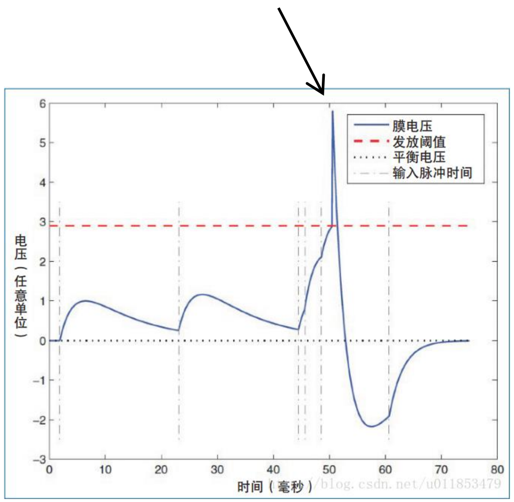


Various Encoding Methods, different spike train codes different feature.

Ref: Panzeri et al, Trends in Neuroscience, 2010

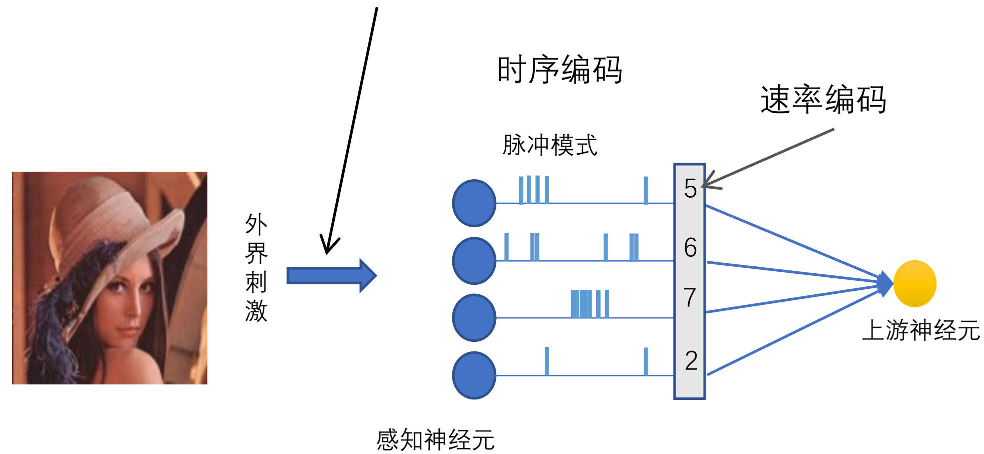
什么是脉冲编码？

动作电位（即脉冲）



当细胞膜电压达到阈值后，神经元会产生尖锐的电压变化，即**神经脉冲**。

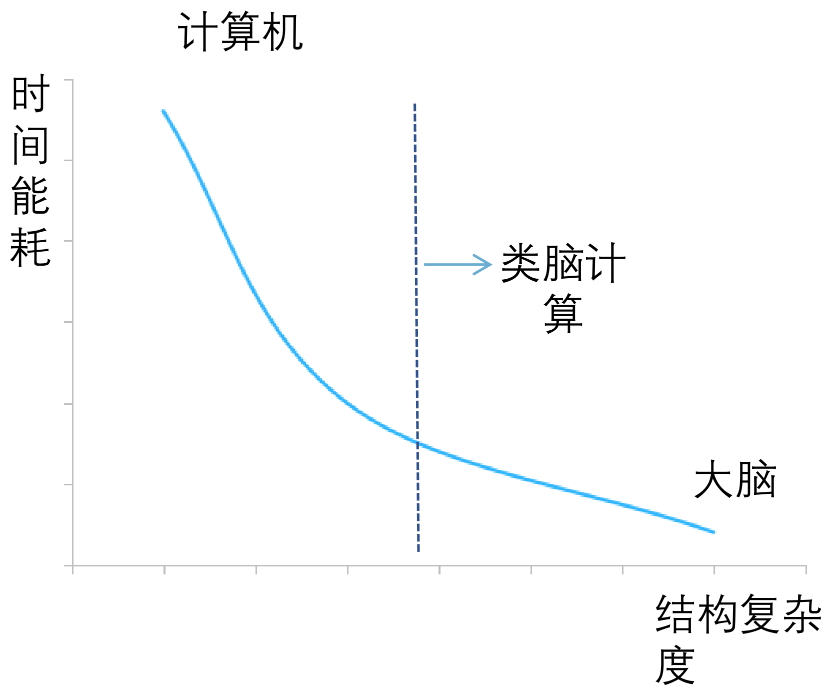
脉冲编码



外界信息将被编码到脉冲模式的时空属性中，

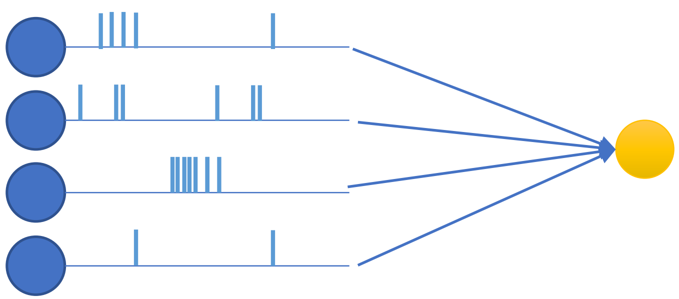
- **时间性：** 每个脉冲都有精确的发放时间；
- **空间性：** 不同区域的信息会被不同的神经元编码。

