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Kyoto University
CHARACTERIZATION OF OPERATORS AND REVERBERATION CYCLES
ASSOCIATED WITH A SINGLE NEURON EQUATION

by

Masako Yamaguchi

Introduction

Since E.R.Caianiello [3] proposed a mathematical model of neural behaviors, numerous contributions have been given by himself and his collaborators regarding mathematical properties of the neural equations. Among these contributions the reverberation phenomenon of a neural network has been one of their main concerns. For instance they investigated neural networks whose reverberation cycles are required not to exceed a preassigned maximal length, as shown in Caianiello and others [1]~[9], [11]~[16]. Their main mathematical techniques rely upon matrix algebra.

On the other hand Kitagawa[10] recently started with discussion of dynamical behaviors of all the possible solutions of the neural equation for the case of single neuron. Among others, Kitagawa [10] introduced various special operators and investigated some characteristic features of the dynamics led by each of these operators. This paper is especially connected with detailed discussions of these operators introduced by Kitagawa [10].

In Section 1 we shall give a necessary and sufficient condition for that all the sequences obtained from the solutions of the neural equation (1.1) form a set of mutually disjoint reverberation cycles and show that the neural system satisfying the above condition is equivalent to that under either of two operators \( L_\alpha \) and \( L_\beta \) introduced by Kitagawa [10]. In section 2 we then define a digraph with respect to each of operators which were introduced by Kitagawa[10] in connection with (1.1). Our graph theoretical consideration shows that there exists a set of \( 2(n+1) \) special operators, called an \( \alpha-\omega \) set of operators, in terms of which any operator associated with (1.1) can be represented in a unique way. In Section 3, we deal with reverberation cycles associated with each of these fundamental operators \( L_\alpha \) and \( L_\beta (\alpha = 0, 1, \ldots, n-1) \). We determine the exact number of all the possible reverberation cycles with any admissible length. Here we make use of a combinatorial method appealing to circular partitions. We then proceed to discuss the reverberation phenomena for operators \( L_\alpha \) and \( L_\beta \) as well. It is shown that the number of all the reverberation cycles
can be reduced to those of reverberation cycles under the operators \( L_{\alpha} \) and \( L_{\gamma} \).

§1. Characterization of the operators \( L_{\alpha} \) and \( L_{\gamma} \)

We shall investigate mathematical properties of a single neuron model represented by a nonlinear difference equation which read:

\[
\begin{align*}
\chi(t + 1) &= 1 \left[ \sum_{k=0}^{\infty} a_k \chi(t-k) - \theta \right] \\
\gamma[u] &= \begin{cases} 1 & \text{if } u > 0 \\ 0 & \text{if } u \leq 0 \end{cases}
\end{align*}
\]

where \( \chi(t) \) is the state \((1, 0)\) of a neuron at the time \( t \) in the set \( I \) of indices \((0, \pm 1, \pm 2, \ldots)\), \( a_k \) is the coupling coefficient from the neuron to itself which is effective \( k \) unit times after firing, and \( \theta \) is the threshold value.

In what follows in this paper we assume that all \( a_k (k=0,1,\ldots,n-1) \) and \( \theta \) are constant independently of \( t \). The functional equation (1.1) is regarded a neural equation (NE) due to Caianiello [1] for a single neuron.

In order to investigate state transition phenomena of (1.1), it is convenient to introduce the following \( n \)-dimensional vector as shown in Kitagawa [10]:

\[
\mathbf{S}_t = (S_t^1, S_t^2, \ldots, S_t^{n-1})
\]

where \( S_t^k \equiv \chi(s) \) and \( S_t^k \) denotes the state of our neuron at time \( t \), while \( S_t^k \) is called an \( n \)-state configuration of our neuron at time \( t \). Let us define the inner product \((\mathbf{a}, \mathbf{b})\) by

\[
(\mathbf{a}, \mathbf{b}) = \sum_{k=0}^{n-1} a_k b_k
\]

where \( \mathbf{a} = (a_0, a_1, \ldots, a_{n-1}) \) and a concurrence function by

\[
\mathcal{Z}(\mathbf{S}_t) = (\mathbf{a}, \mathbf{S}_t) - \theta,
\]

which reduces the functional equation (1.1) to

\[
\mathbf{S}_{t+1} = 1[\mathcal{Z}(\mathbf{S}_t)].
\]
In connection with (1.6) Kitagawa [10] introduced the operator \( L \) of n-dimensional vectors defined by

\[
\mathcal{L}(\vec{d}_0, \vec{d}_{-1}, \ldots, \vec{d}_{-n+2}, \vec{d}_{-n+1}) = (\mathcal{L}(\vec{d}_1), \vec{d}_2, \ldots, \vec{d}_{n+2})
\]

The five characteristic features of the functional equation of (1.1) have been pointed out by Kitagawa[10], one of which is the translatability of associated operators. An operator \( L \) defined by (1.7), namely

\[
\mathcal{L}(\vec{d}_t) = (\mathcal{L}(\vec{d}_t), \vec{d}_{t-1}, \ldots, \vec{d}_{t-n+2})
\]

with

\[
\mathcal{L}(\vec{d}_t) = \mathcal{I} [\mathcal{L}(\vec{d}_t)]
\]

is translatable, i.e., commutative with all translations \( T^\alpha \), where \( T^\alpha z(t) \equiv z(t+\alpha) \), in the sense that we have

\[
T^\alpha (\mathcal{L}(\vec{d}_t)) = \mathcal{L}(T^\alpha (\vec{d}_t))
\]

for all \( t \) and \( \alpha \). Because of this translatability property, we may and shall confine our discussion to a transition :

\[
\mathcal{L}(\vec{d}_{n-1}, \ldots, \vec{d}_1, \vec{d}_0) = (\mathcal{L}(\vec{d}_n), \vec{d}_{n-1}, \ldots, \vec{d}_0)
\]

for any \( \vec{d} = (\vec{d}_{n-1}, \ldots, \vec{d}_0) \) in the n-state configuration space \( X_n \), which is defined by

\[
X_n = \{ \vec{d} = (\vec{d}_{n-1}, \ldots, \vec{d}_1, \vec{d}_0) ; \vec{d}_i = 1 \text{ or } 0, i = 0, 1, \ldots, n-1 \}
\]

Now we shall give the following

Definition 1.1. A solution \( x(t) \) of the functional equation (1.1) is said to have a reverberation cycle, abbreviated by RVC, of period \( R \) if the following equality holds:

\[
x(\text{t+R}) = x(t)
\]

for any \( t \in I = \{ 0, 1, 2, \ldots \} \).

Let us define \( \mathcal{L}^t(\vec{d}) \equiv \mathcal{L}(\mathcal{L}^{t-1}(\vec{d})) \) and \( \mathcal{I}^t(\vec{d}) \equiv \vec{d} \).

Lemma 1.1. The equality (1.13) holds if and only if the following equality holds :

\[
\mathcal{L}^t(\vec{d}_t, \vec{d}_{t-1}, \ldots, \vec{d}_{t-n+2}, \vec{d}_{t-n+1}) = (\vec{d}_t, \vec{d}_{t-1}, \ldots, \vec{d}_{t-n+2}, \vec{d}_{t-n+1})
\]

for any \( t \in I \).

Proof. The proof is trivial.

Because of Lemma 1.1, our search for any reverberation cycle is equiva-
lent to that for the solutions of equation (1.7) with the condition (1.14).

For the operator $L$, an immediate observation gives the following

Lemma 1.2. For any assigned $n$-state configuration in $X_n$ the number of state configurations transformed to $\mathcal{S}$ by an application of $L$ is at most two.

In particular, when any assigned $\mathcal{S}$ belongs to some reverberation cycle there is one and only one $\mathcal{S}'$ such that $L(\mathcal{S}') = \mathcal{S}$.

