Comparability between Ramified Sets

By Tadashi Ohkuma

Introduction

By "a ramified set", we mean a partially ordered set $X$ in which for any element $a$, the set of all elements less than $a$ makes a well-ordered subset of $X$. Such a set is called "un tableau ramifié" in [4] and [5] or "a tree" in [6]. (In [4], by "un ensemble ramifié" is meant a rather general set which is called "a tree" in [2]).

In connection with Souslin's Problem, investigation of ramified sets has been proceeded by many authors including especially Prof. George Kurepa whose contribution in this branch is distinguished ([4], [5], [6]). But it seems that most works concerning those sets are concentrated to the problem of finding conditions in order that a ramified set becomes countable, or of finding propositions about ramified sets, which turn out to be equivalent to Souslin's Problem, and that few results are obtained about internal structures of ramified sets themselves or about reciprocal relations which take place among them.

In this paper we are interested in the structures of ramified sets
and a relation between them, especially comparison between them and processes by which larger ramified sets are constructed of smaller ones, and we obtained some results which seem fundamental in the theory of structures of ramified sets themselves.

It is well-known that any topological space is uniquely decomposed into the union of its perfect part and scattered part. Especially all scattered sets, i.e., sets with void perfect parts, in the real line are well-ordered by the order of homeomorphic imbedding. Similar situations occur about ramified sets. A ramified set is uniquely decomposed into the union of its resoluble part and perfectly irresoluble part (see Def. 7 and Th. 4).

As the means of comparison between ramified sets, in place of homeomorphic imbedding for topological spaces, it seems suitable to apply the relation $\propto$ such that $X \propto Y$ implies the existence of an increasing mapping of $X$ into $Y$, which appears in the so-called comparison theorem in the usual proof of Lusin's 2nd Principle (see [7], pp. 208-221) in the theory of analytic sets. Since $\propto$ is a quasi-ordering between ramified sets, $X$ and $Y$ such that $X \propto Y$ and $Y \propto X$ are regarded as equivalent. Then we shall see in Theorem A all resoluble ramified sets with potencies less than a given regular cardinal number $\kappa_{\beta}$ are well-ordered by $\propto$ under the identification of equivalent sets, and that any resoluble ramified set can be compared with any other one (resoluble or not).

Speaking of general ramified sets with potencies less than $\kappa_{\beta}$ including irresoluble ones, they do not seem to be well-ordered by $\propto$. In fact, under the assumption of continuum hypothesis, they make neither a ramified family nor a totally ordered family, and we shall see in Theorem B continuum hypothesis implies the existence of a countable descending sequence of ramified sets, and a pair of ramified sets which are not comparable with each other.

It is the main purpose of this paper to prove Theorem A and Theorem B.

Contents and composition of this paper are as follows.

We provide some preliminaries concerning ordinal numbers in Chapter I. In §1, functions $\alpha_{\nu}(\lambda)$ assigned to each $\nu$ such that $1 \leq \nu < \omega_{\beta}$ are defined. They are defined so that an ordinal number $\lambda$ with $\lambda = \omega_{\beta}$ is characterized by means of the function $\alpha_{\nu}$, and when $2 < \nu < \omega_{\beta}$, a number $\lambda$ with $\lambda = \alpha_{\nu}(\omega_{\beta}^\eta)$ for any $\eta < \nu$ is characterized by means of $\alpha_{\nu}$. For a limit number $\lambda$, the least ordinal number $\nu = gn(\lambda)$ such that $\lambda < \alpha_{\nu}(\omega_{\beta}^\eta)$ is especially interesting, and according to the number $gn(\lambda)$ and some properties of $\lambda$ relating to functions $\alpha_{\nu}$, we shall set up a classification of ordinal numbers less than a certain number $\beta^*$ in §2.
In Chapter II, central notion and Main Theorems are mentioned. In §1 definitions of ramified sets, relation \( \prec \) and several notations are given. In §2 our Main Theorems A and B are stated, and then the proof of Theorem A is oriented. Briefly speaking, Theorem A is attributed to the existence of a sequence \( R \) of resoluble ramified sets \( N_\lambda, \lambda < \beta^\alpha \), each of which satisfies certain conditions D.1), D.2) and D.3) mentioned there. Principle 1 to construct \( N_\lambda \) is stated at the end of §2, where by several operations on ramified sets similar to cardinal or ordinal arithmetic operations on general partially ordered sets (see [2] or [3]) are studied in advance.

Chapter III is devoted to show that every \( N_\lambda \) constructed according to Principle 1 satisfies D.1), D.2) and D.3). In § 1 some lemmas concerning \( N_\lambda \) are prepared. § 2, § 3 and § 4 correspond to the three cases respectively to which every number less than \( \beta^\alpha \) is allotted by Definition 3, and consequently to the different form of \( N_\lambda \) given by Principle 1 in each case.

Chapter IV consists of two parts. In § 1 we are interested in a ramified set \( S_\lambda \) defined for each \( \lambda = \alpha_\xi(\omega^{\xi+1}_\beta) \). \( S_\lambda \) is irresoluble, but it is situated by \( \prec \) at the least upper bound to the ascending sequence \( N_\xi, \xi < \lambda \), within the family of all ramified sets with potencies less than \( \alpha_\beta \), and accordingly it is comparable by \( \prec \) with any other ramified set (resoluble or not). § 2 is devoted to prove Theorem B, and examples to confirm Theorem B are introduced by modifications of \( S_\lambda \).