为什么研究脉冲编码？



类脑计算旨在模拟大脑的信息处理能力以**提高性能，降低能耗**。

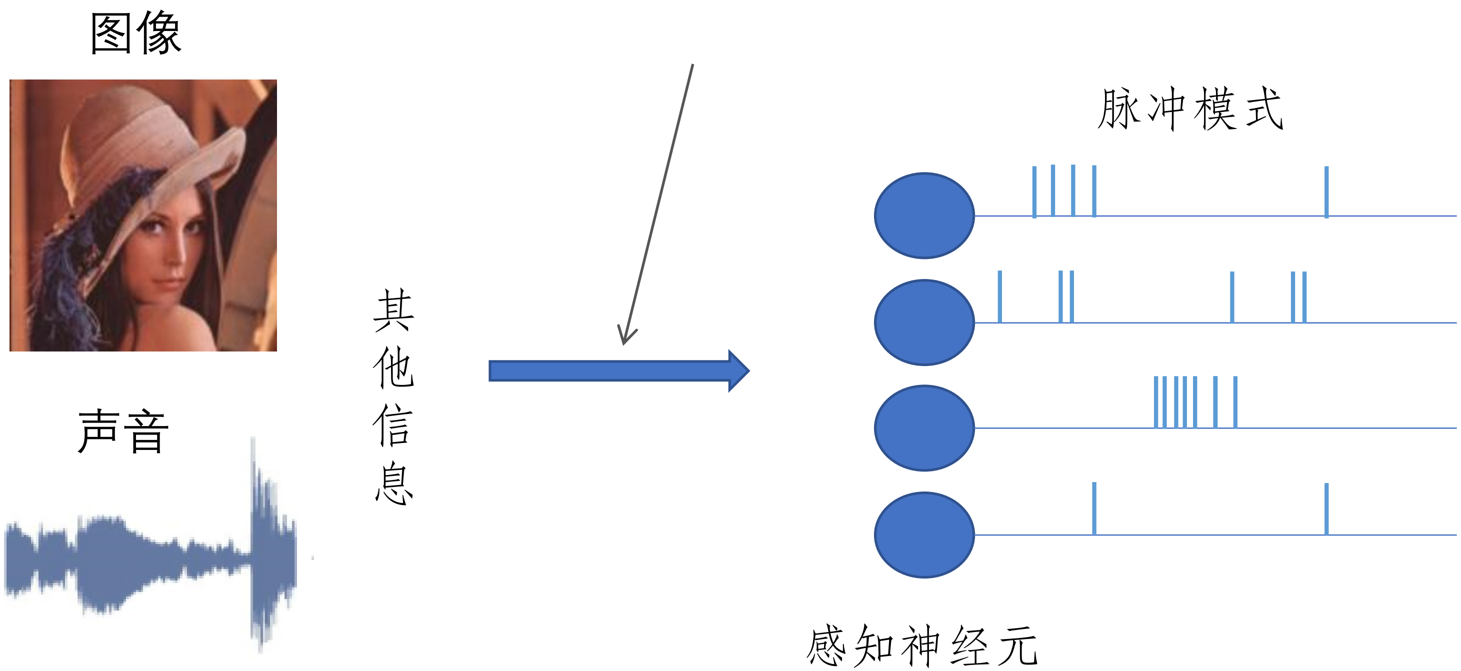
脉冲神经网络
（Spiking Neural Network）



脉冲神经网络是发展类脑计算的关键模型。

怎样研究脉冲编码？

通过对**生物模型**进行建模，或者直接从**统计或概率等数学模型**出发，构建编码算法。



脉冲编码的研究方向：根据应用场景，设计其他形式的信息以脉冲模式进行表达，以便脉冲神经网络更好地学习。

ANN到SNN

- ◆ 传统ANN网络在一系列领域取得了最前沿的进展
- ◆ 神经形态芯片提供实时、低功耗计算性能

困难

神经形态芯片

- ➢ 使用脉冲作为计算单元，事件驱动型计算模式
- ➢ 使用低精度突触把内存与局部计算保持数据移动和允许并行分布式操作
- ➢ 使用约束连接来实现神经元扇出有效从而大大减少网络流量芯片上

传统神经网络

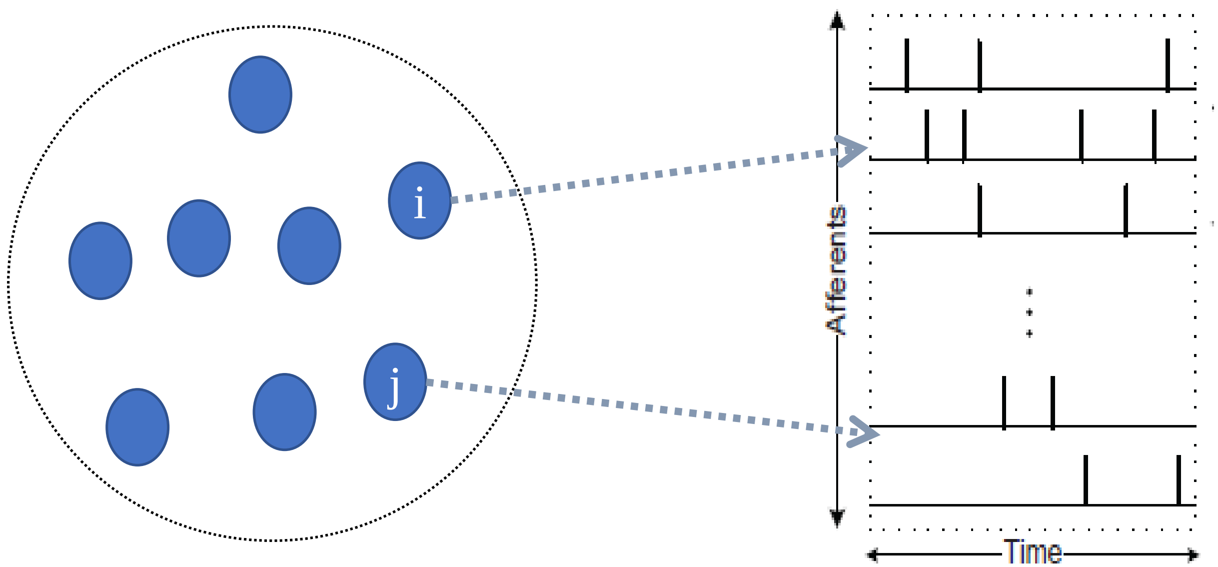
- ➢ 连续输出神经元
- ➢ 高精度的突触
- ➢ 对每个神经元的输入数量没有限制

难兼容

S. K. Esser, P. A. Merolla, J. V. Arthur, A. S. Cassidy, R. Appuswamy, A. Andreopoulos et al., Proceedings of the National Academy of Sciences, vol. 113, no. 41, pp. 11 441–11 446, 2016.
P. U. Diehl, D. Neil, J. Binas, M. Cook, S. C. Liu, and M. Pfeiffer, in International Joint Conference on Neural Networks, 2015, pp. 1–8.

Spiking Neural Activities

Population of neurons – **Spatiotemporal pattern**



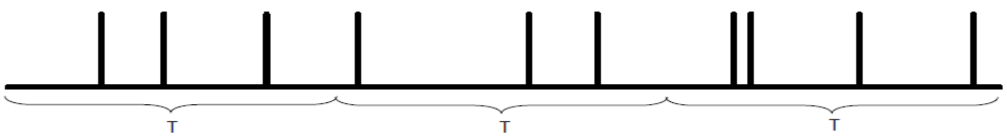
Neuron Population

Spatiotemporal

Coding Schemes - Rate Coding

Assume that information about the stimulus is contained in the firing rate of the neuron. Use firing rates to describe the properties of all types of sensory or cortical neurons.

- ✓ Set an encoding time window and count the number of spikes within it.