Kitagawa[10] was concerned with the following special operator;

$$(1.15) \quad L_{\mathcal{D}_0} (\mathcal{S}_{n-1}, \ldots, \mathcal{S}_1, \mathcal{S}_0) \equiv (\mathcal{S}_0, \mathcal{S}_{n-1}, \ldots, \mathcal{S}_1)$$

for any state configuration $(\mathcal{S}_{n-1}, \ldots, \mathcal{S}_1, \mathcal{S}_0)$ in $X_n$ and showed that for any state configuration there exists a positive integer $R$ such that equality (1.14) holds, that is, any $n$-state configuration in $X_n$ belongs to some reverberation cycle, under the operator $L_{\mathcal{D}_0}$. Here we shall introduce the another special operator

$$(1.16) \quad L_{\mathcal{S}_0} (\mathcal{S}_{n-1}, \ldots, \mathcal{S}_1, \mathcal{S}_0) \equiv (\mathcal{S}_0, \mathcal{S}_{n-1}, \ldots, \mathcal{S}_1)$$

for any $(\mathcal{S}_{n-1}, \ldots, \mathcal{S}_0)$ in $X_n$.

In connection with these operators $L_{\mathcal{D}_0}$ and $L_{\mathcal{S}_0}$ just introduced, it is important to observe that there exist sets of coupling coefficients $\{a_k\}$ and the threshold value $\theta$ for any of which the operator $L$ associated with the functional equation (1.1) is equivalent to one of these two operators $L_{\mathcal{D}_0}$ and $L_{\mathcal{S}_0}$.

Lemma 1.3. There exist sets of coupling coefficients $\{a_i; i=0, 1, \ldots, n-1\}$ and the threshold value $\theta$ such that (i) $L(\mathcal{S}) = \mathcal{S}_0$ for any $\mathcal{S} = (\mathcal{S}_{n-1}, \ldots, \mathcal{S}_0)$ in $X_n$ or (ii) $L(\mathcal{S}) = \mathcal{S}_0$ for any $\mathcal{S} = (\mathcal{S}_{n-1}, \ldots, \mathcal{S}_0)$ in $X_n$.

Proof. The case (i). For any $\mathcal{S} = (\mathcal{S}_{n-1}, \ldots, \mathcal{S}_0)$ in $X_n$, let us assume $L(\mathcal{S}) = \mathcal{S}_0$ which holds if and only if the following inequalities hold:

$$(1.17) \quad a_{n-1} + \sum_{j=1}^{n-1} a_j \theta = 0$$

$$(1.18) \quad \sum_{j=1}^{n-1} a_j \theta - \theta > 0$$

for any set $(i_1, i_2, \ldots, i_h), 0 \leq h \leq n-1$, such that $0 \leq i_1 < i_2 < i_h \leq n-2$.

For any fixed $a_1, i=0, 1, 2, \ldots, n-2$, let us put

$$(1.19) \quad A^{(i)} \equiv \sum_{a_i \geq 0} a_i$$
(1.20) \[ A^{(\gamma)} = \sum_{a_i<o} A_i \quad i=0,1,\ldots,n-1 \]

It is trivial that (1.17) and (1.18) for \( a_{n-1} \) and \( \theta \) hold true if

\[ a_{n-1} + A^{(\gamma)} \equiv \theta < A^{(\gamma)}. \]

The case (ii). This is quite similar to the case (i).

Under each of these operators \( L_{\bar{x}} \) and \( L_{\bar{x}} \), any solution of (1.1) is dependent on the sole state \( \bar{z}_{(n-1)} \) exactly \( n \) step before the time \( t \).

Now we shall prove the following

Theorem 1.1. The necessary and sufficient condition for that any \( n \)-state configuration \( \bar{z} = (\bar{z}_{n-1}, \ldots, \bar{z}_0) \) in \( X_n \) belongs to some reverberation cycle is that

\[ L = L_{\bar{x}} \quad \text{or} \quad L_{\bar{x}} \], that is, \( 1[z(\bar{z})] = \bar{z}_0 \quad \text{or} \quad \bar{z}_0. \]

Proof. (1) Necessity. For any \( \bar{z} = (\bar{z}_{n-1}, \ldots, \bar{z}_0) \), let us put

(1) \[ \bar{z}^{(0)} = (\bar{z}_{n-1}, \ldots, \bar{z}_1, 0) = (\bar{z}, 0), \]

(1) \[ \bar{z}^{(0)} = (\bar{z}_{n-1}, \ldots, \bar{z}_1, 1) = (\bar{z}, 1), \]

(1.22)

(iii) \[ \min_{\bar{z} \in X_{n-1}} Z(\bar{z}^{(0)}) \equiv \ell \]

(iv) \[ \max_{\bar{z} \in X_{n-1}} Z(\bar{z}^{(0)}) \equiv u. \]

Now it is evident that the following three cases exhaust all the possibilities:

Case 1. \( \ell > 0 \)

Case 2. \( u \leq 0 \)

Case 3. \( \ell \leq 0 < u \).

Case 1. In this case, for any \( \bar{z} = (\bar{z}_{n-1}, \ldots, \bar{z}_0) \) \( Z(\bar{z}^{(0)}) \), and hence we have

\[ \ell \leq Z(\bar{z}^{(0)}) \]

(1.23)
which implies
\[(1.24) \quad 1 \left[ \mathcal{I} \left( \mathcal{D}^{(0)} \right) \right] = 0, \]
because \( l[z(\mathcal{D}^{(0)})] = 1 \), i.e., \( L(\mathcal{D}^{(0)}) = L(\mathcal{D}^{(0)}) \), contradicts Lemma 1.2.

From (1.23) and (1.24), we have \( L(\mathcal{D}^{(0)}, \cdots, \mathcal{D}^{(0)}_i, \mathcal{D}^{(0)}_0) = (\mathcal{D}^{(0)}_0, \mathcal{D}^{(0)}_{n-1}, \cdots, \mathcal{D}^{(0)}_i) \)
for any \( \mathcal{D} = (\mathcal{D}^{(0)}_{n-1}, \cdots, \mathcal{D}^{(0)}_i, \mathcal{D}^{(0)}_0) \) in \( X_n \), which means that \( L \) is equivalent to the operator \( L_{\mathcal{D}^{(0)}_0} \).

Case 2. In this case for any \( \widehat{\mathcal{D}} = (\mathcal{D}^{(0)}_{n-1}, \cdots, \mathcal{D}^{(0)}_i) \), \( z(\mathcal{D}^{(0)}) \leq 0 \), and hence we have
\[(1.25) \quad 1 \left[ \mathcal{I} \left( \mathcal{D}^{(0)} \right) \right] = 0, \]
which implies, in view of Lemma 1.2,
\[(1.26) \quad 1 \left[ \mathcal{I} \left( \mathcal{D}^{(0)} \right) \right] = 1 \]
as in Case 1.

From (1.25) and (1.26), we have \( L(\mathcal{D}^{(0)}_{n-1}, \cdots, \mathcal{D}^{(0)}_i, \mathcal{D}^{(0)}_0) = (\mathcal{D}^{(0)}_0, \mathcal{D}^{(0)}_{n-1}, \cdots, \mathcal{D}^{(0)}_i) \) for any \( \mathcal{D} = (\mathcal{D}^{(0)}_{n-1}, \cdots, \mathcal{D}^{(0)}_i, \mathcal{D}^{(0)}_0) \) in \( X_n \), which implies that \( L \) is equivalent to the operator \( L_{\mathcal{D}^{(0)}_0} \).

