Simulation of Orientation Contrast Sensitive Cell Behavior in TiViPE

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Abstract Many cells in the primary visual cortex respond differently when a stimulus is placed outside their classical receptive field (CRF) compared to the stimulus within the CRF alone, permitting integration of information at early levels in the visual processing stream that may play a key role in intermediate-level visual tasks, such a perceptual pop-out [11], contextual modulation [7, 3, 4], and junction detection [13, 3, 5]. In this paper we construct a computational model in programming environment TiViPE [9] of orientation contrast type of cells and demonstrate that the model closely resembles the functional behavior of the neuronal responses of non orientation (within the CRF) sensitive 4Cβ cells [5], and give an explanation of the indirect information flow in V1 that explains the behavior of orientation contrast sensitivity.

1 Introduction

Neurons in the primary visual cortex (V1) respond in well defined ways to stimuli within their classical receptive field (CRF), but these responses can be modified by additional peripheral stimuli. The size of the periphery (non classical surround) provides input from a larger portion of the visual scene than originally thought, permitting integration of information at early levels in the visual processing stream. Recent works indicate that neuronal surround modulation at cross-orientation, an orientation orthogonal to the preferred orientation of the classical receptive field, might play a key role in intermediate level visual tasks, such as perceptual pop-out [11], contrast facilitation [2, 15], and contextual modulation [7, 3, 4]. The strength of this contextual influence on a neuron can be predicted from a model of local connection based on simple overlap with particular features, which indicates that local intra cortical circuitry could endow neurons with a graded specialization for processing angular visual features such as corners and junctions [13, 3, 5].

Depending on the orientation of an inner and outer grating pattern, these neuronal cells have the tendency to respond strongly to a center orientation

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preference or orientation contrast[3] between inner and outer pattern. Neuronal output activity was enhanced in both cat and macaque primary visual cortex (V1) when, a surrounding field at a significantly different orientation (30 degrees or more) was added to the preferred orientation of the classical receptive field [13]. Cells in layer 4Cβ, which are non-orientation sensitive within their CRF, also show these response profiles indicating that there must be a strong feedback from other areas (within V1) that create these more complex profiles. We assume that these cells obtain feedback from complex cells in layers 2, 3, 5, and 6 of V1. The aim of this paper is to setup a computational model of this type of cells which we will term *orientation contrast cells*, and to simulate these cells in visual programming environment TiViPE [9].

The paper is organized as follows: Section 2 elaborates on the properties of non orientation tuned cells with respect to orientation contrast, their pathway in early vision, and provides a computational model. Section 3 gives a TiViPE simulation that provides the results of this model when applied to the stimuli given by Jones et al [5]. The paper finishes with a discussion.

2 Non Orientation Tuned Cells

In primate V1 cells 94 percent had a response to orientation contrast stimuli that exceeded the response to the inner stimulus alone, independent from the diameter of the surround patch, while the responses were somewhat inhibitory when the orientation of the inner and outer stimuli were the same, compared to the response to the inner stimulus alone [5]. They found that the responses of 4Cβ cells could be modulated by varying both orientation of a center grating patch (inside the CRF) and a surround grating patch (outside the CRF), despite the cell's lack of orientation tuning within the CRF. Its response output was extremely sensitive to orientation differences between center and surround patches.

The LGN parvo cellular cells (P) have center-surround shaped receptive field profiles which optimally respond to a spot of light. In a feed-forward processing stream one could expect a similar receptive field type in layer 4Cβ. For instance, a set of center-surround profiles that are aligned in a certain way, may respond strongly to a line or bar of a specific orientation. However, such profile does not provide center orientation preference nor is it able to provide a measure for center-surround orientation contrast. The modulation of its response behavior must be caused by an indirect (feedback loop) information stream, as illustrated in Figure 1.

2.1 Organization of the Primary Visual Cortex

The primary visual cortex (V1) consists of six layers (1-6) between the pial surface and the underlying white matter. The principal layer for inputs from the

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[3] Orientation contrast is the difference between preferred orientation of a center patch (which roughly covers the CRF) and preferred orientation of a surround patch (outside the CRF). This contrast is strongest when the center and surround orientations are orthogonal and weakest when both are the same.