Finally we add an appendix where we specify case \( \beta = 1 \). In this case not only the family of all resoluble ramified sets but also the family of all ramified sets including irresoluble ones with potencies less than \( \alpha_1 \) is well-ordered by \( \prec \) (Theorem C). The proof is obtained similarly to Theorem A. By inserting \( S_\xi \) defined in II, § 1 among sequence \( R \), we get a sequence \( R' \) where any term \( M_\lambda \) satisfies a certain condition D.2') besides D.1). Theorem C follows from the existence of such a sequence.

**Chapter I. Preliminaries on Ordinal Numbers**

In this chapter, we shall provide some preliminaries concerning ordinal numbers. In § 1 a function \( \alpha_\xi(\lambda) \) of ordinal numbers \( \lambda \) is defined, which is assigned to each \( \nu \) such that \( 1 \leq \nu < \omega_\beta \) where \( \omega_\beta \) is a fixed regular initial number greater than \( \omega_\alpha \). In § 2 we shall set up a classification of ordinal numbers less than a certain number \( \beta^\alpha \), referring to these functions \( \alpha_\xi \). This classification, as well as functions \( \alpha_\xi \), will become a basis in constructing a certain sequence \( R \) of ramified sets in a latter chapter.
1. Certain functions $\alpha_\nu$ on ordinal numbers

Throughout this paper small Greek letters are used to denote ordinal numbers or ordinal-number-valued functions without stating special notice in each occurrence. Letters $\omega$ and $\omega_\beta$ are used with usual meaning. $i$, $k$, $m$ and $n$ stand for finite numbers. In terminologies: “limit numbers”, “isolated numbers”, “regular numbers”, “singular numbers”, “segments”, “rests”, “cofinal to” etc. and operations $\text{cf}(\lambda)$, $\xi + \zeta$, $\xi \zeta$, $\xi^{\zeta}$ etc., we follow usual definitions (for example see [1]). To avoid confusion, we distinguish between terms “a power” and “the potency” of an ordinal number $\lambda$: the former means $\lambda^\xi$, while the latter means $\lambda$. Capital Greek letters are used to denote sets or sequences (not necessarily countable) of ordinal numbers. Besides usual notations we shall define the following.

**DEFINITION 1.** $\text{ls}(\lambda)$ denotes the greatest limit segment of $\lambda$, i.e., $\text{ls}(\lambda)$ is the greatest limit number which does not exceed $\lambda$.

$\text{fr}(\lambda)$ denotes the greatest finite rest of $\lambda$, i.e., $\text{fr}(\lambda)$ is the finite number $n$ with $\lambda = \text{ls}(\lambda) + n$.

$\rho_\lambda$ denotes the characteristic function of limit numbers, i.e., $\rho_\lambda = 1$ if $\lambda$ is a limit number, and $\rho_\lambda = 0$ if $\lambda$ is an isolated number.

Let $\omega_\beta$ be an arbitrarily given regular initial number greater than $\omega_0$. $\beta$ will be fixed throughout this paper (however in proving Theorem A (ii), it is utilized that $\beta$ is arbitrarily given). Now we shall define functions $\alpha_\nu(\lambda)$ of $\lambda$ assigned to each $\nu$ such that $1 \leq \nu < \omega_\beta$. These functions will play a main rôle in this paper.

**DEFINITION 2.** (i). Put $\alpha_1(\lambda) = \lambda$, and $\alpha_\nu(0) = 0$ for any $\nu$ such that $1 \leq \nu < \omega_\beta$.

Assume that $\nu = \eta + 1$ and $\alpha_\nu(\lambda)$ is already defined for any $\lambda$, put

$$
\alpha_\nu(\mu + 1) = \alpha_\eta(\omega_\beta^{\alpha_\nu(\mu) + \rho_\mu}) \quad \text{and} \quad \alpha_\nu(\mu) = \sup_{\xi < \mu} \alpha_\nu(\xi) \text{ for a limit number } \mu.
$$

Assume that $\nu$ is a limit number such that $1 \leq \nu < \omega_\beta$, and $\alpha_\eta(\lambda)$ is already defined for any $\lambda$ and $\eta$ such that $1 \leq \eta < \nu$, put $\mu = \nu \delta + \xi$ where $0 \leq \xi < \nu$ and

$$
\alpha_\nu(\mu) = \alpha_\xi(\omega_\beta^{\alpha_\nu(\nu \delta + \xi) + 1}) \quad \text{if } \xi > 0,
$$

$$
\alpha_\nu(\mu) = \sup_{\xi < \mu} \alpha_\nu(\xi) \quad \text{if } \xi = 0.
$$

Finally $\beta^\eta = \sup_{\nu < \omega_\beta} \alpha_\nu(1)$.

(ii). If $\nu$ is an isolated number less than $\omega_\beta$, then $\Phi_\nu^\nu$ denotes the class
of all limit numbers and \( \Phi_\nu \) denotes the class of all isolated numbers.

If \( \nu \) is a limit number such that \( 0 < \nu < \omega_\beta \), then \( \Phi_\nu \) denotes the class of all numbers with forms \( \nu \delta \) and \( \Phi_\nu \) denotes the class of all numbers with forms \( \nu \delta + \zeta \) where \( 0 < \zeta < \nu \).