Case 3. Now let us introduce an \((n-1)\)-state configuration
\[(1.27) \quad \mathcal{D}^{(c)} = (\mathcal{D}^{(c)}_{n-1}, \cdots, \mathcal{D}^{(c)}_i), \]
where
\[(1.28) \quad \mathcal{D}^{(c)}_j = \begin{cases} 1 & \text{if } \alpha_j < 0 \\ 0 & \text{if } \alpha_j \geq 0 \end{cases} \quad j = 1, 2, \cdots, n-1, \]
and another one
\[(1.29) \quad \mathcal{D}^{(r)} = (\mathcal{D}^{(r)}_{n-1}, \cdots, \mathcal{D}^{(r)}_i), \]
where
\[(1.30) \quad \mathcal{D}^{(r)}_j = \begin{cases} 1 & \text{if } \alpha_j > 0 \\ 0 & \text{if } \alpha_j \leq 0 \end{cases} \quad j = 1, 2, \cdots, n-1. \]

Then it is clear that
\[(1.31) \quad \mathcal{L} = \mathcal{I} \left( \mathcal{D}^{(c)} \right), \]
\[(1.32) \quad \mathcal{U} = \mathcal{I} \left( \mathcal{D}^{(r)} \right). \]

Now we shall prove that the Case 3 does not occur by ad absurdum.

Let \( \mathcal{L} \neq 0 \). Then it follows that
\[(1.33) \quad 1 \left[ \mathcal{I} \left( \mathcal{D}^{(c)} \right) \right] = 0 \]
which implies, in view of Lemma 1.2,
\[(1.34) \quad 1 \left[ \mathcal{I} \left( \mathcal{D}^{(c)} \right) \right] = 1, \]
which is equivalent to
\[ (1.35) \quad \mathcal{Z}((\widehat{\mathcal{Q}}^{-}, 0)) > 0. \]
From (1.33) and (1.35) we have
\[ (1.36) \quad \mathcal{Z}((\widehat{\mathcal{Q}}^{-}, I)) - \mathcal{Z}((\widehat{\mathcal{Q}}^{-}, 0)) = \alpha_{m-j} < 0. \]

On the other hand let \( u > 0 \). Then it follows that
\[ (1.37) \quad \mathcal{Z}((\widehat{\mathcal{Q}}^{+}, I)) = 1, \]
which implies, in view of Lemma 1.2.
\[ (1.38) \quad \mathcal{Z}((\widehat{\mathcal{Q}}^{+}, 0)) = 0, \]
which is equivalent to
\[ (1.39) \quad \mathcal{Z}((\widehat{\mathcal{Q}}^{+}, 0)) \leq 0. \]
From (1.37) and (1.39) we have
\[ (1.40) \quad \mathcal{Z}((\widehat{\mathcal{Q}}^{+}, I)) - \mathcal{Z}((\widehat{\mathcal{Q}}^{+}, 0)) = \alpha_{m-j} > 0. \]
But (1.36) and (1.40) are mutually contradictory, showing that the Case 3 does not exist.

(2) Sufficiency. This is trivial, because, for any \( \mathcal{Q} \) in \( X_{n} \) we have
\[ (1.41) \quad L_{\mathcal{Q}_{e}}^{2n} (\mathcal{Q}) = \mathcal{Q}, \]
\[ (1.42) \quad L_{\mathcal{Q}_{e}}^{n} (\mathcal{Q}) = \mathcal{Q}, \]
which show that any \( \mathcal{Q} \) in \( X_{n} \) belongs to some RVC of at most length \( 2n \) and respectively under successive applications of \( L_{\mathcal{Q}_{e}}^{2} \) and those of \( L_{\mathcal{Q}_{e}}^{n} \), respectively. q.e.d.

Our Lemma 1.3 and Theorem 1.1 give us a characteristic of \( L_{\mathcal{Q}_{e}}^{2} \) and \( L_{\mathcal{Q}_{e}}^{n} \) in the realm of functional operators defined by (1.11).

§2. Graphical representation of the operator \( L \)

In this Section a digraph \( G_{L} \) is defined for each operator \( L \) introduced by (1.11), and we shall represent \( G_{L} \) in terms of a set of specific operators which includes \( L_{\mathcal{Q}_{e}}^{2} \) and \( L_{\mathcal{Q}_{e}}^{n} \) as its members.

Definition 2.1. A digraph \( G = (X_{n}, \Gamma) \) is called to be a digraph with respect to the operator \( L \) when the set of arcs is given by
\[ \Gamma = \{ (\mathcal{Q}, \mathcal{Q}) \mid \mathcal{Q} \in X_{n} \}. \]
In this case we denote the digraph by \( G_{L} = (X_{n}, \Gamma_{L}) \).

Let us define the following operations between two digraphs:

Définition 2.2. For any two digraphs \( G = (X, \Gamma) \) and \( G' = (X, \Gamma') \),
\[ (2.1) \quad G + G' = (X, \Gamma \cup \Gamma'), \]
\[ (2.2) \quad G.G = (X, \Gamma \cap \Gamma'). \]

Definition 2.3. The total number of arcs in a digraph \( (X_{n}, \Gamma) \)
which starts from an assigned $\mathcal{F}$ in $X_n$ is called to be the outdegree of $\mathcal{F}$ in the digraph $(X_n, \Gamma)$. 

Definition 2.4. The number of arcs in a digraph $(X_n, \Gamma)$ which comes to an assigned $\mathcal{F}$ in $X_n$ is called to be the indegree of $\mathcal{F}$ in the digraph $(X_n, \Gamma)$. 

From the definition of $\Gamma_L$ and Lemma 1.2 we have immediately the following.

Corollary 2.1. For a digraph $G_L = (X_n, \Gamma_L)$ w.r.t. an operator $L$, we have

\begin{align}
(2.3) \quad \text{outdegree of } \mathcal{F} &= 1 \\
(2.4) \quad \text{indegree of } \mathcal{F} &\leq 2,
\end{align}

for any $\mathcal{F} \in X_n$. In particular any $\mathcal{F}$ belongs to some reverberation cycle if and only if indegree of $\mathcal{F} = 1$.

Definition 2.5. A digraph $G = (X_n, \Gamma)$ is called to be $\mathcal{L}$-complete if, any $\mathcal{F} = (\mathcal{F}_{n-1}, \cdots, \mathcal{F}, \mathcal{F}_0)$ contains two arcs $(\mathcal{F}, (\mathcal{F}_{n-1}, \cdots, \mathcal{F}))$ and $(\mathcal{F}, (\mathcal{F}_{n-1}, \cdots, \mathcal{F}))$.

Definition 2.6. A digraph $G = (X_n, \Gamma)$ is called to be $\mathcal{L}$-complement to a digraph $G_L = (X_n, \Gamma_L)$ w.r.t. an operator $L$ if $G + G_L$ is $\mathcal{L}$-complete, denoted by $G = G_L^\perp$.

Lemma 2.1. For any operator $L$, there exists one and only one operator $L$ such that a digraph $G_L^\perp$ w.r.t. the operator $\overline{L}$ is an $\mathcal{L}$-complement to the digraph $G_L$ w.r.t. the operator $L$.

Proof. For any operator $L$ there exist the set \{ $a_i$ : $i = 0, 1, \ldots, n-1$ \} of coupling coefficients and threshold value $\theta$ corresponding to the operator $L$. Because of density of the set of real numbers, we may and we shall confine the set \{ $a_i$ : $i = 0, 1, \ldots, n-1$ \} and $\theta$ such that exact inequalities hold

\begin{align}
(2.5) \quad \mathbb{E}(\mathcal{F}; \mathcal{A}, \theta) = \begin{cases} 
1 & \text{if } \mathbb{E}(\mathcal{F}; \mathcal{A}, \theta) > 0 \\
0 & \text{if } \mathbb{E}(\mathcal{F}; \mathcal{A}, \theta) < 0,
\end{cases}
\end{align}

where $\mathbb{E}(\mathcal{F}; \mathcal{A}, \theta) = (\mathcal{A}, \mathcal{F}) - \theta$ for $\mathcal{A} = (a_0, a_1, \ldots, a_n)$ and any $\mathcal{F}$ in $X_n$.