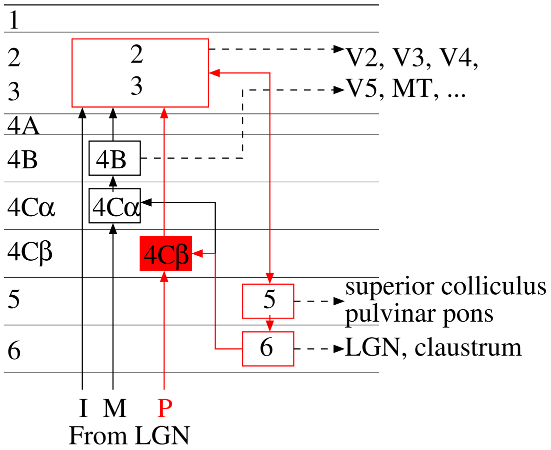

Figure 1. Information flow in the primary visual cortex (V1) based on anatomical connections [6]

lateral geniculate nucleus (LGN) is layer 4, which is subdivided into four sub layers (4A, 4B, 4Cα, and 4Cβ), see also Figure 1. This flow can be described by means of input, intra cortical, and output connections [6]:

- **Inputs.** Axons from magno cellular (M) and parvo cellular (P) cells in the lateral geniculate nucleus (LGN) end on spiny stellate cells in the sub layers of 4C, and these cells project axons to layers 2, 3, or 4B. Axons from cell in the intra laminar (I) zones of the LGN project directly to layers 2 and 3.
- **Intra cortical connections.** Axon collaterals of the pyramidal cell in layers 2 and 3 project to layer 5 pyramidal cells, whose axon collaterals project both to layer 6 pyramidal cells and back to cells in layers 2 and 3. Axon collaterals of layer 6 pyramidal cells then make a loop back to layer 4C onto smooth stellate cells.
- **Outputs.** Each layer, except for 4C, has outputs and each is different. Cells in layers 2, 3, and 4B project to extra striate visual cortical areas. Cells in layer 5 project to the superior colliculus, the pons, and pulvinar. Cells in layer 6 project to claustrum and back to the LGN.

The assumption that a 4Cβ cell receives input from simple (layer 2) or complex cells (layer 3) through layers 5 and 6 makes it plausible that these cells have a far more complex receptive field profile than one can expect from a feed-forward mechanism alone.

2.2 Orientation Sensitive Input Responses

In order to model the profiles suggested by [5] we assume that layer 4Cβ receives complex cell (indirect) input from layers 2, 3, 5, and 6. A computational model of simple and complex cells [8, 14] is used to form the input of the orientation contrast cells and is introduced only briefly.

The receptive fields of simple cells can be modeled by complex valued Gabor functions:

$$\widehat{G}_{\sigma,\theta}(x,y) = \exp\left(i\frac{\pi x_1}{\sqrt{2}\sigma\lambda}\right)\exp\left(-\frac{x_1^2+\gamma^2 y_1^2}{2\sigma^2}\right) \quad , \tag{1}$$

where $i = \sqrt{-1}$, $x_1 = x\cos\theta + y\sin\theta$ and $y_1 = y\cos\theta - x\sin\theta$. Parameters σ, λ, γ, and θ represent scale, wavelength, spatial aspect ratio, and orientation, respectively. These Gabor functions have been modified, such that their integral vanishes and their one-norm (the integral over the absolute value) becomes independent of σ, resulting in $G_{\sigma,\theta}(x,y) = \eta\widehat{G}_{\sigma,\theta}(x,y)$, where $\eta = \eta^+_{\mathrm{Re}}$ for the positive valued real part of $\widehat{G}$, $\eta = \eta^-_{\mathrm{Re}}$ for the negative valued real part of $\widehat{G}$, and $\eta = \eta_{\mathrm{Im}}$ for the imaginary part of $\widehat{G}$. For details about these constants see [8]. A spatial convolution was used to transform input image $I(x,y)$ by these operators to yield the simple cell operator, and the amplitude of the complex values [10]

$$\mathcal{C}_{\sigma,\theta} = ||I * G_{\sigma,\theta}|| \tag{2}$$

was taken to obtain the complex cell operator.[4] This operator forms the basis of the orientation contrast cell operator $\mathcal{O}$ to be described later in this paper. A high value at a certain combination of (x,y) and θ represents evidence for a contour element (bar or edge) oriented orthogonally to θ. Orientations are sampled linearly $\theta_j = \pi/N, j = 0,\ldots,N-1$, and the scales are sampled $\sigma_k = \sigma_{k-2} + \sigma_{k-1}$, for $k = 2\ldots S-1$, where σ_0 and σ_1 represent constants.