For \( \lambda < \beta^\omega \), \( \varphi_\nu(\lambda) \) denotes the greatest number in \( \Phi_\nu \) which does not exceed \( \lambda \) and \( \varphi_\nu(\lambda) \) denotes the number \( \zeta \) such that \( \lambda = \varphi_\nu(\lambda) + \zeta \). The representation \( \lambda = \xi + \zeta \) where \( \xi = \varphi_\nu(\lambda) \) and \( \zeta = \varphi_\nu(\lambda) \) is called the \( \varphi_\nu \)-decomposition of \( \lambda \).

**REMARK.** If \( \nu \) is an isolated number, then \( \varphi_\nu(\lambda) = \text{ls}(\lambda) \) and \( \varphi_\nu(\lambda) = \text{fr}(\lambda) \). In general if \( \mu \in \Phi_\nu \), then \( \varphi_\nu(\mu + \xi) = \varphi_\nu(\xi) \) for any \( \xi < \beta^\nu \).

It follows from the definition that, if \( \lambda \in \Phi_\nu \), then the function \( \alpha_\nu(\mu) \) of \( \mu \) with a constant \( \nu \) is continuous at \( \mu = \lambda \).

**EXAMPLES.** \( \alpha_2(1) = \omega_\beta \), \( \alpha_2(2) = \omega_\beta \omega_\beta \), \( \alpha_2(3) = \omega_\beta \omega_\beta \omega_\beta \) etc.. In general \( \alpha_{\nu + 1}(1) = \alpha_\nu(\omega_\beta) \). If \( \nu \) is a limit number and \( 0 < \xi < \nu < \omega_\beta \), then \( \alpha_\nu(\xi) = \alpha_\xi(\omega_\beta) = \alpha_{\nu + 1}(1) \).

Hereafter we assume that a number denoted by \( \nu \) or \( \eta \), which is mainly used as the suffix of a function \( \alpha_\nu \) or as the index of a power \( \omega_\nu \) of \( \omega_\nu \), is greater than 0 and less than \( \omega_\beta \), without mentioning special notices in each occurance.

**Lemma 1.1.** The function \( \alpha_\nu(\omega_\beta^\eta) \) of \( \mu \) with a constant \( \nu \) is continuous at any limit number \( \mu > 0 \).

Proof. Since \( \nu < \omega_\beta \), \( \omega_\beta^\nu \in \Phi_\nu \). Hence the function \( \alpha_\nu(\lambda) \) of \( \lambda \) is continuous at \( \lambda = \omega_\beta^\nu \). Since the function \( \omega_\beta^\nu \) of \( \mu \) is continuous at any limit number \( \mu > 0 \), \( \alpha_\nu(\omega_\beta^\nu) \) is continuous at any limit number \( \mu > 0 \).

**Lemma 1.2.** \( \mu \leq \alpha_\nu(\mu) \).

Proof. In the case where either \( \nu = 1 \) or \( \mu = 0 \), our lemma is trivial. Assume \( \theta \leq \alpha_\nu(\theta) \) for any \( \theta \) and \( \eta \) with \( 1 \leq \eta < \nu \), and \( \xi \leq \alpha_\nu(\xi) \) for any \( \xi < \mu \).

**Case 1.** \( \nu = \eta + 1 \) and \( \mu = \xi + 1 \).

In this case \( \alpha_\nu(\xi + 1) = \alpha_\xi(\omega_\beta^\nu(\xi + 1)) \geq \omega_\beta^\nu(\xi + 1) = \omega_\beta^\nu(\xi + 1) \). If \( \xi \) is an isolated number, then \( \omega_\beta^\xi \geq \xi \), since \( \omega_\beta^\xi \) is a limit number. If \( \xi \) is a limit number, then \( \rho_\xi = 1 \) and \( \omega_\beta^{\xi + 1} \geq \xi + 1 \). Hence in either case \( \alpha_\nu(\xi + 1) \geq \xi + 1 = \mu \).

**Case 2.** \( \nu = \nu \delta + \zeta \) where \( 0 < \zeta < \nu \).

In this case \( \alpha_\nu(\mu) = \alpha_\zeta(\omega_\beta^{\nu \delta + \xi} \delta+1) \geq \omega_\beta^{\nu \delta + \xi} \delta+1 \omega_\beta^{\nu \delta + \xi} \delta+1 \). In this case \( \alpha_\nu(\mu) = \sup \alpha_\nu(\xi) \geq \sup \xi = \mu \).

**Case 3.** \( \mu \in \Phi_\nu \).

In this case \( \alpha_\nu(\mu) = \sup \alpha_\nu(\xi) \geq \sup \xi = \mu \).

Hence our lemma is proved by double induction on \( \mu \) and \( \nu \).
Lemma 1.3. If $\eta < \nu$ and $\mu > 0$, then $\alpha_\nu(\omega_\mu) \leq \alpha_\nu(\omega_\mu)$. 
Proof. Since $\omega_\mu \in \Phi_\nu$ for any $\mu$, $\xi < \omega_\mu$ implies $\alpha_\nu(\xi) \leq \alpha_\nu(\omega_\mu)$. If $\nu = \eta + 1$ and $\mu = \xi + 1$, then $\omega_\mu \supset \mu + 1$ and $\alpha_\nu(\omega_\mu) \supset \alpha_\nu(\mu + 1)$ $= \alpha_\nu(\omega_\mu) \supset \alpha_\nu(\omega_\mu)$ by Lemma 1.2.