Now let us introduce the operator $L$ corresponding to the set \{ $\mathcal{J}_i$ : $i = 0, 1, \ldots, n-1$ \} and threshold value $\overline{\theta}$, where $\overline{a}_i = -a_i$ for $i = 0, 1, \ldots, n-1$ and $\overline{\theta} = -\theta$. Then for any $\mathcal{F}$ in $X_n$

\begin{align}
(2.6) \quad \mathbb{E}(\mathcal{F}; \mathcal{A}, \overline{\theta}) \geq 0 \quad \text{if and only if} \quad \mathbb{E}(\mathcal{F}; \mathcal{A}, \overline{\theta}) \leq 0 \quad \text{where} \quad \mathcal{A} = (\overline{a}_0, \overline{a}_1, \ldots, \overline{a}_{n-1}).
\end{align}

(2.6) is equivalent to say that, for any $\mathcal{F}$.
(2.7) \[ \mathcal{L} \left( J_{n-1}, \ldots, J_1, J_0 \right) = (J_1, J_{n-1}, \ldots, J_n) \]
implies and is implied by
(2.8) \[ \mathcal{L} \left( J_{n-1}, \ldots, J_1, J_0 \right) = (J_1, J_{n-1}, \ldots, J_n) \]
This means that \( G_L \) is \( \mathcal{L} \)-complete, this is to say, \( G_L \) is \( \mathcal{L} \)-complement

to \( G_L \). The uniqueness of the operator \( L \) is trivial. q.e.d.

Lemma 2.2. For any operator \( L \), we have the equation
(2.9) \[ G^* \cdot G_L = G_L \cdot G^* = G_L, \]
(2.10) \[ G^* + G_L = G_L + G^* = G_L \]
where \( G^* \) is the \( \mathcal{L} \)-complete digraph.

Proof. This is evident from the definition of \( G^* \).

Now let us consider a system of operators consisting of \( \{ L_{\omega} \}, \{ L_{\omega} \} \)
\((\omega = 0, 1, \ldots, n-1)\), \( L_{\omega} \) and \( L_{\omega} \) which are introduced in Kitagawa [10] and
defined in the following way:
(2.11) \[ L_{\omega} \left( J_{n-1}, \ldots, J_1, J_0 \right) \equiv (J_{n-1}, \ldots, J_1, J_0) \quad \eta = 0, 1, \ldots, n-1 \]
(2.12) \[ L_{\omega} \left( J_{n-1}, \ldots, J_1, J_0 \right) \equiv (J_{n-1}, \ldots, J_1, J_0) \quad \eta = 0, 1, \ldots, n-1 \]
(2.13) \[ L_{\omega} \left( J_{n-1}, \ldots, J_1, J_0 \right) \equiv (\omega, J_{n-1}, \ldots, J_1, J_0) \]
(2.14) \[ L_{\omega} \left( J_{n-1}, \ldots, J_1, J_0 \right) \equiv (1, J_{n-1}, \ldots, J_1, J_0), \]
for any \( J_{n-1}, \ldots, J_1, J_0 \) in \( X_n \). The set of all these operators is called
to be the \( \mathcal{L} \)-\( \omega \) set of operators in \( X_n \).

Similarly as in Lemma 1.3 we obtain

Lemma 2.3. There exist the sets of coupling coefficients \( \{ d_{\omega} \} \quad \eta = 0, 1, \ldots, n-1 \)
and threshold value \( \phi \) corresponding to each of the operators
defined by (2.11), (2.12), (2.13) and (2.14), respectively.

Lemma 2.4. We have the equations
(2.15) \[ G_{L_{\omega}} + G_{L_{\omega}} = G^* \]
(2.16) \[ G_{L_{\omega}} + G_{L_{\omega}} = G^* \]
for \( \omega = 0, 1, \ldots, n-1 \), where \( G^* \) is the \( \mathcal{L} \)-complete digraph.

Proof. This is evident from the definition of each operators.

From Lemma 2.4, we have immediately the following

Corollary 2.2. We have relations
(2.17) \[ G_{L_{\omega}} = G_{L_{\omega}} \]
(2.18) \[ G_{L_{\omega}} = G_{L_{\omega}} \]
for $\mathcal{L} = 0,1, \ldots, n-1$.

Corollary 2.3. We have relations

(2.19) $G_{\mathcal{L}_2} \cdot G_{\mathcal{L}_2} = G_{\mathcal{L}}$

(2.20) $G_{\mathcal{L}_\mathcal{L}} \cdot G_{\mathcal{L}_\mathcal{L}} = G_{\mathcal{L}}$

for $\mathcal{L} = 0,1, \ldots, n-1$, where $G_{\mathcal{L}}$ denote a special digraph when the set of arcs reduced to an empty set $\mathcal{L}$.

Any operator $L$ defines and is defined by $\mathcal{L}$ such that $I[L(\mathcal{L})] = \mathcal{L}$ because we have

(2.21) $\mathcal{L}(\mathcal{L}) = (1[2(\mathcal{L})], \mathcal{L}_2, \ldots, \mathcal{L}_i) = (L, L_{n-1}, \ldots, L_0)$.

This fact makes us possible to introduce the notion

(2.22) $(\mathcal{L}_1; \mathcal{L}_2) \in \mathcal{L}$.

Now a representation of any operator $L$ in $X_n$ on the basis the set of operators by the help of the notion (2.22) is given by the following

Theorem 2.1. A digraph $G_L$ w.r.t. any assigned operator $L$ in $X_n$ is represented by

(2.23) $G_L = \sum_{(\mathcal{L}_1; \mathcal{L}_2) \in \mathcal{L}} \sum_{j=0}^{m} \mathcal{G}(\mathcal{L}_1, \mathcal{L}_2)^{j} \mathcal{G}(\mathcal{L}_3, \mathcal{L}_4)$

where digraphs $\mathcal{G}(\mathcal{L}_1, \mathcal{L}_2)$ and $\mathcal{G}(\mathcal{L}_3, \mathcal{L}_4)$ are defined by

(2.24) $\mathcal{G}(\mathcal{L}_1, \mathcal{L}_2) = \begin{cases} G_{\mathcal{L}_1} \mathcal{L}_2 & \text{if } \mathcal{L}_1 = \mathcal{L}_2 \\ G_{\mathcal{L}_1} \mathcal{L}_2^{-1} & \text{if } \mathcal{L}_1 = \mathcal{L}_2^{-1} \\ G_{\mathcal{L}_1} \mathcal{L}_2 & \text{if } \mathcal{L}_1 = \mathcal{L}_2 \\ G_{\mathcal{L}_1} \mathcal{L}_2^{-1} & \text{if } \mathcal{L}_1 = \mathcal{L}_2^{-1} \end{cases}$

(2.25) $\mathcal{G}(\mathcal{L}) = \begin{cases} G_{\mathcal{L}_1} \mathcal{L}_2 & \text{if } \mathcal{L} = \mathcal{L}_1 \\ G_{\mathcal{L}_1} \mathcal{L}_2^{-1} & \text{if } \mathcal{L} = \mathcal{L}_1^{-1} \\ G_{\mathcal{L}_1} \mathcal{L}_2 & \text{if } \mathcal{L} = 0 \\ G_{\mathcal{L}_1} \mathcal{L}_2^{-1} & \text{if } \mathcal{L} = 0 \end{cases}$

Proof. Let us denote any arc in digraph $G_L$ by

(2.26) $((\mathcal{L}_{n-1}, \ldots, \mathcal{L}_1; \mathcal{L}_2), (\mathcal{L}_1, \mathcal{L}_{n-1}, \ldots, \mathcal{L}_1)) = (\mathcal{L}, \mathcal{L}')$

which implies and is implied by $(\mathcal{L}_1; \mathcal{L}_2) \in \mathcal{L}$. By the definitions of the digraphs $\mathcal{G}(\mathcal{L}_1; \mathcal{L}_2)$ and $\mathcal{G}(\mathcal{L}_1; \mathcal{L}_2)$, we have