Encoding time window and spikes

- ✓ The temporal average of spike times is defined as the mean firing rate by the following equation:

$$r = \frac{n_{sp}}{T} = \frac{1}{T}\int_0^T s(t)dt$$

Advantage:
relative easy to measure firing rates experimentally.

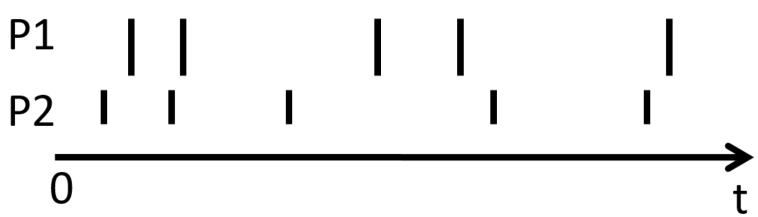
Disadvantage:
neglects all the information possibly contained in the exact timing of the spikes.

Coding Schemes - Temporal Coding

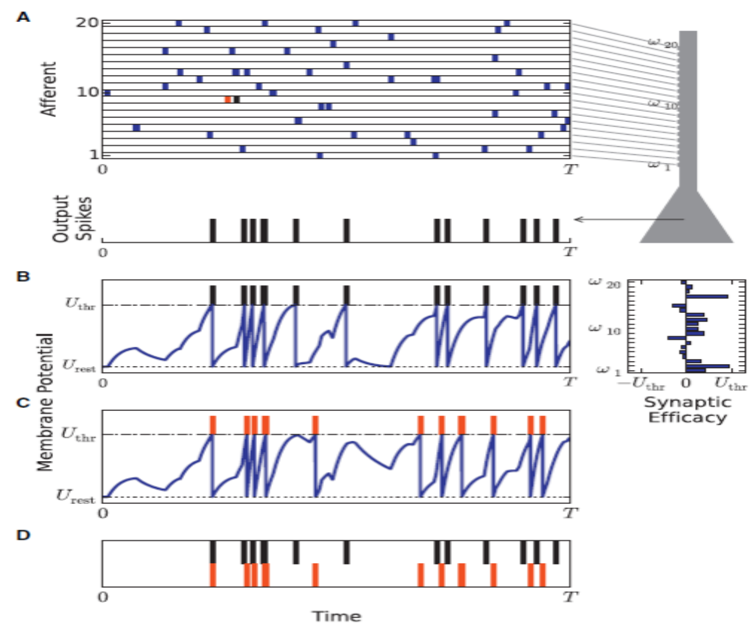
Recent studies have found that the temporal resolution of the neural code is on a millisecond time scale, indicating that precise spike timing is a significant element in neural coding.

- In order to specify the timing of each spike, we use Dirac function to describe spikes.
- Then a cluster of spikes or a spike train, is in the form of the following equation:

$$s(t) = \sum_i \delta(t - t_i)$$

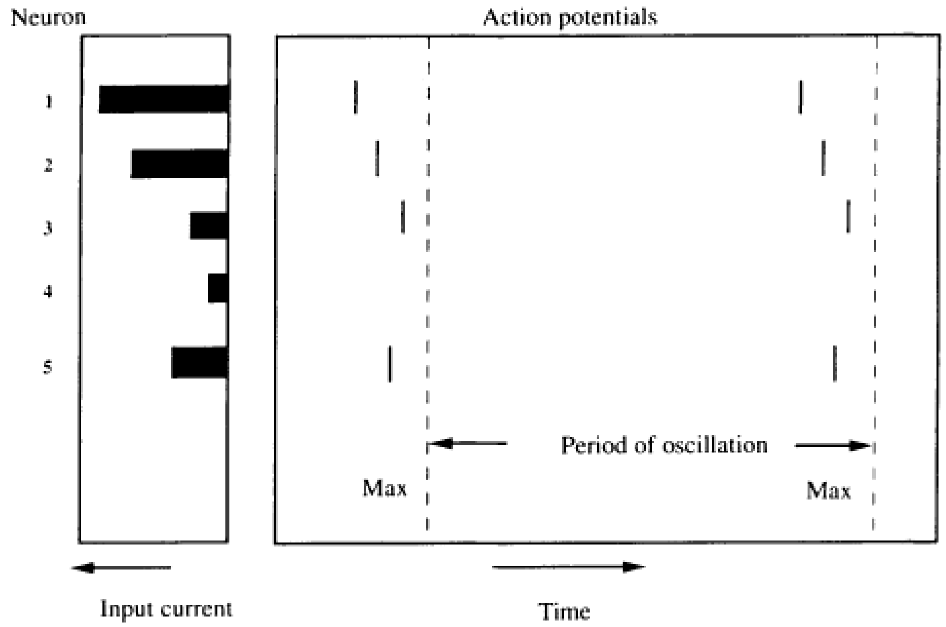


A cluster of spike train



Simulation: precise timings of spikes

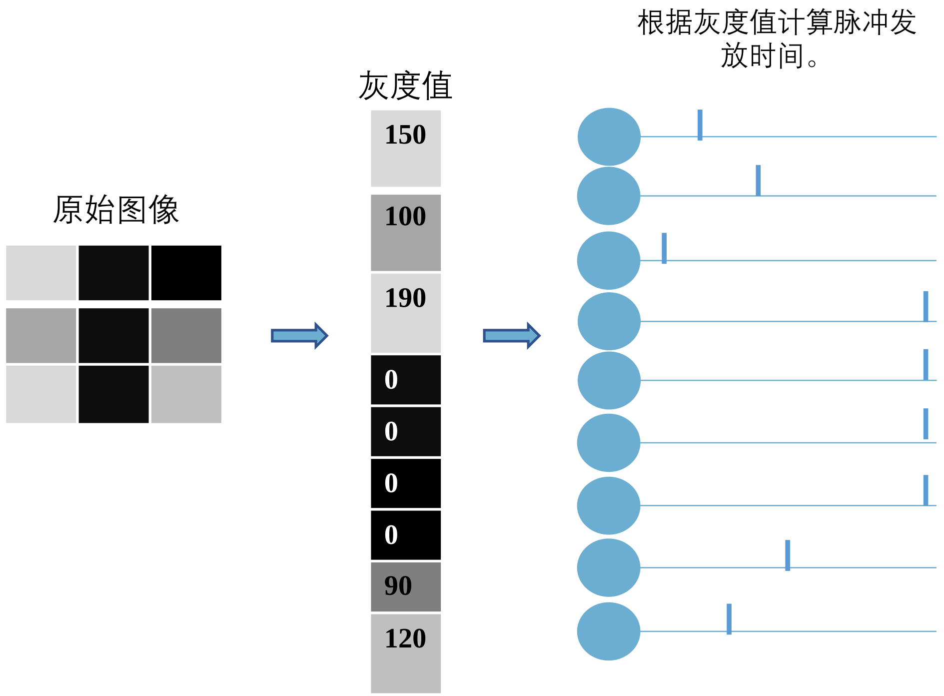
Coding Schemes - Latency Coding



- The latency of neural response is determined by the intensity of stimulus.
- The larger intensity of stimulus is, the earlier the neuron fires.