2.3 Orientation Contrast and Center Orientation Preference

Neuronal cells in area V1 respond to both orientation contrast and center orientation. Depending on the size and orientation of the peripheral patch compared to the preferred orientation of the center patch (which covers the CRF) the response is inhibitory or excitatory. When the patch is similar in size compared to its center patch the cell tends to respond strongly to orientation contrast, while a patch that has a diameter of four times the diameter of the central patch tends to respond strongly to the preferred orientation of the central patch [5]. These findings suggest a varying gain value that depends on the size of the surround patch. This is modeled as follows:

$$G_x(s) = \left[-\frac{2s^2}{30} - \frac{s}{10} + \frac{2}{3}\right]^{\geq 0} \quad , \tag{3}$$

where s denotes the surround patch diameter in degrees, and $[x]^{\geq 0} = x$ if $x \geq 0$ and 0 otherwise. The curve obtained by varying the surround patch diameter is illustrated in Figure 2a.

The normalized response profile (weight matrix) is modeled as a blend between orientation contrast preference and preferred center orientation:

$$W(c_p, c_o, c_s, s_o, s_s) = G_x(s_s/c_s)X(c_o, s_o) + G_c C(c_p, c_o), \tag{4}$$

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[4] The preferred orientation $\theta \in [0,\pi)$, since $\mathcal{C}_{\sigma,\theta} = \mathcal{C}_{\sigma,\theta+\pi}$.

where c_p, c_o, and c_s denote the preferred orientation, used orientation, and diameter of the center patch, all between 0 and 360 degrees. Likewise s_o, and s_s denote the used orientation and diameter of the surround patch. The normalized orientation contrast profile is as follows:

$$X(c_o, s_o) = \begin{cases} 0.5 - 0.5\cos\left(\frac{|c_o - s_o|\pi}{W_x}\right) & \text{if } \alpha_X(c_o, s_o) \le W_x \\ 1 & \text{otherwise} \end{cases}, \tag{5}$$

where $W_x = 90$ degrees is a constant, and $\alpha_X(c_o, s_o) = \min(|c_o - s_o|, |360 + c_o - s_o|, |360 + s_o - c_o|)$. The normalized preferred center orientation is

$$C(c_p, c_o) = \begin{cases} 0.5\cos\left(\frac{|c_p - c_o|\pi}{W_c}\right) + 0.5 & \text{if } \alpha_C(c_p, c_o) \le W_c \\ 0 & \text{otherwise} \end{cases}, \tag{6}$$

where $W_c = 90$ degrees is a constant, and $\alpha_C(c_p, c_o) = \min(|c_p - c_o|, |360 + c_p - c_o|)$.

The response of the 4Cβ cell as measured by [5] in Figure 6 shows a maximum response of around 70 while the minimum response is around 15. To obtain the response profile as given in Figure 2b-d the following response was used:

$$R_W = 70(W + 0.2). \tag{7}$$

2.4 Orientation Contrast Cell Operator

The response of a center patch which covers the CRF is obtained as follows:

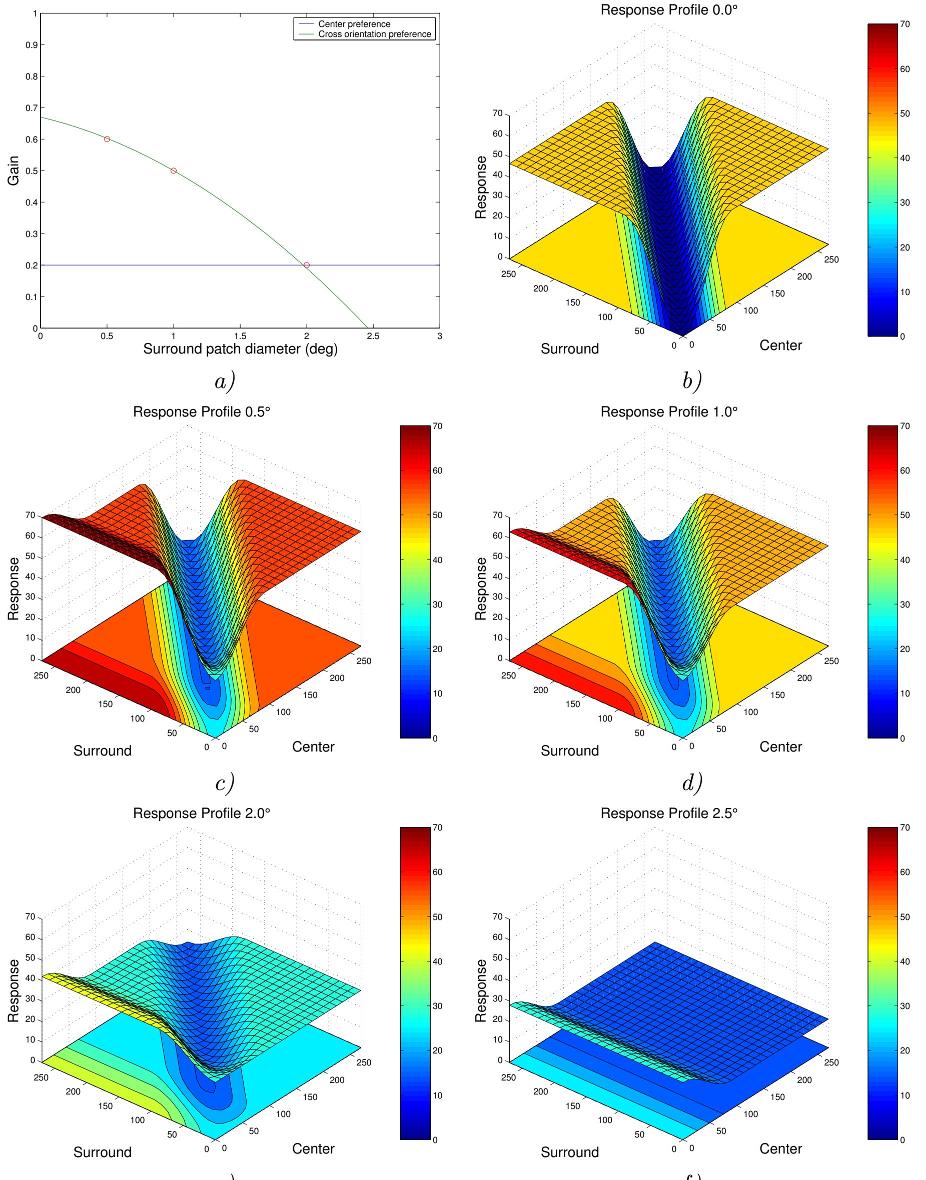
$$\mathbf{C}_{\sigma,c_s} = \mathcal{C}_{\sigma,\theta_i} * g_{c_s/6}, \tag{8}$$

where $\theta_i = i\pi/N$, $i = 0, \ldots, N$, and $g_\sigma(x, y) = 1/(2\pi\sigma^2)\exp(-(x^2 + y^2)/2\sigma^2)$ is a 2D Gaussian function.

The response of a surround patch is obtained by taking the maximum response of differently sized surround patches

$$\mathbf{S}_{\sigma,c_s,s_{\min},s_{\max},Q} = \max_{(x1,y1)} (W(c_p, c_o, c_s, s_o, s_s) - W_s) \max_j \left(\widehat{\mathcal{C}}_{\sigma,\theta_i}(x_1, y_1)\right), \tag{9}$$

where $\widehat{\mathcal{C}}_{\sigma,\theta_i} = \mathcal{C}_{\sigma,\theta_i} * g_{s_{s_j}/6}$, $s_{s_j} = j(s_{\max} - s_{\min})/(Q - 1) + s_{\min}$ has a linearly increasing patch size between $s_{\min}$ and $s_{\max}$, $j = 0, \ldots, Q - 1$, and Q is the number of surround patch sizes. Let $j_{\max}$ denote the index j for which holds $\widehat{\mathcal{C}}_{\sigma,\theta_i}$ is maximal. Weight W from (4) is in the 0 to 90 degree range, since we assume that the grating pattern is static rather than moving in a specific direction, W_s is an inhibitive weight, and $(x1, y1)$ are the spatial positions of the outer stimulus. Since these patches largely overlap resampling is used to reduce computational time. Preferred center orientation c_p, center orientation c_o, surround orientation s_o, and surround patch size s_s are as follows:



a) b) c) d) e) f)