(2.27) $(\mathcal{L}_1, \mathcal{L}_2) \in \mathcal{G}(\mathcal{L}_1; \mathcal{L}_2)$

for $\mathcal{L} = 0,1, \ldots, n-1$, and also

(2.28) $(\mathcal{L}_1, \mathcal{L}_2) \in \mathcal{G}(\mathcal{L}_1; \mathcal{L}_2)$

which give us
\[(2.29) \quad (\delta, \delta') \in \mathcal{G}(\delta) \prod_{\ell=0}^{n-1} \mathcal{G}(\delta, \delta_{\ell}). \]

Hence we have
\[(2.30) \quad \mathcal{G}_{n} \subseteq \sum_{(\delta, \delta') \in \mathcal{L}} \mathcal{G}(\delta) \prod_{\ell=0}^{n-1} \mathcal{G}(\delta, \delta_{\ell}). \]
\[\delta = (\delta_{n-1}, \ldots, \delta_{0}) \in X^{n}_{\mathcal{L}}.\]

On the other hand, for any \((\delta, \delta') \in \mathcal{L}\) we have
\[(2.31) \quad \mathcal{G}(\delta) \prod_{\ell=0}^{n-1} \mathcal{G}(\delta, \delta_{\ell}) = ((\delta_{n-1}, \ldots, \delta_{0}, \delta'_{0}), (\delta, \delta_{n-1}, \ldots, \delta'_{0}))\]
where \(\delta = (\delta_{n-1}, \ldots, \delta_{0})\), because the set of arcs in the digraphs defined by
\[(2.32) \quad \prod_{\ell=0}^{n-1} \mathcal{G}(\delta, \delta_{\ell})\]
consists of two arcs
\[(2.33) \quad ((\delta_{n-1}, \ldots, \delta_{0}, \delta'_{0}), (\delta, \delta_{n-1}, \ldots, \delta'_{0}))\]
\[(2.34) \quad ((\delta_{n-1}, \ldots, \delta_{0}, \delta'_{0}), (\delta, \delta_{n-1}, \ldots, \delta'_{0}))\]
to which the multiplication of digraph \(\mathcal{G}(\delta')\) leads to \((2.31)\).

Equation \((2.30)\) together with \((2.31)\) gives us \((2.23)\), as we were to prove. q.e.d.
§3. The number of reverberation cycles

In this Section we shall deal with the $d$-set of operators defined in Section 2 and obtain the number of all reverberation cycles with possible length.

We shall define a notion of a circular partition for any positive integer. The total number of circular partitions $\mathcal{I}$ is then given by virtue of the number of ordered partitions each of which is usually called composition after P.A. Macmahon. So far as our enumerations of reverberation cycles are concerned, the advantage of the notion of circular of partitions is that it makes us possible to introduce the notion of equivalent classes in the set of all ordered partitions.

A partition of a positive integer $n$ is a represented by a sum of positive integers as follows:

$$ n = t_1 + t_2 + \cdots + t_k, $$

where $t_i \geq 1$, $1 \leq i \leq k$, for $k = 1, 2, \ldots, n$, Eq. (3.1) is called a $k$-partition of $n$ and denoted by $(t_1, t_2, \ldots, t_k)$. An ordered $k$-partition is called by $k$-ordered partition. It is conventional to abbreviate repeated parts, by use of exponents; for example, 6-ordered partition $(2, 3, 2, 3, 2, 3)$ of $n=15$ is written $(2, 3)^3$. A special permutation $\sigma$ of $(t_1, t_2, \ldots, t_k)$ is defined by

$$ \sigma(t_1, t_2, \cdots, t_k) = (t_{k}, t_1, t_2, \cdots, t_{k-1}) $$

and let us put

$$\sigma^j(t_1, t_2, \cdots, t_k) = \sigma(\sigma^{j-1}(t_1, t_2, \cdots, t_k))$$

$$\sigma^0(t_1, t_2, \cdots, t_k) = (t_1, t_2, \cdots, t_k)$$

for $j \geq 1$.

Definition 3.1. Two $k$-ordered partitions, $(t_1, t_2, \ldots, t_k)$ and $(s_1, s_2, \ldots, s_k)$, of $n$ are called to be equivalent if there exists a positive integer $j$ ($1 \leq j \leq k$) such that

$$\sigma^j(t_1, t_2, \cdots, t_k) = (s_1, s_2, \cdots, s_k).$$

Let us denote by $P^k_n$ the set of all the possible $k$-ordered partitions of $n$ and by $C^k_n$ the set of all the possible equivalent classes of $P^k_n$, each element of which is called a $k$-circular partitions of $n$. The equivalent class containing the $k$-ordered partition $(t_1, t_2, \ldots, t_k)$ is denoted by $E(t_1, \ldots, t_k)$. **
In what follows we shall denote by \# A the number of all the elements belonging to a set A.

Lemma 3.1. For any k-ordered partition \((t_1, t_2, \ldots, t_k)\) of n, for which \# \(E_{\binom{t_1}{t_2}, \ldots, t_k} = j\) holds, there is a positive \(d\) for which we have

\[
\begin{aligned}
(1) & \quad \binom{t_1}{t_2, \ldots, t_k} = (t_1, t_2, \ldots, t_d) d, \quad \text{with } d_j = k, \\
(2) & \quad \# E_{(t_1, t_2, \ldots, t_d)} = j, \\
(3) & \quad d \text{ is a divisor of g.c.m. of } n \text{ and } k, \text{ denoted by } d \mid (n, k).
\end{aligned}
\]

Proof. Because of \(\binom{t_1}{t_2, \ldots, t_k} = (t_1, t_2, \ldots, t_k)\), we have

\[
\binom{t_1}{t_2, \ldots, t_k} \leq \frac{n}{k} \leq k.
\]

It is evident that (3.6) is valid for \(j = 1\) or \(k\). Now let us assume that \(1 < j < k\). This implies that there exists a uniquely determined positive integer \(h = \frac{k}{j} \leq k\) such that

\[
\begin{aligned}
(3.8) & \quad \binom{t_1}{t_2, \ldots, t_k} = (t_1, t_2, \ldots, t_k) \\
(3.9) & \quad \binom{t_1}{t_2, \ldots, t_k} = (t_1, t_2, \ldots, t_k) \quad \text{for } i = 1, 2, \ldots, h - 1.
\end{aligned}
\]

It is clear that \(h\) is a divisor of \(k\), because the equation

\[
(3.10) \quad \binom{t_1}{t_2, \ldots, t_k} = \binom{t_1}{t_2, \ldots, t_k}
\]

with \(k = sh + r\), for \(0 \leq r < h - 1\), gives us \(r = 0\). Hence any k-ordered partition of \(E_{(t_1, t_2, \ldots, t_k)}\) can be written as follows:

\[
(3.11) \quad \binom{t_1}{t_2, \ldots, t_k} = \binom{t_1, t_2, \ldots, t_k}
\]

for \(p = 0, 1, \ldots, k / d\) and \(i = 0, 1, \ldots, h - 1\), which implies \(h = j\). In consequence we have

\[
(3.12) \quad \binom{t_1}{t_2, \ldots, t_k} = (t_1, t_2, \ldots, t_j) d
\]

with \(dj = k\). The equality \(d \sum_{i=1}^{j} t_i = n\) gives us \(d \mid n\) which implies, in view of \(dj = k\), \(d \mid (n, k)\). q.e.d.