Ref.: Hopfield, J.J.(1995). Pattern recognition computation using action potential timing for stimulus representation. Nature, 376, 33-36.

编码方法一：时滞编码



公式：

$$t_i = f(s_i) = t_{max} - ln(\alpha \cdot s_i + 1)$$

优点： 每个输入神经元只发放一个脉冲，计算简单快捷。

缺点： 丢弃了后续的脉冲信息。

应用： 图像等静态数据编码。

时滞编码（latency coding）：越强的外部刺激，会促使感知神经元越早产生脉冲。

Ponulak, F., & Kasinski, A. (2011). Introduction to spiking neural networks: Information processing, learning and applications. Acta Neurobiologiae Experimentalis, 71(4), 409–33.

编码方法一：时滞编码

150	22
100	48
190	1
0	/
0	/
0	/
0	/
90	53
120	37

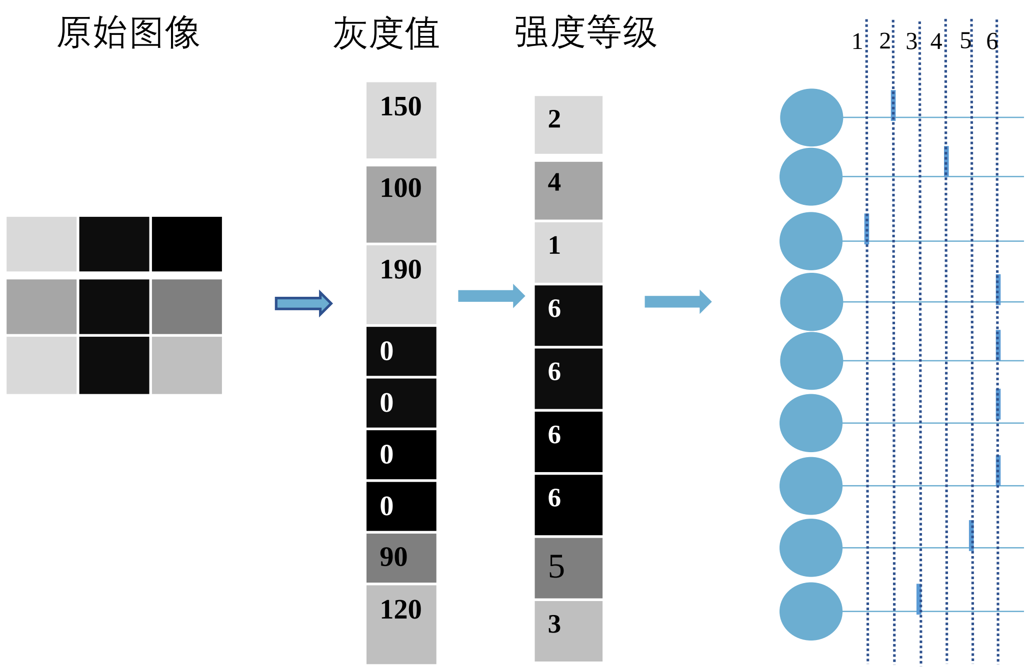
简化版的实现方式是 t(i) = T-ceil(T*(input(i)/max_num))+1
编码的周期为T;ceil是取上界的函数;input(i)是第i个神经元的输入;
max_num是所有输入中的最大值

如果输入如左1图所示
假定T=100
max_num = 190

意味着第i个神经元 在T-ceil(T*(input(i)/max_num))+1处发放脉冲。所以发放的时间如左图2所示，第4-7个神经元不发放脉冲

```
% 时滞编码函数定义
function[spike_trains] = generate_latency_spikes(input,scalor,n,T)
spike_trains = zeros(T,n);
max_num=max(max(input));
for i=1:n
    if input(i) ~= 0
        spike_trains(T-ceil(T*(input(i)/max_num))+1,i) = 1;
    end
end
end
```

编码方法二：等级排序编码



公式：

$f(s_i) = onset + r_i.\Delta t$

优点：

- 每个输入神经元只发放一个脉冲；
- 不需要计算精确脉冲时间；
- 计算极快。

缺点：

- 丢弃了后续的脉冲信息；
- 不能反应各输入值间的相对差异。

应用： 图像等静态数据编码。

等级排序编码（rank-order coding）：哺乳动物能够对图像进行极快地分类，原因是视觉皮层细胞能将外界刺激强度分配不同的脉冲时间。

Delorme, A., Perrinet, L., & Thorpe, S. J. (2001). Networks of integrate-and-fire neurons using Rank Order Coding B: Spike timing dependent plasticity and emergence of orientation selectivity. Neurocomputing, 38–40, 539–545.

编码方法二：等级排序编码

灰度值	强度等级	发放时间
150	2	20
100	4	60
190	1	0
0	6	/
0	6	/
0	6	/
0	6	/
90	5	80
120	3	40

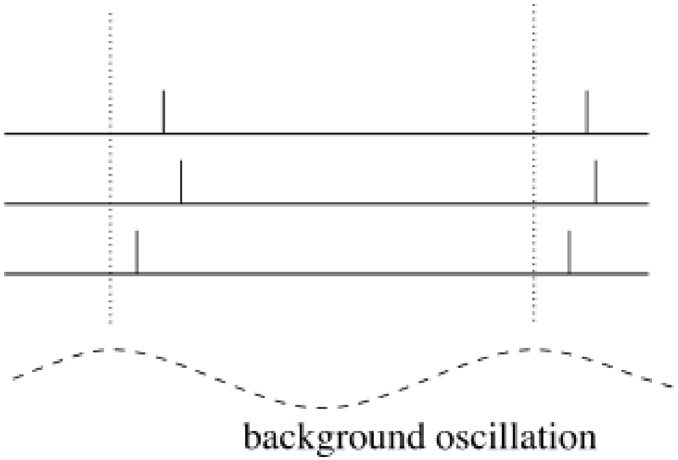
```
% 等级排序编码函数定义
function[spike_trains] = generate_order_spikes(input,scalor,n,T)
unique_input=unique(input);
unique_input=unique_input(unique_input~=0);
sorted_input=sort(unique_input，descend');
[index_m,index_n]=size(unique_input);
interval=T/(index_m*index_n);
spike_trains = zeros(T,n);
for i=1:n
    if(input(i)~=0)

spike_trains(int32(interval*(find(sorted_input==input(i)))),i) =
1;
    end
end
end
```