If $\nu$ is a limit number and $\mu = \xi + 1$, then $\alpha_\nu(\omega_\mu) \supset \alpha_\nu(\omega_\mu + \eta) = \alpha_\nu(\omega_\mu) \supset \alpha_\nu(\omega_\mu) = \alpha_\nu(\omega_\mu)$.

If $\mu$ is a limit number and either $\nu = \eta + 1$ or $\nu$ is a limit number, then $\alpha_\nu(\omega_\mu) \supset \alpha_\nu(\omega_\mu + \xi) \supset \alpha_\nu(\omega_\mu + \xi) = \alpha_\nu(\omega_\mu)$ (refer to the cases above).

Therefore our lemma is proved by induction on $\nu$.

Remark. In general $\eta < \nu$ does not imply $\alpha_\mu(\mu) \leq \alpha_\nu(\mu)$. For example, $\alpha_\nu(1) = \alpha_\nu(\omega_\mu) \supset \alpha_\nu(\omega_\mu + 1)$ while $\alpha_\nu(1) = \alpha_\nu(\omega_\mu) = \omega_\mu$.

Lemma 1.4. If $\xi < \mu$, then $\alpha_\nu(\xi) \leq \alpha_\nu(\mu)$.
Proof. It is trivial for $\nu = 1$. For $\mu \in \Phi_\nu$, this lemma follows from definition. If $\nu = \eta + 1$ and $\mu = \xi + 1$, then $\alpha_\nu(\mu) = \alpha_\nu(\omega_\mu)$ by Lemma 1.2. Hence in the case $\nu = \eta + 1$ our lemma is proved by induction on $\mu$.

Assume that $\nu$ is a limit number and $\mu = \nu \delta + \xi$ where $0 < \xi < \nu$, then $\alpha_\nu(\mu) = \alpha_\nu(\omega_\mu)$ implies $\alpha_\nu(\nu \delta) \leq \alpha_\nu(\mu)$.

Hence $\xi \leq \nu \delta$ implies $\alpha_\nu(\xi) \leq \alpha_\nu(\mu)$.

If $\nu \delta < \xi < \mu$ and $\xi = \nu \delta + \zeta$ where $0 < \zeta < \xi$, then $\alpha_\nu(\mu) = \alpha_\nu(\omega_\mu)$ $\supset \alpha_\nu(\omega_\mu) = \alpha_\nu(\xi)$ by Lemma 1.3. Hence our lemma is proved also in the case where $\nu$ is a limit number.

Lemma 1.5. We have $\omega_\mu = \lambda$ if and only if $\lambda = \alpha_\nu(\mu)$ for a limit number $\mu > 0$.
Proof. Assume that $\mu$ is a limit number, then $\alpha_\nu(\mu) = \sup \alpha_\nu(\mu + 2) = \sup \omega_\mu$ by Lemma 1.1.

Conversely assume $\omega_\mu = \lambda$. Since $\alpha_\nu(\mu)$ is a continuous function of $\mu$ and unbounded by $\mu \leq \alpha_\nu(\mu)$, there exists the greatest number $\mu$ such that $\alpha_\nu(\mu) \leq \lambda$. If $\mu$ is an isolated number, then $\rho_\mu = 0$ and $\lambda \leq \alpha_\nu(\mu + 1) = \omega_\mu$ contradicting $\lambda = \omega_\mu$. Hence $\mu$ is a limit number. If $\alpha_\nu(\mu) \leq \lambda$, then putting $\lambda = \alpha_\nu(\mu) + \xi$ where $0 < \xi < \nu$, we have $\omega_\mu = \omega_\mu \supset \omega_\mu$ $\supset \alpha_\nu(\xi + 1)$ $\supset \alpha_\nu(\mu + 1) > \lambda$ contradicting $\omega_\mu = \lambda$. Hence $\omega_\mu = \lambda$ implies $\lambda = \alpha_\nu(\mu)$ for a limit number $\mu$.

Theorem 1. If $\xi + 1 \nu$, then for any $\mu > 0$, except the case where $\nu$ is a limit number, $\mu = \nu \delta + \xi$ and $0 < \xi < \nu$, there exists an ordinal number $\lambda_\mu, \nu, \xi > 0$ such that $\alpha_\nu(\lambda_{\mu, \nu, \xi}) = \alpha_\nu(\omega_\mu \supset \omega_\mu + \xi)$.

Proof. If $\nu = \xi + 1$ and $\mu = \xi + 1$, then $\alpha_\nu(\mu) = \alpha_\nu(\omega_\mu \supset \omega_\mu + \xi)$ and $\alpha_\nu(\xi) + \rho_\xi > 0$. Hence $\lambda_{\mu, \nu, \xi} = \alpha_\nu(\xi) + \rho_\xi$. If $\nu = \xi + 1$ and $\mu$ is a limit number.
greater than 0, then \( \alpha_\nu(\mu) = \sup_{\xi < \mu} \alpha_\nu(\xi + 2) = \sup_{\xi < \mu} \alpha_\nu(\omega_\delta^\xi(\xi + 1)) = \alpha_\nu(\omega_\delta^{\xi+1}) \) by Lemma 1.1. Hence \( \lambda_{\mu, \nu, \xi} = \alpha_\nu(\mu) \).