Let us put

\[
(3.13) \quad \binom{t_1}{t_2, \ldots, t_k} = \# \binom{t_1}{t_2, \ldots, t_k} = (t_1, t_2, \ldots, t_k) \quad \text{for } d_j = k.
\]

We shall give the following

Lemma 3.2. For any positive integer \(n\) and \(k\), \(1 \leq \frac{k}{n} \leq n\), we have

\[
(3.14) \quad \sum_{j=1}^{k} \binom{t_1}{t_2, \ldots, t_k} = \binom{j}{k - j}.
\]

Proof. It is trivial that for any positive integer \(n\) and \(k\), \(1 \leq \frac{k}{n} \leq n\),
we have

\[ \# P_{n,k} = \left( \frac{n-1}{k-1} \right). \]

On the other hand, we have, from Lemma 3.1,

\[ \# P_{n,k} = \sum_{d \mid (n,k)} \# \left\{ (t_1, \ldots, t_k) : (t_1, \ldots, t_k) \in P_{n,k}, \# E(t_1, \ldots, t_k) = \frac{k}{d} \right\} \]

and

\[ \# \left\{ (t_1, \ldots, t_k) : (t_1, \ldots, t_k) \in P_{n,k}, \# E(t_1, \ldots, t_k) = \frac{k}{d} \right\} = \sum_{d \mid (n,k)} \Psi \left( \frac{n}{d}, \frac{k}{d} \right) \]

for any \( d \mid (n,k) \).

From (3.16) and (3.17), we have

\[ \# P_{n,k} = \sum_{d \mid (n,k)} \Psi \left( \frac{n}{d}, \frac{k}{d} \right), \]

which gives us the equality (3.14), because of (3.15). q.e.d.

From Lemma 3.2, we have immediately the total number of \( k \)-circular partitions of \( n \) in the following:

Lemma 3.3. For any positive integer \( n \) and \( k, 1 \leq k \leq n \), we have

\[ \# C_{n,k} = \sum_{d \mid (n,k)} \Psi \left( \frac{n}{d}, \frac{k}{d} \right). \]

At this stage it is useful to appeal to the special property of the famous Möbius function which is defined

\[ \mu(d) = \begin{cases} 1 & \text{if } d = 1, \\ 0 & \text{if } d \text{ is not square-free}, \\ (-1)^v & \text{if } d \text{ is a product of } v \text{ distinct prime numbers}, \end{cases} \]

for any positive integer \( d \). In fact we observe, as in the classical use of the Möbius function, the following theorem.

Theorem 3.1. For any positive integer \( n \) and \( k, 1 \leq k \leq n \), we have the equality

\[ \Psi (n,k) = \sum_{d \mid (n,k)} \mu(d) \left( \frac{n}{d} - 1 \right). \]

Now we shall first give the number of reverberation cycles with all the possible lengths under each of two operators \( \mathcal{L}_0 ^\sigma \) and \( \mathcal{L}_0 ^\zeta \), by using the results given above. First of all we shall explain the correspondence between state configuration(s) and an ordered partition. As a conventional notation of any \( n \)-state configuration \( \mathcal{C} = (\mathcal{L}_0 ^{\sigma_0}, \ldots, \mathcal{L}_0 ^{\zeta_0}) \) we abbreviate the same consecutive states in its composition, by use of exponents; for example, a 6-state configuration \((1,1,1,0,0,1)\) is written by \((1^3, 0^2, 1^1)\). In this way any \( n \)-state con-
figuration $\delta$ can be written

$$\delta = (\delta^t_1, \delta^t_2, \ldots, \delta^t_{k-1}, \delta^t_k) \quad \text{for } k = \text{even}$$

or

$$\delta = (\delta^t_1, \delta^t_2, \ldots, \delta^t_{k-1}, \delta^t_k) \quad \text{for } k = \text{odd},$$

where $\delta = 1 \in C$, $\bar{\delta} = \delta$, $t_i = n$ and $t_i \geq 1$ for $i = 1, 2, \ldots, k$. Now the k-dimensional vector $(t_1, t_2, \ldots, t_k)$ defined just now forms a k-ordered partition of $n$ and is uniquely determined for each assigned n-state configuration. Such a k-dimensional vector is called to be a k-ordered partition associated with n-state configuration. It is evident that for any k-ordered partition $(t_1, t_2, \ldots, t_k)$ there exist exactly two n-state configurations with each of which the partition $(t_1, t_2, \ldots, t_k)$ is associated, and these two state configurations are mutually conjugate.

In what follows we denote by $R_n(k)$ the number of reverberation cycles with length $R$ under the operator $L$ defined in state configuration space $X_n$.

3.1. The operator $L_{\delta}$

In this subsection we shall define our discussion to the operator $L_{\delta}$.

Under the operator $L_{\delta}$ we have immediately the following

Corollary 3.1. For any n-state configuration $\delta$ in $X_n$, a reverberation cycle containing $\delta$ includes also its conjugate n-state configuration $\bar{\delta}$ in $X_n$.

Lemma 3.4. For any assigned reverberation cycle there exists an odd integer $k$ uniquely determined such that (i) there exists k-ordered partition $(t_1, t_2, \ldots, t_k)$ associated with some n-state configuration in the reverberation cycle, (ii) the set of all the ordered partitions associated with n-state configurations in the reverberation cycle consists of the set $E(t_1, t_2, \ldots, t_k)$, where $E(t_1, t_2, \ldots, t_k)$ denotes the equivalent class of k-ordered partitions containing the ordered partition $(t_1, t_2, \ldots, t_k)$ given (i) and the set of $(k+1)$-ordered partitions.

Proof. For any reverberation cycle, we may we shall note that there exists some n-state configuration $\delta$ which associates with a k-ordered partition of $n$, denoted by $(t_1, t_2, \ldots, t_k)$, with an odd integer $k$. This is due to the fact that in general, for any even integer $\ell$ and any n-state configuration $\delta = (\delta^s_1, \delta^s_2, \ldots, \delta^s_{\ell-1})$, $\delta^s_\ell = 1$ or 0, n-state configuration $L_{\delta} \delta$ associated with $(\ell-1)$-ordered partition $(s_1, s_2, \ldots, s_{\ell-1})$.

In connection with $(t_1, t_2, \ldots, t_k)$, let us divide the set of 2n integers $I = \{1, 2, \ldots, 2n\}$ into the mutually disjoint sets.
(3.24) \[ I^{(o)} = \{ i \mid i = \sum_{j=1}^{k} t_j, \sum_{j=1}^{k} t_j + n, \; \alpha = 1, 2, \ldots, k \} \]
and
(3.25) \[ I^{(a)} = \{ i \mid i \in I, \; i \notin I^{(o)} \} \].

Since the set of all the n-state configurations belonging to the reverberation cycle is written by \( \{ L_{\lambda}^{i}(d) ; i \in I \} \), in view of the definition of the operator \( L_{\lambda} \), the set of all the ordered partitions associated with each state configuration in \( \{ L_{\lambda}^{i}(d) ; i \in I^{(a)} \} \) is equal to the set \( E(t_1, t_2, \ldots, t_k) \), while any n-state configuration in \( \{ L_{\lambda}^{i}(d) ; i \in I^{(a)} \} \) associates with a \((k+1)\)-ordered partition of \( n \). q.e.d.

The converse assertion of Lemma 3.4 is given by the following

**Lemma 3.5.** For any odd integer \( k \) and any equivalent class \( E(t_1, t_2, \ldots, t_k) \), there exists an reverberation cycle uniquely determined which has an n-state configuration, associating with the \( k \)-ordered partition \((t_1, t_2, \ldots, t_k)\).

**Proof.** The set of the n-state configurations in \( X_n \), with each of which \( k \)-ordered partition \((t_1, t_2, \ldots, t_k)\) is associated, consists of the following two state configurations.

(3.26) \[ (1^{t_1}, 0^{t_2}, \ldots, 0^{t_{k-1}}, 1^{t_k}) \]
and
(3.27) \[ (0^{t_1}, 1^{t_2}, \ldots, 1^{t_{k-1}}, 0^{t_k}) \].

On the other hand, in view of Corollary 3.1, these two n-state configurations belong to the same reverberation cycle, which implies, by Lemma 3.4, that for any assigned equivalent class \( E(t_1, t_2, \ldots, t_k) \) with an odd integer \( k \) there exists one and only one reverberation cycle. q.e.d.