Figure 2. Modeled response profiles (7) of a non orientation tuned layer 4Cβ cells to varying the orientation of both center and surround patch, for a comparison with the measured responses, see Fig. 6 of [5]. *a)* Blending curve between orientation contrast and center orientation preference. *b)* Modeled profile for $s_s = 0$, which gives solely a preference to orientation contrast. *c-e)* Profiles for $s_s = 0.5$, 1.0, and 2.0 degrees, respectively. *f)* Modeled profile for $s_s \geq 2.5$, which solely prefers the center orientation. Parameters used are preferred center orientation $c_p = 0$ degrees, and center radius $c_s = 0.5$ degrees

$$c_p = c_o = \begin{cases} 180i/N & \text{if } i \leq N/2 \\ 180(N-i)/N & \text{otherwise} \end{cases} \tag{10}$$

$$s_s = s_{\min} + j_{\max} \frac{s_{\max} - s_{\min}}{Q-1} \tag{11}$$

$$s_o = \begin{cases} 180 j_{\max}/N & \text{if } j_{\max} \leq N/2 \\ 180(N - j_{\max})/N & \text{otherwise} \end{cases} \tag{12}$$

The cross-orientation operator which comprises a center response and a surround response that depends on the center response is as follows:

$$\mathcal{O}_{\sigma,c_s,s_{\min},s_{\max},Q} = (\mathbf{C}_{\sigma,c_s} + w\mathbf{S}_{\sigma,c_s,s_{\min},s_{\max},Q}) * g_{c_s/6}, \tag{13}$$

where weight $w = \mathbf{C}_{\sigma,c_s}/R$ is a weight that is dependent on the center response $\mathbf{C}$. In all simulations constant $R = 255$ was used to bound w between 0 and 1.

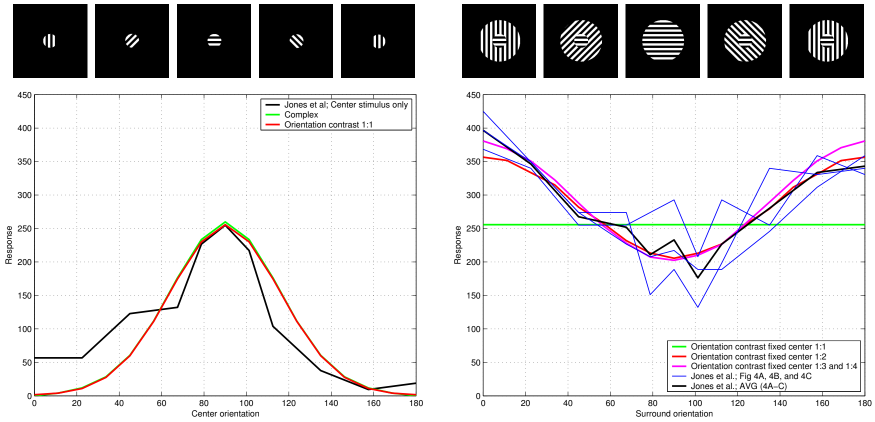
3 Responses to Test Patterns

The input stimuli used in the simulation have a center radius of 24 pixels and surround radii of 24 (Figure 3a), 48, 72 (Figure 3b), or 96 pixels. The block gratings consist of alternating black and white bars which are both 8 pixels wide. A complex cell operator $\mathcal{C}_{\sigma,\theta}$ with $\sigma = 4\sqrt{2}$ and an orientation θ corresponding to the preferred orientation of the grating pattern yields an optimal response (255), see also Figure 3a, for the complex cell operator $\mathcal{C}$ in the center of the input stimuli of Figure 3a and b. When the center-only input stimulus is applied to orientation contrast operator ($\mathcal{O}$) for the preferred horizontal center orientation the $\mathcal{O}$-operator has a very similar response profile compared to the $\mathcal{C}$-operator, but where the results of $\mathcal{C}$-operator remain the same, the $\mathcal{O}$-operator is influenced by its surround as illustrated in Figure 3b ("Orientation contrast fixed center 1:3"). The profile is very similar to the one given by [5].