如果输入如左1图所示
假定T=100;
除去0排序后共5个强度等级，所以interval=T/5=20
意味着第i个神经元在int32(interval*(find(sorted_input==input(i))))处发放脉冲,所以发放的时间如左3图所示。实际效果中输入为0时于100处发放脉冲和不发放脉冲是一样的。

时间编码

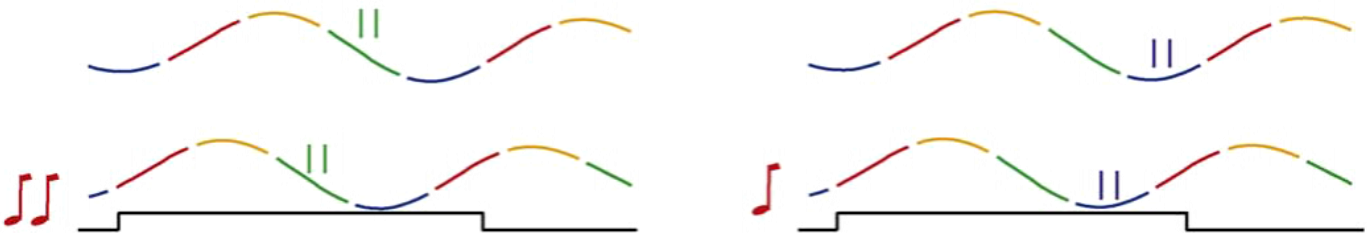
相位编码



- **定义：**
  - 将神经元的振荡作为内部参考信号进行编码，神经元脉冲序列可以编码脉冲相位相对于背景振荡的信息。
- **生物依据：**
  - 大鼠海马体振荡过程中的脉冲相位传递了关于动物空间位置的信息，但是这些信息不能被神经元脉冲发放速率所完全解释

Coding Schemes - Phase Coding

Assign different phases to spikes and the capacity of spikes increase with the additional phase information.

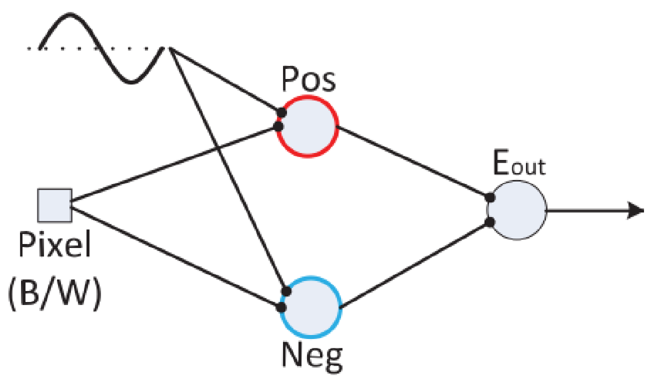


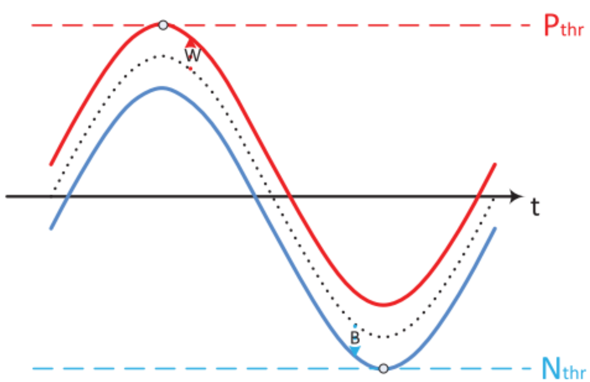
Advantage:
- Using the biological mechanism of SMO
- Compress the spatial information of spike patterns

Application:
- ◆ Compression or reconstruction

Yu, Q., Tang, H., Tan, K. C., & Li, H. (2013). Precise-Spike-Driven synaptic plasticity: Learning hetero-association of spatiotemporal spike patterns. PLoS ONE, 8(11), 1–16.

Coding Schemes - Phase Coding





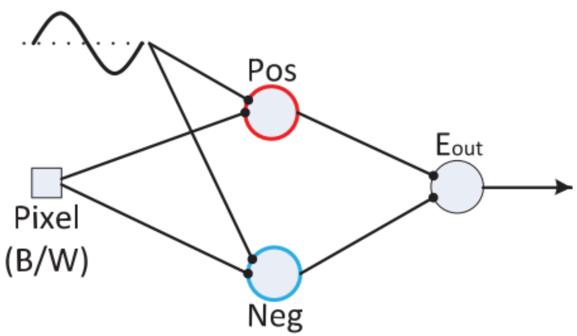
- Encoding unit consists of **a positive neuron (Pos), a negative neuron (Neg)** and **an output neuron (Eout)**.
- Each encoding unit is connected to a pixel and a subthreshold membrane potential oscillation (SMO).
- Whenever the membrane potential crosses the **threshold**, a spike is generated.

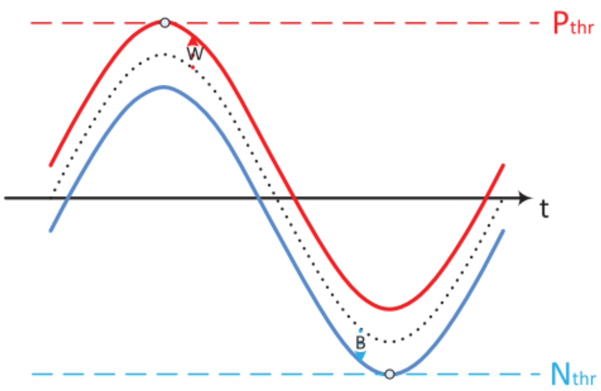
Formula:

$$i_{osc} = A_{osc} \cos(\omega t + \phi_i)$$
$$\phi_i = \phi_0 + (i-1) \cdot \Delta\phi$$

Yu, Q., Tang, H., Tan, K. C., & Li, H. (2013). Precise-Spike-Driven synaptic plasticity: Learning hetero-association of spatiotemporal spike patterns. PLoS ONE, 8(11), 1–16.