Now the length of a RVC is defined by the number of all the different n-state configurations belonging to the RVC. We observe

**Lemma 3.6.** For any odd integer \( k \) and any \( k \)-ordered partition \((t_1, t_2, \ldots, t_k)\) of \( n \), for which \# \( E(t_1, t_2, \ldots, t_k) = j \) holds, the length of reverberation cycle corresponding to \( E(t_1, t_2, \ldots, t_k) \) is given by \( \frac{2n}{d_j} \), where \( d_j = k \).

**Proof.** For any odd integer \( k \) and any \( k \)-ordered partition \((t_1, t_2, \ldots, t_k)\), for which \# \( E(t_1, t_2, \ldots, t_k) = j \) holds, let us denote an n-state configuration which \((t_1, t_2, \ldots, t_k)\) is associated by

(3.26) \[ \tilde{\sigma} = (\tilde{\sigma}^{t_1}, \tilde{\sigma}^{t_2}, \ldots, \tilde{\sigma}^{t_k}) \].

From Lemma 3.1, we have the equation

(3.27) \[ (t_1, t_2, \ldots, t_k) = (t_1, t_2, \ldots, t_j) \tilde{\sigma} \]
with \( d = k \), which implies,

\[
\Delta = (A \bar{A})^m \Delta
\]

(3.28)

\[
\Delta = \left( \Delta \right)_{\Delta} \left( \Delta \right)_{\Delta} \cdots \left( \Delta \right)_{\Delta} = \left( A \bar{A} \right)^m \Delta
\]

(3.29)

where \( m = \frac{d-j}{2} \), because both of \( d \) and \( j \) are odd integers. Hence we have

\[
\Delta \left( \Delta \right) = \left( A \bar{A} \Delta \right)^m = \left( A \bar{A} \right)^m \Delta
\]

(3.30)

\[
\Delta \left( \left( \Delta \right)_{\Delta} \right) = \left( A \bar{A} \Delta \right)^m = \left( A \bar{A} \right)^m \Delta = \Delta
\]

(3.31)

\[
\left( \Delta \right)_{\Delta} \left( \Delta \right)_{\Delta} \left( \Delta \right)_{\Delta} = \left( A \bar{A} \Delta \right)^m = \left( A \bar{A} \right)^m \Delta
\]

(3.32)

where \( R = \sum_{i=1}^{k} t_i = \frac{n}{k} \) and \( E \left( \frac{R}{k} \right) \). On the other hand, since \( \Xi(E(t_1, t_2, \ldots, t_j)) = j \), we have

\[
\left( \Delta \left( \Delta \right) \right)_{\Delta} \left( \Delta \right)_{\Delta} \left( \Delta \right)_{\Delta} = \left( t_1, t_2, \ldots, t_j \right)
\]

(3.34)

for \( i = 1, 2, \ldots, j-1 \), which implies, in view of (3.32), that we have

\[
\left( \Delta \left( \Delta \right) \right)_{\Delta} \left( \Delta \right)_{\Delta} \left( \Delta \right)_{\Delta} \neq \Delta
\]

(3.34)

for \( j = 1, 2, \ldots, j-1 \). (3.31) and (3.34) give us that the length of RVC is equal to \( \frac{2R}{d} \), q.e.d.

**Lemma 3.7.** The set of all the possible lengths of reverberation cycles is given by

\[
2 \frac{n}{k} = d \text{ is an odd integer such that } d \mid n
\]

(3.35)

Proof. According to Lemma 3.1 and Lemma 3.6, for any odd integer \( k \) and \( d \mid (n,k) \), the length of RVC corresponding to \( E(t_1, t_2, \ldots, t_k) \), for which \( \Xi(E(t_1, t_2, \ldots, t_k)) = \frac{n}{k} \) holds, is given by the set

\[
\left\{ \frac{n}{k} \frac{k}{d}, \frac{n}{d} \mid (n,k) \text{ s.t. } k \text{ is an odd integer, } d \mid n \right\}
\]

(3.36)

which is nothing but the set (3.35). q.e.d.

After these preparations, we reach to the final result of this subsection which read:

**Theorem 3.2.** For any odd integer \( d \) such that \( d \mid n \), the number of reverberation cycles with the length \( 2R = 2^d \) is given by

\[
N_{\frac{n}{d}} \left( 2R \right) = \frac{2^d - d}{d} \sum_{d \mid \lambda} \mu(\lambda) \lambda^{\lambda/2R}
\]

(3.37)

Proof. Because of Lemma 3.6, for an odd integer \( d \) such that \( d \mid n \), the set of all the equivalent classes of ordered partitions to each of which a reverberation cycle with length \( 2^d \) corresponds, is given by

\[
\mathcal{D} = \left\{ \left( \Xi(t_1, t_2, \ldots, t_j) \right)^j \left( t_1 \right)^{k_1} \left( t_2 \right)^{k_2} \cdots \left( t_j \right)^{k_j} \mid k_1 + k_2 + \cdots + k_j = \frac{n}{d} \right\}
\]

(3.38)
In view of Lemma 3.3, we have

$$\# D = \sum_{1 \leq j, k \leq R \overline{d}} \nu(R, j, k)$$

which implies, from Theorem 3.1,

$$\# D = \sum_{1 \leq j, k \leq R \overline{d}} \sum_{d' \mid (d, k)} \mu(d') \left( \frac{R}{d'} - \frac{1}{2} \right) \left( \frac{R}{d'} \right)^{-1} = \sum_{d' \mid R \overline{d}} \mu(d') \sum_{k=1}^{\left[ \frac{R}{d} \right]} \left( \frac{R}{d} \right)^{k}$$

But Lemma 3.4 and 3.5 show that RVC with length \(2R = \frac{2}{d} \), which, in view of (3.40), gives us (3.37), as we were to prove.

Corollary 3.2. We have the following equation,

$$\lambda = \sum_{d' \mid R \overline{d}} \frac{2}{d'} \sum_{k=1}^{\left[ \frac{R}{d'} \right]} \left( \frac{2}{d'} \right)$$

where \( \lambda \) is given by (3.37).

3.2. The operator \( L_\omega \)

In this subsection we confine our discussion to the operator \( L_\omega \).

Quite similarly as the case of the operator \( L_\varphi \), so we omit the proofs.

Lemma 3.8. For any assigned reverberation cycle there exists an even integer \( k \) uniquely determined such that (i) there exists a \( k \)-ordered partition \( (t_1, t_2, \ldots, t_k) \) associated with an n-state configuration in the reverberation cycle, (ii) the set of all the ordered partitions associated with n-state configurations in the reverberation cycle consists of the set \( E(t_1, t_2, \ldots, t_k) \) and the set of \( (k+1) \)-ordered partitions of \( n \).

Lemma 3.9. For any even integer \( k \) and any equivalent class \( E(t_1, t_2, \ldots, t_k) \), (i) if \# \( E(t_1, t_2, \ldots, t_k) \) is an odd integer, then there exists a reverberation cycle uniquely determined such that an n-state configuration in the reverberation cycle associates with a \( k \)-ordered partition in the \( (t_1, t_2, \ldots, t_k) \), while (ii) if \# \( E(t_1, t_2, \ldots, t_k) \) is an even integer, then there exists two reverberation cycles such that these are mutually conjugate reverberation cycles and each of these reverberation cycle contains an n-state configuration which associates with \( k \)-ordered partition \( (t_1, t_2, \ldots, t_k) \) of \( n \).