Assume that our assertion is true for any \( \nu \) such that \( \xi < \nu \leq \eta \), and we shall inductively show that there exists a \( \lambda_{\mu, \nu, \xi} > 0 \) such that \( \alpha_\nu(\mu) = \alpha_\nu(\omega_\delta^{\mu, \nu, \xi}) \).

**Case 1.** \( \eta = \nu + 1 \) and \( \mu = \xi + 1 \).

In this case put \( \xi = \omega_\delta^{\nu+1} \), then since \( \xi \) is a power of \( \omega_\delta \), the arguments \( \zeta \) and \( \nu \) of \( \alpha_\nu(\xi) \) would not fall into the excepted case, and there exists a \( \lambda_{\zeta, \nu, \xi} > 0 \) such that \( \alpha_\nu(\xi) = \alpha_\nu(\omega_\delta^{\nu+1}) \). Since \( \alpha_\nu(\mu) = \alpha_\nu(\xi) \), putting \( \lambda_{\mu, \nu, \xi} = \lambda_{\zeta, \nu, \xi} \), \( \lambda_{\mu, \nu, \xi} \) satisfies the condition.

**Case 2.** \( \eta = \nu + 1 \) and \( \mu \) is a limit number.

As we saw in Case 1, for any \( \xi < \mu \) there exists a \( \lambda_{\xi+1, \nu, \xi} > 0 \) such that \( \alpha_\nu(\xi + 1) = \alpha_\nu(\omega_\delta^{\xi+1}) \). Put \( \lambda_{\mu, \nu, \xi} = \sup_{\xi < \mu} \lambda_{\xi+1, \nu, \xi} \) then \( \alpha_\nu(\mu) = \sup_{\xi < \mu} \alpha_\nu(\xi + 1) = \sup_{\xi < \mu} \alpha_\nu(\omega_\delta^{\xi+1}) = \alpha_\nu(\omega_\delta^{\mu, \nu, \xi}) \) by Lemma 1.1. Hence \( \lambda_{\mu, \nu, \xi} \) is the required ordinal number.

**Case 3.** \( \eta \) is a limit number and \( \mu = \eta \delta + \xi \).

In this case \( \alpha_\nu(\mu) = \alpha_\nu(\omega_\delta^{\eta \delta + \xi}) \), and putting \( \lambda_{\mu, \nu, \xi} = \alpha_\nu(\eta \delta + \xi + 1) \), \( \lambda_{\mu, \nu, \xi} \) satisfies the condition.

**Case 4.** \( \eta \) is a limit number and \( \mu = \eta \delta + \xi \) where \( \xi < \eta \).

In this case put \( \xi = \omega_\delta^{\eta \delta + \xi} \), then since \( \xi \) is a power of \( \omega_\delta \), the arguments \( \xi \) and \( \xi \) of \( \alpha_\nu(\xi) \) would not fall into the excepted case, and there exists a \( \lambda_{\zeta, \eta, \xi} > 0 \) such that \( \alpha_\nu(\xi) = \alpha_\nu(\omega_\delta^{\eta \delta + \xi}) \). Since \( \alpha_\nu(\mu) = \alpha_\nu(\xi) \), putting \( \lambda_{\mu, \nu, \xi} = \lambda_{\xi, \eta, \xi} \), \( \lambda_{\mu, \nu, \xi} \) satisfies the condition.

**Case 5.** \( \eta \) is a limit number and \( \mu = \eta \delta \).

Put \( \Xi = \{ \xi : \xi = \eta \delta + \xi, \delta < \delta, \delta \leq \delta < \eta \} \), then \( \Xi \) is cofinal to \( \eta \delta \). As we saw in Case 1 and 4 for any \( \xi \in \Xi \) there exists a \( \lambda_{\xi, \eta, \xi} > 0 \) such that \( \alpha_\nu(\xi) = \alpha_\nu(\omega_\delta^{\eta \delta + \xi}) \). Put \( \lambda_{\mu, \nu, \xi} = \sup_{\xi \in \Xi} \lambda_{\xi, \eta, \xi} \), then \( \alpha_\nu(\mu) = \sup_{\xi \in \Xi} \alpha_\nu(\xi) = \sup_{\xi \in \Xi} \alpha_\nu(\omega_\delta^{\eta \delta + \xi}) \). Hence \( \lambda_{\mu, \nu, \xi} \) is the number required.

Therefore in any case we can find a \( \lambda_{\mu, \nu, \xi} \) required in our assertion, and the proof is completed.

Especially putting \( \xi = 2 \), we can assert that, if \( \nu \geq 3 \), then for any \( \mu > 0 \), except where \( \nu \) is a limit number and \( \mu = \nu \delta + 1 \), there exists a \( \lambda_{\mu, \nu, \xi} > 0 \) such that \( \alpha_\nu(\mu) = \alpha_\nu(\omega_\delta^{\mu, \nu, \xi}) \). Since \( \lambda = \omega_\delta^{\mu, \nu, \xi} \) is a limit number, following Corollaries 1-3 immediately follow from Lemma 1.5.

**Corollary 1.** If \( \nu \geq 3 \) and \( \mu > 0 \), except the case where \( \nu \) is a limit number and \( \mu = \nu \delta + 1 \), we have \( \omega_\delta^{\mu, \nu, \xi} = \alpha_\nu(\mu) \).