编码方法三：相位编码





神经元会实时接收输入值。每一个输入值，会根据正负分配到Pos或Neg神经元中，并对齐到其对应最近的SMO波峰或波谷上，使得Eout神经元生成脉冲。

优点：

- 利用了SMO的生物机制。
- 可压缩脉冲模式的空间信息

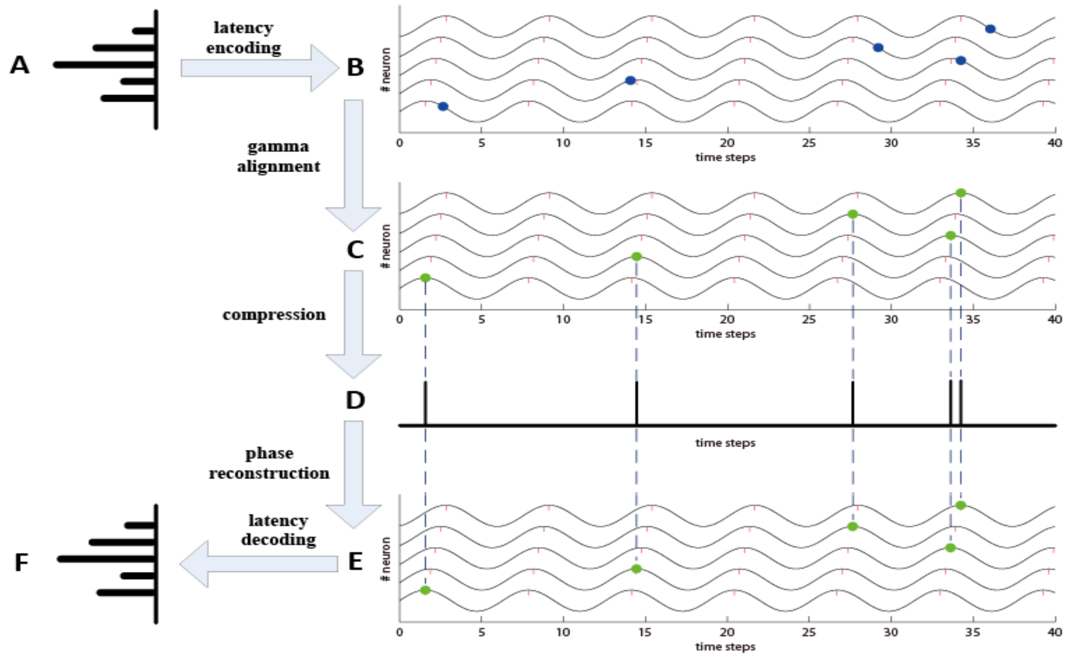
应用：

- 适用于压缩或重构等应用。

Yu, Q., Tang, H., Tan, K. C., & Li, H. (2013). Precise-Spike-Driven synaptic plasticity: Learning hetero-association of spatiotemporal spike patterns. PLoS ONE, 8(11), 1–16.

Coding Schemes – Latency&phase Coding

Latency-phase coding with a combination of latency coding and phase coding



Encoding & decoding scheme.
(A) Original stimuli. (B) Latency-encoded pattern. (C) Latency-phase encoded pattern. (D) Compressed spike train. (E)Reconstructed pattern. (F) Decoded stimuli

- Visual information carried by the intensities is converted into the **latencies of spikes**.
- The spikes are assigned with **phase information** according to their corresponding oscillations.
- After latency encoding and alignment operation, the spikes is generated at peaks of **the subthreshold oscillations.**

Nadasdy, Z. (2009). Information encoding and reconstruction from the phase of action potentials. Frontiers in Systems Neuroscience.

Coding Schemes - Population Coding

Represent stimuli by using by the joint activities of **a group of neurons** rather than single neurons.

Advantage:

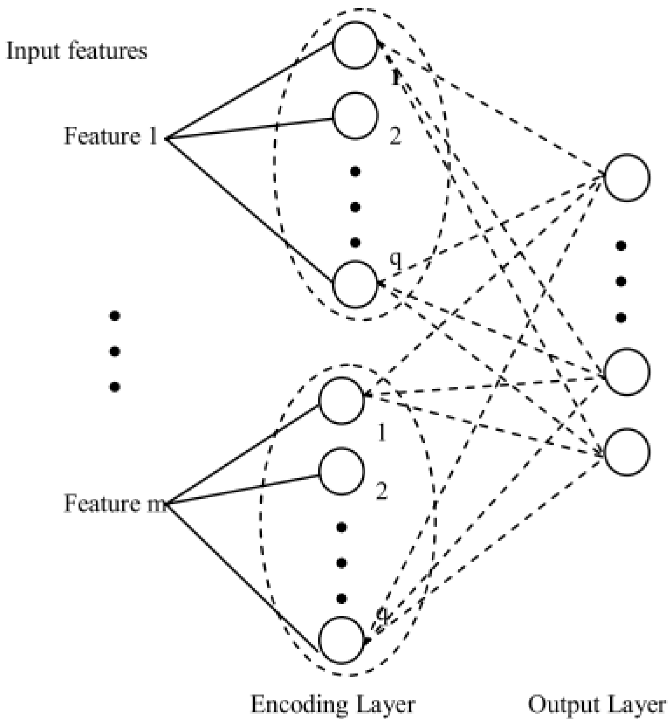
- Reflect the input stimuli into a high dimensional space
- Avoid disastrous results from the damage to single cells

Disadvantage:

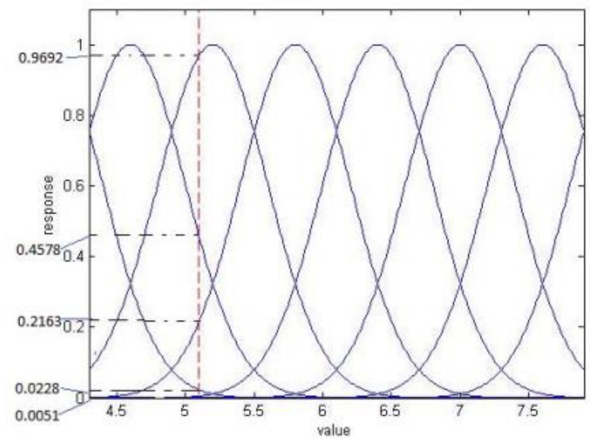
Increase the computation

Application:

Improve the robustness of the model



Feed-forward SNN with adaptive output layer



0.35 is encoded to a spike train of 5 neurons [0.9692,0.4578,0.2163,0.0228,0.0051]

Encoding of a real-valued feature of 5.1 using eight Gaussian receptive fields neurons

Snippe HP. Parameter extraction from population codes: A critical assessment.
Neural Computation. 1996; 8: 511–529. doi: 10.1162/neco.1996.8.3.511 PMID: 8868565

