

*I've done the math enough to know the dangers of our second guessing  
Doomed to crumble unless we grow and strengthen our communication*

~ Tool

## 1 The Model

There are two players, a sender and a receiver, and a state of nature  $q \in [0, 1]$  that is known to the sender but not the receiver. Let  $g$  denote the density of  $q$ . The sender sends an *intended* message  $m(q) \in [0, 1]$ . The receiver receives a noisy version of the intended message, which we call the *received* message,  $\tilde{m} = m(q) + e$ .  $e$  is distributed according to a continuous density  $f$  with support  $[-\bar{e}, \bar{e}]$ , where for some integer  $N \geq 2$ ,  $\bar{e} = \frac{1}{2N}$ .

We specify  $f$  as follows. Let  $x : [-\bar{e}, \bar{e}] \rightarrow [0, 1]$  be given by

$$x(e) = \frac{1}{2} \left[ 1 + \frac{e}{\bar{e}} \right] \quad (1)$$

Consider, as an example, the Beta PDF:

$$f(e) = x(e)^{a-1} (1 - x(e))^{b-1} \quad (2)$$

for constants  $a > 0$  and  $b > 0$ . The receiver then takes an action  $a(\tilde{m}) \in [0, 1]$ . Both sender and receiver have utility over the state,  $q$ , and the receiver's action,  $a$ , of

$$U(q, a) = -\frac{1}{2}(q - a)^2 \quad (3)$$

Prior to the start of the game, the sender can specify an intended message function  $m(q)$  that she will use. The receiver chooses an action based upon the function  $m(q)$  and the received message  $\tilde{m}$ , and we denote this function  $a(\tilde{m})$ . We work backward and start with the optimal action, given  $m(q)$  and  $\tilde{m}$ .

Fix a message function  $m$ . Let  $Q(\tilde{m})$  denote the set of all states  $q \in [0, 1]$  such that for some noise  $e \in [-\bar{e}, \bar{e}]$ ,  $\tilde{m} = m(q) + e$ . In set builder notation,

$$Q(\tilde{m}) = \{q \in [0, 1] \mid m(q) - \bar{e} \leq \tilde{m} \leq m(q) + \bar{e}\}. \quad (4)$$

Finally, define

$$q_+(\tilde{m}) \equiv \sup Q(\tilde{m}) \quad (5)$$

$$q_-(\tilde{m}) \equiv \inf Q(\tilde{m}) \quad (6)$$

$q_+(\tilde{m})$  and  $q_-(\tilde{m})$  are the highest and lowest states that could possibly be associated with the received message  $\tilde{m}$ . Define

$$I(\tilde{m}; \alpha, \beta, \gamma) \equiv \int_{\alpha}^{\beta} q^{\gamma} f(\tilde{m} - m(q)) dq \quad (7)$$

Suppose that the receiver receives the message  $\tilde{m} \in [-\bar{e}, 1 + \bar{e}]$ .  $q|\tilde{m}$  has support  $[q_-(\tilde{m}), q_+(\tilde{m})]$  and density

$$g(q|\tilde{m}) = \frac{f(\tilde{m} - m(q))g(q)}{\int_0^1 f(\tilde{m} - m(t))g(t)dt} \quad (8)$$

The receiver's problem is to

$$\max_{a(\tilde{m})} \int_{q_-(\tilde{m})}^{q_+(\tilde{m})} U(q, a)g(q|\tilde{m})dq. \quad (9)$$

The receiver's optimal action is simply the expected value of the state,  $q$ , given the received message  $\tilde{m}$  :

$$a(\tilde{m}) = \int_{q_-(\tilde{m})}^{q_+(\tilde{m})} qg(q|\tilde{m})dq = \frac{I(\tilde{m}; q_-(\tilde{m}), q_+(\tilde{m}), 1)}{I(\tilde{m}; q_-(\tilde{m}), q_+(\tilde{m}), 0)} \quad (10)$$

It will be helpful to refer to the *cost* of a message function. Let the cost functional  $C$  be given by

$$C[m] \equiv \int_0^1 \int_{-\bar{e}}^{\bar{e}} (q - a(m(q) + e))^2 f(e) dedq, \quad (11)$$

where  $a$  is the receiver's optimal action from Equation (10).  $C[m]$  is the expected loss for a given message function  $m$ . The integrand is the loss for a given state  $q$  and action  $a(\tilde{m})$ . The interior integral integrates over the possible exogenous errors, to generate the expected loss given the state. The exterior integral integrates over possible states. Therefore, the *sender's problem* is to choose a message function  $m$  that minimizes  $C[m]$ :

$$\min_{m \in M} C[m] \quad (12)$$

where  $M$  is the space of weakly increasing piece-wise continuous functions on  $[0, 1]$ . The change of variables  $\tilde{m} = m(q) + e$  and an application of Fubini's Theorem yield

$$C[m] = \int_0^1 \int_{m(q)-\bar{e}}^{m(q)+\bar{e}} (q - a(\tilde{m}))^2 f(\tilde{m} - m(q))g(q)d\tilde{m}dq \quad (13)$$

$$= \int_{-\bar{e}}^{1+\bar{e}} \int_{q_-(\tilde{m})}^{q_+(\tilde{m})} (q - a(\tilde{m}))^2 f(\tilde{m} - m(q))g(q)dq d\tilde{m}. \quad (14)$$

We consider the costs of identity (“ $\mathcal{I}$ ”) and discrete (“ $\mathcal{D}$ ”) message functions.