Lemma 3.10. For any integer \( k \), \( d \mid (n, k) \) and any \( k \)-ordered partition \( (t_1, t_2, \ldots, t_k) \), for which \# \( E(t_1, t_2, \ldots, t_k) \) holds, the length \( R \)
of reverberation cycle corresponding to $E(t_1, t_2, \ldots, t_n)$ is given as follows:

(i) for the case that $j$ is an odd integer, $R = \frac{2\pi}{d}$,

(ii) for the case that $j$ is an even integer, $R = \frac{\pi}{d}$

Lemma 3.11. The set of all the possible lengths of reverberation cycle is given by

$$\left\{ \frac{n}{d} \ ; \ d \mid n \right\}.$$

(3.42)

Theorem 3.3. For any positive integer $d$ such that $d \mid n$, the number of reverberation cycles with length $R = \frac{2\pi}{d}$ is given by

(i) for any odd integer $R \geq 3$,

$$N_{\varepsilon}^n (R) = \frac{1}{R} \sum_{d' \mid R \ ; \ d' \text{ odd}} \mu(d') \left( 2^{Rd'} - 2 \right)$$

while

$$N_{\varepsilon}^n (1) = 2$$

(ii) for any even integer $R$,

$$N_{\varepsilon}^n (R) = \frac{2}{R} \sum_{d' \mid R} \mu(d') \left( 2^{Rd'} - 2 \right) + \sum_{d' \mid R} \mu(d') \left( 2^{2Rd'} - 2 \right) + \frac{1}{R} \sum_{d' \mid R} \mu(d') \left( 2^{Rd'} \right)$$

(3.45)

3.3 The other operators belonging to the $\mathcal{J}$ set

In view of Theorem 1.1, we should notice that, in contrast with $L_{\varepsilon}$ and $L_{\varepsilon}$, there exists their respective subsets of n-state configurations, each of which does not belong to an RVC for each $L_{\varepsilon}$ and $L_{\varepsilon}$ when $l \leq n - 1$, but each of which reaches to an n-state configuration belonging to some RVC after finite applications of each of these operators. In short, each of these n-state configurations is transient. In spite of the existence of these transient state configurations, it will be shown in this subsection that so far as the n-state configurations belonging to the RVC are concerned, the number of RVC's in each of $L_{\varepsilon}$ and $L_{\varepsilon}$ can be reduced to those of $L_{\varepsilon}$ which were already given in Subsection 3.1 and 3.2.

Theorem 3.4. For any positive integer $d \mid (n-1)$, we have

$$N_{\varepsilon}^n \left( \frac{n-1}{d} \right) = N_{\varepsilon}^{n-1} \left( \frac{n-1}{d} \right)$$

(3.46)

$$N_{L_{\varepsilon}}^n \left( \frac{2n-1}{d} \right) = \begin{cases} N_{\varepsilon}^{n-1} \left( \frac{2n-1}{d} \right) & \text{for an odd integer } d \\ 0 & \text{for an even integer } d \end{cases}$$

(3.47)

for $l = 1, 2, \ldots, n-1$.

The proof is omitted.
It may be noted that an n-state configuration in $X_n$ can attain to some RVC at least $\ell$ applications of $L_{\omega_k}^{\ell}$ $(L_{\omega_k}^{\ell} = 1, 2, \ldots, n-1)$, i.e., the length of transient phrase is at most $\ell$.

On the other hand it is immediately to observe that any n-state configuration in $X_n$ except $(1, 1, \ldots, 1)$ ($(0, 0, \ldots, 0)$) belongs to a transient phrase under the operator $L_{\omega}(L_{\omega}^{-})$, while the n-state configuration $(1, 1, \ldots, 1)$ ($(0, 0, \ldots, 0)$) in $X_n$ constitutes a RVC with length one under the operator $L_{\omega}$ ($L_{\omega}^{-}$).

References


西尾：オペレータクラス ${\omega}$ に属する threshold function
は特殊なものですね。定数として小なので、そんなものになってしま
るのか。
山口：${\omega}$ に属するオペレータに応対する結合係数ですか
ね。また…
西尾：すくにかかりますね。一番目だけとってきて、それ
だけが、大きい係数にして。
山口：ええ、その点を非常に大きくして。conjugateにする場
合には、1 と零の値にして。
西尾：ひっくり返すわけですね。一番に目をつけたのは何
故かといえば、まず、ひきなりむずかしいんで全部はや
かな・から。
甘利：一番最後の結論をもう一度いうと，${\omega}$ という特
殊オペレータで表わされる回路を考える。そこで、状態は
2 個あるだけだけども、二つの状態は，${\omega}$ によって，い
くつかのサイクルをつくる。そこで長さが $(m-l)/d$ のサイ
クルが何個あるかを知らべてみると，その数は，その簡化式
をみたす。そういったことですか。
山口：はい。
西尾：それは枝がはえていてもいいのですね。
山口：こちら（$L_0^e, L_{\omega}^e, d = 1, 2, \cdots$）は枝がはえて
います。こちらのオペレータは…。
甘利： ええ、0になるときだけまたま枝がなくなるわけですね。
山口： はい、すべてがサイクルになっています。
甘利： しかし、西尾さんのおっしゃった通りだけです、少しずつなLドというの。Threshold functionのなかだからきめめて特殊な形をしていきますね。グラフの話ができましたか。
山口： いつも何とあってよく、結局はまとまった図数方程式でまとめてしかいません。
甘利： これの結論というものは、例えば、n=10では、Lが大きいですが、サイクルの数は少々ぐらいあるのですそうで、
山口： n=10で、L=0の場合を考えています。例ええば、RVCの長さが4であるものは、
\[ N^{10}_{L=0}(4) = \frac{1}{4} \sum_{d | 4} \mu(d') 2^{|d'|} = \frac{1}{4} (4) = 1. \]
従って210個あるstate configurationのなかで長さが4のRVCの数は1個ということになります。
甘利： 最大周期はどの位になりますか。
山口： それは、周期の長さは2nの2で与えられますから、
\[ d = 1 \text{ ときまで} \text{ はなれ} \text{ です。} \]
西尾: これほどできるのですね。二つで。
甘利: とうございます。納得いきまし。直接的には...。しかし、
一般の回路だと最大周期は2nより大きくならずしょう。
西尾: こう考えたらどうですか。いまの甘利さんの仮想に関係あるのですか。結局，Caianielloのモデルで1-elementの
場合は，McCulloch-Pittsのモデルの（n+1）-elementsの回路と
同じで、あるの結線を限ったものがL_d,wになるわけですね。
だからその回路の最大周期ということがあります。
甘利: 今のモデルは等価的には、不適期のない神経要素を
リング状にならべておいて、途中は1本の信号印を出してゆく。
つまり単なるshift registerです。ただ最後だけが、他の
n個からすべて結線がある。それをは、一般のn要素から
なる網を回路のいくつか特殊な場合ですね。で、いまのL_d,wは、
そのままでも特に1番目だけから線をひっぱってゆくとい
う更に特殊な場合になっている。そしてこれからの場合は全
部説がかかっている。それでは、この論文の最初のモデルの
場合には、最大が小位の周期のRVCが出現するかという
ことですね。
西尾: しかも小位きっちりやるというのはひっかかいが
もし小位せんね。
甘利: そうですね。
面尾： 不等式ではあるが、このあたりに最大同期があると
いうのはもちろんたくありませんけども。この場合
ではいえども、それについてですらが解けていりわけ
ですね。それと、一般的の回路で、最大同期だけを求める場合
とどちらがやさしいか。後者は不等式をおさえるということ
ぐらいになるでしょう。そんな意味からすると、ニノの話は
きっちりいていて、結果はすっきりしています。

甘利： グラフがでてきたと整数論的なものがでてきたから楽
しんでですね。話は全然変りけりど、いまのでを０あるいは
１をやるということになりなで、例えば０と１との間の実数
とすると、そして、例の１[0]という関数もこのままだと。
０または１という値しかとらないから、それもある連続関数
とすると、話は、むずかしくなりますか。例えば、ランダム
に結合した神経回路の活動度のようなものですね。１の個数
のパーセントと相対不応期を入ると、同じ形の式が得らな
ます。ただかぎり０と１の間の実数になるというだけです。も
との差分方程式のものだけは高階の差分方程式ですね。

西尾： この講演に関して、ニノはfiniteなStateのオートマ
スタを含む場合ですね。それらの状態連鎖図について、サイク
ルに給があるものを作り、それらのcharacterizationsというこ
とですね。僕らは、それをセル・オートマトンでやっている
この場合は、関関数の場合で、あまりともということも、十分身にしみています。このだけできたらされがです。