**Corollary 2.** If \( \nu \geq 2 \) and \( \mu > 0 \), then \( \alpha_\nu(\mu) \) is a power of \( \omega_\delta \).
Corollary 3. If $v \geq 2$ and $\mu > 0$, then $\alpha_{v+1}(\mu + 1) = \alpha_s(\alpha_{v+1}(\mu) \cdot \omega_\beta)$. If $v$ is a limit number greater than 0, $\delta \geq 1$ and $2 \leq \xi < v$, then $\alpha_s(\nu^\delta + \xi) = \alpha_s(\nu^\delta + \xi)$.

Corollary 4. If $\mu$ is a limit number and $2 \leq v < \omega_\beta$, then $\alpha_s(\alpha_{v+1}(\mu + 1) \cdot \omega_\beta) = \alpha_s(\alpha_{v+1}(\mu) \cdot \omega_\beta)$.

Proof. If $v$ is a limit number, then $\alpha_s(\alpha_{v+1}(\mu) = \omega_s^{\nu_{v+1}(\mu)}$, and hence $\nu_s(\alpha_{v+1}(\mu) = \alpha_s(\alpha_{v+1}(\mu) \cdot \omega_\beta) \geq \alpha_s(\alpha_{v+1}(\mu) \cdot \omega_\beta)$.

If $v$ is an isolated number $\eta + 1$, then $\alpha_s(\alpha_{v+1}(\mu + 1)) = \alpha_s(\alpha_{v+1}(\mu)) \cdot \omega_\beta)$.

Lemma 1.6. Let $\nu$ be an ordinal number greater than 1. Then $\alpha_s(\lambda) = \lambda$ if and only if $\lambda = \alpha_{v+1}(\mu)$ for a limit number $\mu$.

Proof. If $\mu$ is a limit number, then $\alpha_s(\alpha_{v+1}(\mu) = \sup \alpha_s(\alpha_{v+1}(\mu + 1)) = \alpha_s(\alpha_{v+1}(\mu))$ by Corollary above.

Conversely assume $\lambda = \alpha_s(\lambda)$. Since the function $\alpha_s(\alpha_{v+1}(\mu)$ of $\mu$ is continuous and unbounded, there exists the greatest number $\mu$ such that $\alpha_s(\alpha_{v+1}(\mu) \leq \lambda$. If $\mu$ is an isolated number, then $\rho_\mu = 0$ and $\lambda < \alpha_s(\alpha_{v+1}(\mu + 1)) = \alpha_s(\alpha_s(\alpha_{v+1}(\mu)) \leq \alpha_s(\lambda)$, contradicting $\lambda = \alpha_s(\lambda)$. Hence $\mu$ is a limit number.

If $\lambda \geq \alpha_s(\alpha_{v+1}(\mu + 1)$, then by Corollary 4 above $\lambda = \alpha_s(\lambda) \geq \alpha_s(\alpha_s(\alpha_{v+1}(\mu + 1)) \geq \alpha_s(\alpha_{v+1}(\mu) \cdot \omega_\beta$. But then, since $\mu$ is a limit number, $\alpha_s(\lambda) \geq \alpha_s(\alpha_s(\alpha_{v+1}(\mu) \omega_\beta) = \alpha_s(\alpha_{v+1}(\mu + 1) \geq \lambda$ contradicting $\lambda = \alpha_s(\lambda)$. Hence $\lambda = \alpha_s(\lambda)$ where $\mu$ is a limit number.

Corollary 1. If $\eta + 2 \leq v$, then $\alpha_s(\alpha_s(\mu)) = \alpha_s(\mu)$ for any $\mu > 0$, except where $\eta > v$

Corollary 2. If $v$ is a limit number greater than 0 and $0 < \xi < v$, then $\alpha_s(\nu^\delta + \xi) = \alpha_s(\nu^\delta + \xi)$.

Proof. By Corollary 1 above $\alpha_s(\nu^\delta) = \alpha_{\xi+1}(\alpha_s(\nu^\delta))$, and hence $\alpha_s(\nu^\delta + \xi) = \alpha_{\xi+1}(\omega_s^{\alpha_s(\nu^\delta)+1}) = \alpha_{\xi+1}(\omega_s^{\alpha_s(\nu^\delta)+1}) = \alpha_{\xi+1}(\alpha_s(\nu^\delta + \xi)) + 1)$.

Lemma 1.7. Let $\nu$ be a limit number greater than 0. In order that $\lambda = \omega_\beta^\delta = \alpha_s(\lambda)$ for any $\eta < v$, it is necessary and sufficient that $\lambda = \alpha_s(\nu^\delta)$ with a $\delta > 0$.

Proof. If $\lambda = \alpha_s(\nu^\delta)$ and $\delta > 0$, then $\lambda = \omega_\beta^\delta$ by Corollary 1 of Theorem 1. Assume $\eta < v$ and put $\Phi = \{\xi | \xi = \nu^\delta + \xi', \xi' < \delta, \eta < \xi', < \nu\}$, then $\Phi$ is cofinal to $\nu^\delta$. By Corollary 1 of Lemma 1.6, $\alpha_s(\alpha_s(\xi)) = \alpha_s(\xi)$ for any $\xi \in \Phi$. Hence $\alpha_s(\lambda) = \sup_{\xi \in \Phi} \alpha_s(\alpha_s(\xi)) = \sup_{\xi \in \Phi} \alpha_s(\xi) = \alpha_s(\nu^\delta) = \lambda$.