## 2 Identity Message

We consider the identity message function,  $m(q) = q$ , only for the case in which  $q$  is uniformly distributed.

$$a(\tilde{m}) = \begin{cases} \bar{a}(\tilde{m}) & \text{if } 1 - \bar{e} < \tilde{m} \leq 1 + \bar{e} \\ a(\tilde{m}) & \text{if } \bar{e} < \tilde{m} \leq 1 - \bar{e} \\ \underline{a}(\tilde{m}) & \text{if } -\bar{e} \leq \tilde{m} \leq \bar{e} \end{cases} \quad (15)$$

where

$$\bar{a}(\tilde{m}) = \frac{I(\tilde{m}; \tilde{m} - \bar{e}, 1, 1)}{I(\tilde{m}; \tilde{m} - \bar{e}, 1, 0)} \quad (16)$$

$$a(\tilde{m}) = \frac{I(\tilde{m}; \tilde{m} - \bar{e}, \tilde{m} + \bar{e}, 1)}{I(\tilde{m}; \tilde{m} - \bar{e}, \tilde{m} + \bar{e}, 0)} \quad (17)$$

$$\underline{a}(\tilde{m}) = \frac{I(\tilde{m}; 0, \tilde{m} + \bar{e}, 1)}{I(\tilde{m}; 0, \tilde{m} + \bar{e}, 0)} \quad (18)$$

Note that the normalizing constant cancels out when computing the conditional expectation. The cost of the identity message function is given by

$$C[m_{\mathcal{I}}] = \int_{-\bar{e}}^{1+\bar{e}} \int_{q_-(\tilde{m})}^{q_+(\tilde{m})} (q - a(\tilde{m}))^2 f(\tilde{m} - q) dq d\tilde{m}. \quad (19)$$

where  $q_+(\tilde{m}) = \min\{\tilde{m} + \bar{e}, 1\}$  and  $q_-(\tilde{m}) = \max\{\tilde{m} - \bar{e}, 0\}$ . Define

$$\bar{z} = \int_{1-\bar{e}}^{1+\bar{e}} \int_{\tilde{m}-\bar{e}}^1 (q - \bar{a}(\tilde{m}))^2 f(\tilde{m} - q) dq d\tilde{m} \quad (20)$$

$$z = \int_{\bar{e}}^{1-\bar{e}} \int_{\tilde{m}-\bar{e}}^{\tilde{m}+\bar{e}} (q - a(\tilde{m}))^2 f(\tilde{m} - q) dq d\tilde{m} \quad (21)$$

$$\underline{z} = \int_{-\bar{e}}^{\bar{e}} \int_0^{\tilde{m}+\bar{e}} (q - \underline{a}(\tilde{m}))^2 f(\tilde{m} - q) dq d\tilde{m} \quad (22)$$

so that  $C[m_{\mathcal{I}}] = \bar{z} + z + \underline{z}$ .

## 3 Discrete Message

Fix an integer  $M \geq 1$  and define  $K = M \times N$ . Define  $d = \frac{1}{2K}$ . Consider the partition

$$0 = x_0 < x_1 < \cdots < x_K < x_{K+1} = 1 \quad (23)$$

of  $[0, 1]$ . For each  $i \in \{0, \dots, K\}$ , define  $X_i = [x_i, x_{i+1})$ . A discrete message with  $K + 1$  messages is given by

$$m_{\mathcal{D}}(q) = \frac{1}{K} \sum_{i=0}^K \chi_{X_i}(q). \quad (24)$$

Let  $k_+, k_- : [-\bar{e}, 1 + \bar{e}] \rightarrow \{0, \dots, K\}$  be given by

$$k_+(\tilde{m}) = \min\{\lfloor \tilde{m}K \rfloor + M, K\} \quad (25)$$

$$k_-(\tilde{m}) = \max\{0, \lfloor \tilde{m}K \rfloor - M\} \quad (26)$$

Note that

$$q_+(\tilde{m}) = x_{k_+(\tilde{m})} \quad (27)$$

$$q_-(\tilde{m}) = x_{k_-(\tilde{m})} \quad (28)$$

The receiver takes the action

$$a(\tilde{m}) = \frac{I(\tilde{m}; x_j, x_{j+1}, 1)}{I(\tilde{m}; x_j, x_{j+1}, 0)} \quad (29)$$

The cost is given by

$$C[m_{\mathcal{D}}] = \int_{-\bar{e}}^{1+\bar{e}} \left[ \int_{x_{k_-(\tilde{m})}}^{x_{k_+(\tilde{m})}} (q - a(\tilde{m}))^2 f(\tilde{m} - m_{\mathcal{D}}(q)) g(q) dq d\tilde{m} \right]. \quad (30)$$

$$= \int_{-\bar{e}}^{1+\bar{e}} \left[ \sum_{j=k_-(\tilde{m})}^{k_+(\tilde{m})-1} \int_{x_j}^{x_{j+1}} (q - a(\tilde{m}))^2 f\left(\tilde{m} - \frac{j}{K}\right) g(q) dq \right] \tilde{m} \quad (31)$$

$$= \sum_{i=-M}^{M+K-1} \int_{\bar{d}i}^{\bar{d}(1+i)} \left[ \sum_{j=k_-(\tilde{m})}^{k_+(\tilde{m})-1} \int_{x_j}^{x_{j+1}} (q - a(\tilde{m}))^2 f\left(\tilde{m} - \frac{j}{K}\right) g(q) dq d\tilde{m} \right] \quad (32)$$

$$(33)$$

It is sufficient to choose the partition  $x_0, \dots, x_{K+1}$  in Equation 23. The first-order for  $x_j$  is