The orientation contrast cell operator $\mathcal{O}$ from (13) has been implemented in visual programming environment TiViPE [9]. The orientation contrast simulation that is represented by a network of connected icons consists of a "ReadImage" icon which generates the input stimulus, its connected "Display" icon yields the images provided in Figure 3a and b. The "ComplexAndEndstopppedResponse" produced the responses of the $\mathcal{C}$-operator (2). Its output forms the input of the "ComplexCrossOrientationResponses" and gives the responses of the $\mathcal{O}$-operator (13). The values at the center of the two other "Display" icons have been used to construct Figure 3c.

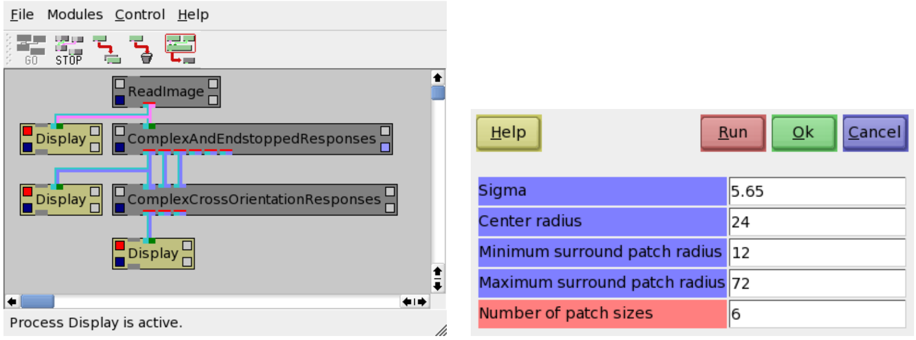
4 Discussion

Many neurons in primary visual cortex (V1) respond differently to a simple visual element presented in isolation compared to when it is embedded in a more



a) *b)*

Figure 3. Response characteristics of orientation contrast sensitive cells, see Figure 4A-F from [5]. *a)* Input stimuli with preferred orientations of 0, 45, 90, 135, and 180 degrees, and below the response profiles to these stimuli of the measured V1 cells, complex cells ($\mathcal{C}$-operator) and orientation contrast type of cell ($\mathcal{O}$-operator). *b)* Input stimuli with surround, with preferred center orientation of 90 degrees and varying surround orientation from left to right from 0 to 180 degrees. The ratio between center and surround of these stimuli is 1:3 (top). Response profiles for measured cells and center-only (1:1), and center-surround (1:2, 1:3, and 1:4) stimuli. Responses have been normalized to the maximum response of the modeled complex cells (255). The inhibitory weight $W_s = 0.45$ which yields similar response profiles as the measured V1 cells



Process Display is active.

Sigma	5.65
Center radius	24
Minimum surround patch radius	12
Maximum surround patch radius	72
Number of patch sizes	6

a) *b)*

Figure 4. *a)* TiViPE network. *b)* Parameters used for cross orientation type of cells

complex stimulus. Typically the surround influence was suppressive when the surround grating was at the neuron's preferred orientation [2], but when the orientation in the surround was perpendicular to the preferred orientation facilitation became evident [13, 12, 2, 5]. The difference is in the modulation by surrounding elements, hence it could provide neurons with a graded specialization for processing junctions [13, 3]. These neurons also respond to a grating or a single bar of a preferred orientation and are in that respect too general to be purely responding to junctions. In the monkey the majority of cells showed response suppression with increasing grating patch diameter [1, 13] therefore it is likely that a group of these neurons responds to junctions and facilitates pop-out patterns [11].

The proposed model for orientation contrast cells uses complex cell input that is provided by the indirect pathway from layers 2, 3, 5, and 6 of V1 and yields appropriate characteristics to test patterns as used by Jones et al [5]. Future work will involve patterns for junction detection, pop-out, and will be applied to natural images. The model itself will be integrated into a highly parallel vision system that will be used in a humanoid robot.

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