编码方法四：群体编码

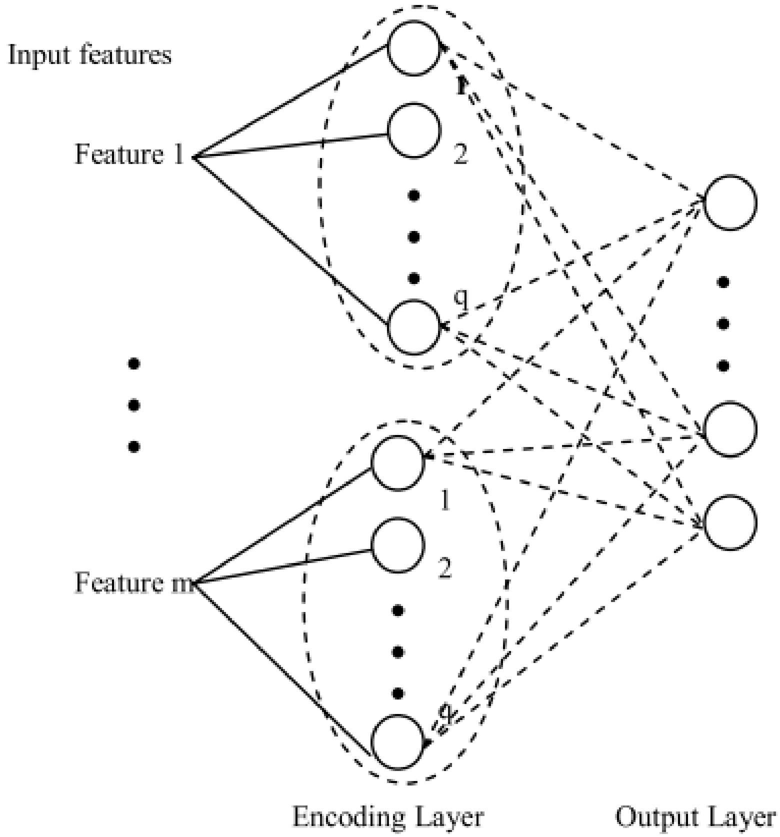


Fig. 3. Feed-forward SNN with adaptive output layer.

群体编码（population coding）：
生物研究表明，大脑接收到的图像或声音的特征由一组神经元的联合活动表示，而非单个神经元。

优点：
- 可扩展编码维度；
- 可提升鲁棒性。

缺点：
计算量提升

应用：
适用于提升模型的鲁棒性

编码方法四：群体编码

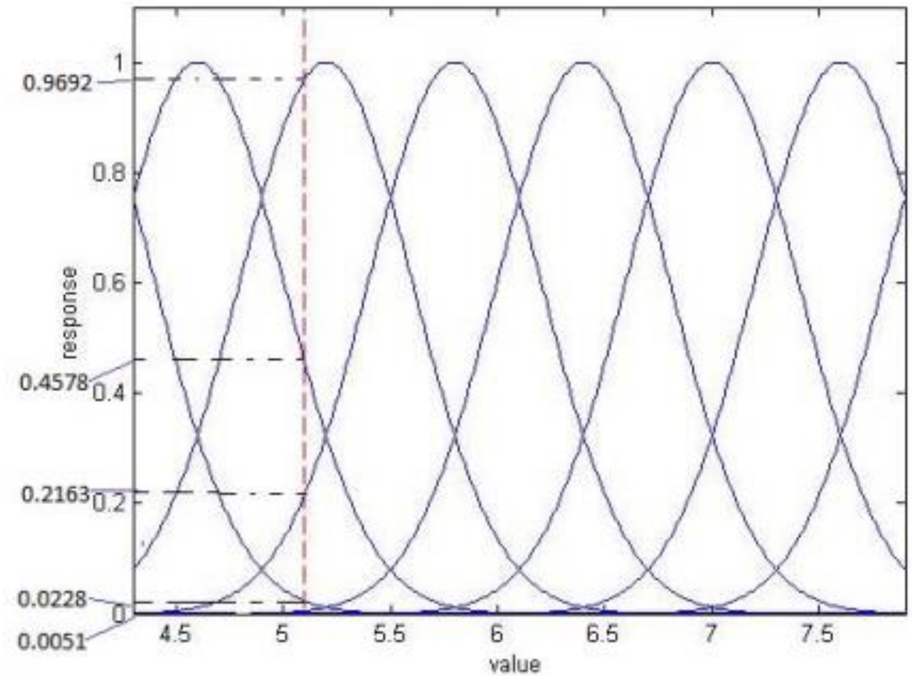


Fig. 1. Encoding of a real-valued feature of 5.1 using eight Gaussian receptive fields neurons.

eg.高斯感受野群体编码机制：一个值为5.1的特征会被编码为[0.9692,0.4578,0.2163,0.0228,0.0051]，这些数值代表5个神经元的脉冲发放时间。

Snippe HP. Parameter extraction from population codes: A critical assessment. Neural Computation. 1996; 8: 511–529. doi: 10.1162/neco.1996.8.3.511 PMID: 8868565

编码方法总结

- **脉冲编码：** 将其他形式的信息编码进脉冲模式的时空属性中。
- **目标：** 以脉冲模式表达信息的主要特征，使脉冲神经网络更好地学习。
- **选用策略：** 针对不同的应用领域有不同的编码方案，

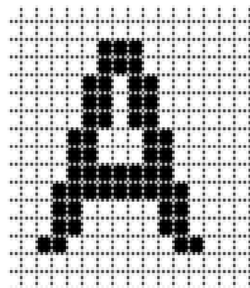
  a.对于**感知类任务**，通常从生物机制出发，构建数学模型，如**时滞编码、等级排序编码。**

  b.一些编码方法是**通用**的，可适用于多数任务，以提升性能，如**相位编码、群体编码。**

  c.也可直接使用**数学方法**进行编码，如**稀疏编码、统计方法。**

Encoding Models (e.g. in retina)

Rate coding

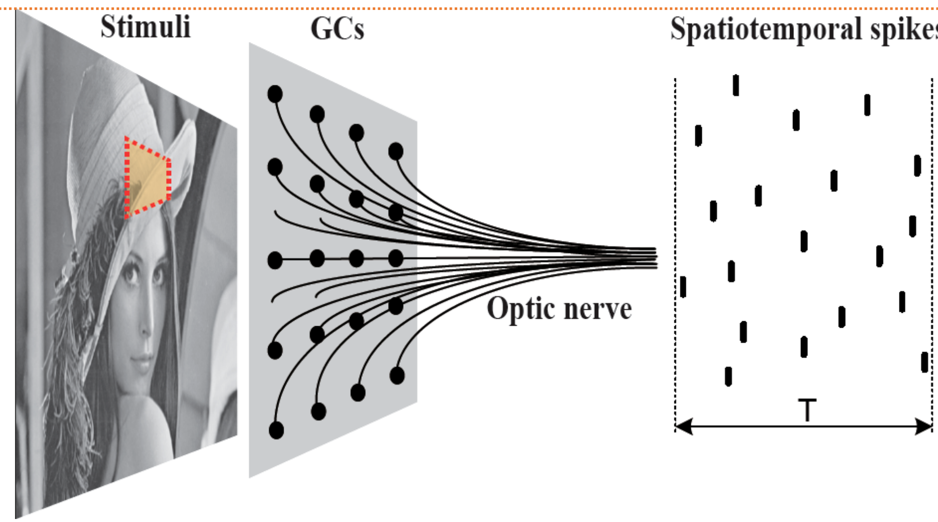


Poisson spiking trains:

2 Hz for black pixels;
50 Hz for white pixels.

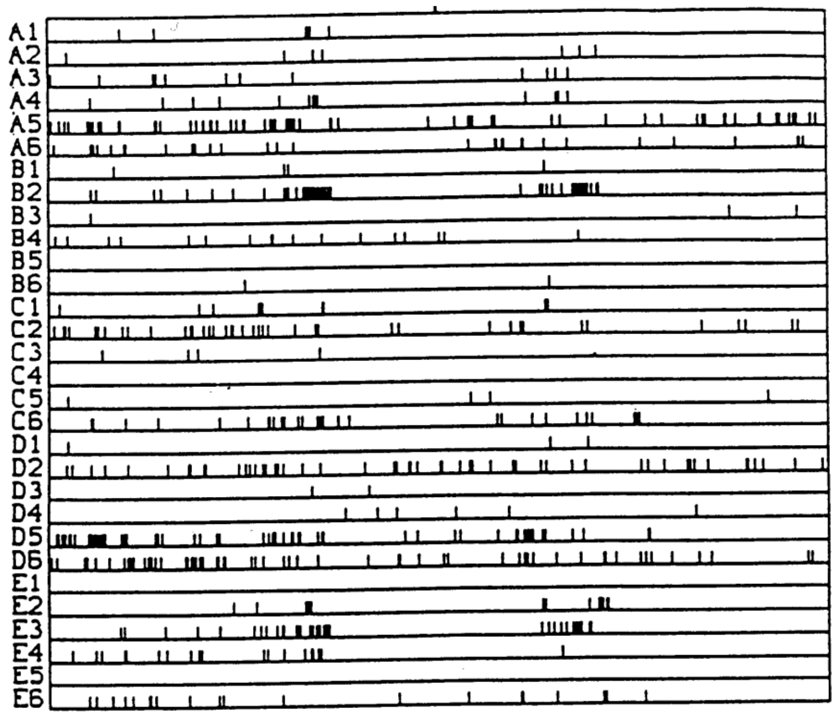
A higher sensory variable corresponds to a higher mean firing rate.

Temporal coding

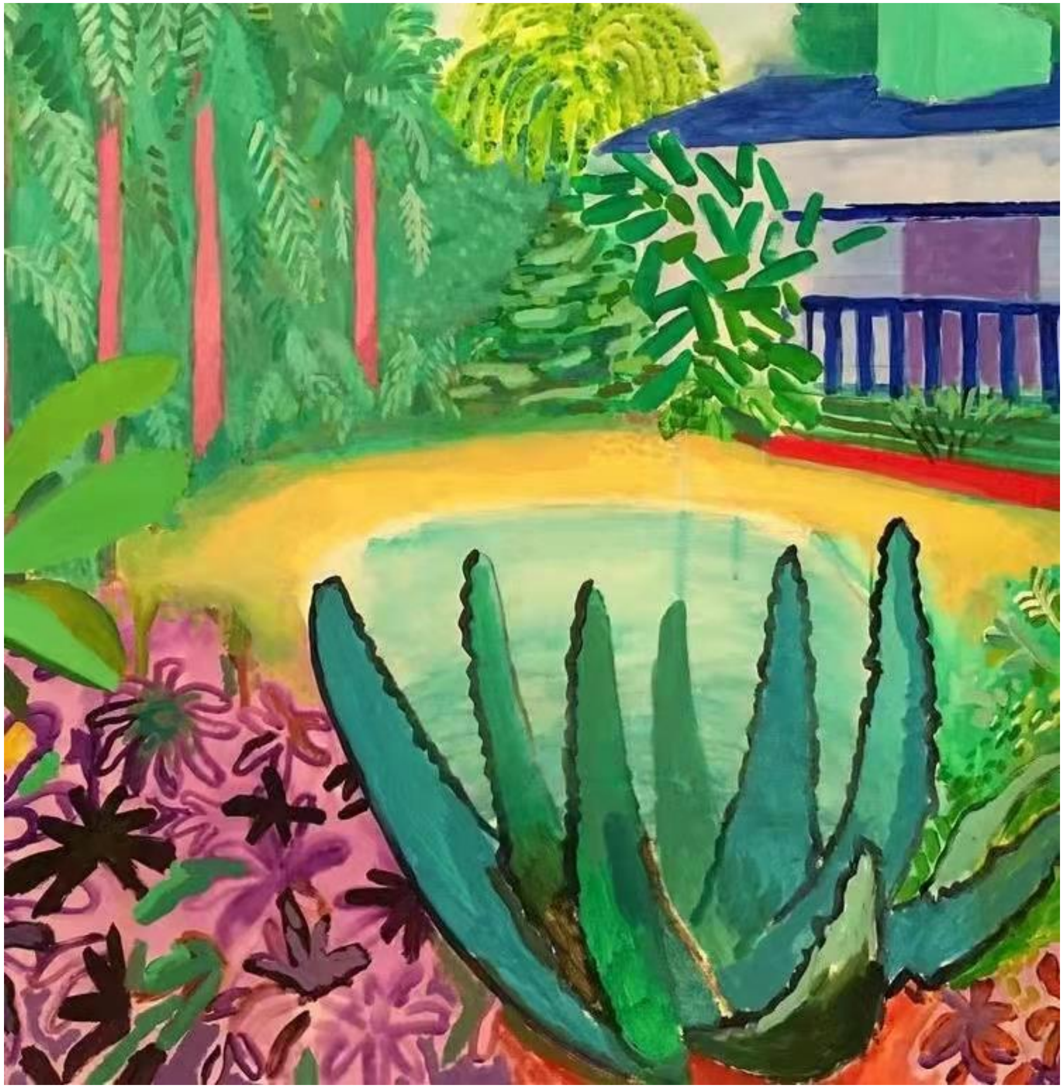


Precise timings of spikes

Raster Plot



脉冲的时空模式，横轴为时间，纵轴为神经元。这种表达脉冲时空模式（Spatio-Temporal Spike Patterns）的图称为 raster plot。




Thank You!