Conversely assume $\lambda = \omega_\beta^\delta = \alpha_s(\lambda)$ for any $\eta < v$. By definition of
\( \alpha_\nu(\nu^\delta) \) for \( \delta > 0 \), the function \( \alpha_\nu(\nu^\delta) \) of \( \delta \), with a fixed \( \nu \), is continuous. Hence there exists the greatest number \( \delta \) such that \( \alpha_\nu(\nu^\delta) \leq \lambda \). If \( \delta = 0 \), then there exists a \( \xi \) such that \( \xi < \nu \) and \( \lambda < \alpha_\xi(\xi) \). But then, since \( \alpha_\xi(\xi) = \alpha_\xi(\omega_\beta) = \alpha_{\xi+1}(1) \) and \( 1 < \lambda \), we have \( \lambda < \alpha_{\xi+1}(1) \leq \alpha_{\xi+1}(\lambda) \) contradicting \( \lambda = \alpha_{\xi+1}(\lambda) \). Hence \( \delta > 0 \). Since \( \alpha_\nu(\nu(\delta + 1)) > \lambda \), there exists the least number \( \xi \) such that \( \lambda < \alpha_\xi(\nu^\delta + 1) \) and \( \lambda < \alpha_\xi(\nu^\delta + \xi) \). If \( \mu > 1 \), then \( \alpha_\mu(\nu^\delta) = \alpha_\mu(\omega_\beta^{\nu^\delta + 1}) > \alpha_\mu(\nu^\delta + 1) \), contradicting \( \lambda = \omega_\beta^\xi \). Hence we have \( \lambda = \alpha_\nu(\nu^\delta) \) where \( \delta > 0 \), which is to be proved.

Summing up Lemma 1.5, 1.6 and 1.7, we have

**Theorem 2.** In order that \( \lambda = \alpha_\nu(\omega_\beta^\nu) \) for any \( \eta < \nu \), it is necessary and sufficient that \( \lambda = \alpha_\mu(\mu) \) with \( \mu \in \Phi \) and \( \mu > 0 \).

**Lemma 1.8.** \( \alpha_\nu(\mu) < \alpha_\nu(\mu + 1) \) for any \( \mu \) and \( \nu \).

Proof. \( \alpha_\nu(\mu) \leq \alpha_\nu(\mu + 1) \) is already proved in Lemma 1.4. Our assertion is trivial for \( \nu = 1 \).

If \( \nu = \eta + 1 \) where \( \eta \geq 1 \), then \( \alpha_\nu(\mu + 1) = \alpha_\nu(\omega_\beta^{\nu(\mu + 1) + 1}) \). If further \( \mu \) is a limit number, then \( \rho_\mu = 1 \) and \( \alpha_\nu(\omega_\beta^{\nu(\mu + 1) + 1}) \geq \alpha_\nu(\mu + 1) > \alpha_\nu(\mu) \). If \( \mu \) is an isolated number, then \( \alpha_\nu(\omega_\beta^{\nu(\mu + 1) + 1}) \geq \alpha_\nu(\mu) \) by Theorem 2. Hence in either case \( \alpha_\nu(\mu + 1) > \alpha_\nu(\mu) \).

Assume that \( \nu \) is a limit number. If further \( \mu \in \Phi \), then \( \alpha_\nu(\mu + 1) = \alpha_\nu(\omega_\beta^{\nu(\mu + 1) + 1}) \). If \( \mu \in \Phi \), then letting \( \mu = \xi + \zeta \) be the \( \varphi \)-decomposition of \( \mu \), \( \zeta > 0 \). \( \alpha_\nu(\mu + 1) = \alpha_\nu(\xi + \zeta + 1) = \alpha_{\zeta+1}(\omega_\beta^{\nu(\xi + 1)}) > \alpha_{\zeta+1}(\alpha_\nu(\xi + 1)) \), since our lemma is already proved for an isolated number \( \xi + 1 \). Furthermore, by Corollary 2 of Lemma 1.6, \( \alpha_{\zeta+1}(\alpha_\nu(\xi + 1)) = \alpha_\nu(\zeta + \xi) = \alpha_\nu(\mu) \).

Hence our lemma is proved also for a limit number \( \nu \).

For \( \nu \geq 2 \), \( \alpha_\nu(\mu) \) is a limit number by Corollary 2 of Theorem 1.

Here we have

**Theorem 3.** Assume \( \nu \geq 2 \), then \( \text{cf} (\alpha_\nu(\mu)) = \beta \) for \( \mu \in \Phi \), and \( \text{cf} (\alpha_\nu(\mu)) = \text{cf} (\mu) = \beta \) for \( \mu \in \Phi^\nu \).

Proof. First we shall consider the case \( \mu \in \Phi \).

Assume that \( \nu \) is an isolated number \( \eta + 1 \) where \( \eta > 0 \). If \( \mu \) is the next number to a limit number \( \xi \), then \( \alpha_\nu(\mu) = \alpha_\nu(\omega_\beta^{\nu(\xi + 1) + 1}) = \text{sup} \{ \alpha_\nu(\omega_\beta^{\nu(\xi + 1)}), \xi \} \). Since the function \( \alpha_\nu(\lambda) \) of \( \lambda \) is increasing by Lemma 1.8, for a sequence \( \Lambda \) of ordinal number \( \xi < \omega_\beta \) cofinal to \( \omega_\beta \), the sequence \( \{ \alpha_\nu(\omega_\beta^{\nu(\xi + 1)}), \xi \in \Lambda \} \) is also cofinal to \( \alpha_\nu(\mu) \). Hence \( \text{cf} (\alpha_\nu(\mu)) = \beta \).

Assume \( \mu = \xi + 1 \) where \( \xi \) is an isolated number and \( \text{cf} (\alpha_\nu(\xi)) = \beta \),
then \( \alpha_s(\mu) = \alpha_s(\omega_\beta^\alpha(\xi)) = \sup_{\xi < \alpha_s(\xi)} \alpha_s(\omega_\beta^\alpha) \). Similarly as the above, for a sequence \( \Lambda \) of ordinal numbers \( \xi < \alpha_s(\xi) \) cofinal to \( \alpha_s(\xi) \), the sequence \( \{ \alpha_s(\omega_\beta^\alpha(\xi)) | \xi \in \Lambda \} \) is also cofinal to \( \alpha_s(\mu) \). Hence \( \text{cf}(\alpha_s(\mu)) = \text{cf}(\alpha_s(\xi)) = \beta \). Hence it is inductively proved that for any isolated number \( \nu \) we have \( \text{cf}(\alpha_s(\mu)) = \beta \).

Next let \( \nu \) be a limit number such that \( 0 < \nu < \omega_\beta \). If \( 0 < \xi < \nu \), then by Corollary 2 of Theorem 1 \( \alpha_s(\nu^\delta + \xi) = \alpha_{\xi + 1}(\alpha_s(\nu^\delta) + 1) \), and since both \( \xi + 1 \) and \( \alpha_s(\nu^\delta) + 1 \) are isolated numbers, \( \text{cf}(\alpha_{\xi + 1}(\alpha_s(\nu^\delta) + 1)) = \beta \). Hence in either case that \( \nu \) is an isolated number or a limit number, \( \nu \geq 2 \) and \( \mu \in \Phi^s \) imply \( \text{cf}(\alpha_s(\mu)) = \beta \).

Next consider the case \( \mu \in \Phi^s \). For \( \mu = 0 \), our statement is trivial. If \( \mu > 0 \), then since \( \alpha_s(\mu) = \sup_{\xi < \mu} \alpha_s(\xi) \) and the function \( \alpha_s(\xi) \) of \( \xi \) is increasing, we have immediately \( \text{cf}(\alpha_s(\mu)) = \text{cf}(\mu) \), and the whole proof is completed.

**Lemma 1.9.** For any \( \lambda < \beta^s \) there exists a \( \nu \) such that \( 0 < \nu < \omega_\beta \) and \( \lambda < \alpha_s(\omega_\beta^\nu) \).

Proof. If \( \lambda = \alpha_s(\omega_\beta^\nu) \) for any \( \nu < \omega_\beta \), then \( \lambda = \sup_{\nu < \omega_\beta} \alpha_s(\omega_\beta^\nu) = \sup_{\nu < \omega_\beta} \alpha_s(1) = \beta^s \).

2. A classification of ordinal numbers

Hereafter any number denoted by a small Greek letter in this paper is assumed less than \( \beta^s \).

**Lemma 1.10.** Let \( \gamma(\mu) \) denote the least number \( \xi \) such that \( \mu < \xi \omega \), then the following three conditions on \( \mu \) are mutually equivalent.

(a). \( \gamma(\mu) = \mu \). (b). Any non-zero rest of \( \mu \) is equal to \( \mu \). (c). There exists a \( \xi \leq \mu \) with \( \mu = \omega_\xi^\parallel \).

For the proof refer to [1] pp. 67-68. Here we omit it.

**Definition 3.** (i). \( \gamma(\mu) \) denotes the number defined in Lemma 1.10. A number \( \mu \) which satisfies conditions in Lemma 1.10 is called a \( \gamma \)-number (see [1], p. 67).

(ii). For \( \lambda < \beta^s \), the least number \( \nu \) such that \( \text{ls}(\lambda) < \alpha_s(\omega_\beta^{\nu+\lambda}) \) (refer to Lemma 1.9) is called the genus of \( \lambda \) and denoted by \( \text{gn}(\lambda) \).

(iii). If \( \lambda = \alpha_s(\mu) \), then we write \( \mu = \alpha_s^{-1}(\lambda) \).

put \( \text{de}(\lambda) = \alpha_s^{-1}(\text{ls}(\lambda)) \), (derivation of \( \lambda \)).

(iv). Let \( \Gamma \) denote the set of all ordinal numbers less than \( \beta^s \).

\( \Gamma^s \) denotes the set of all \( \lambda \in \Gamma \) with \( \text{gn}(\lambda) = s \).

\( \Gamma^s \) denotes the set of all \( \lambda \in \Gamma \) with \( \text{cf}(\text{ls}(\lambda)) < \beta \).

\( \Gamma^d \) denotes the set of all \( \lambda \in \Gamma \) such that \( \text{cf}(\text{ls}(\lambda)) = \beta \) and \( \text{de}(\lambda) \) is not a \( \gamma \)-number.
Ramified Sets

\( \Gamma^v \) denotes the set of all \( \lambda \in \Gamma \) such that \( cf(ls(\lambda)) = \beta \) and \( de(\lambda) \) is a \( \gamma \)-number.

Put \( \Gamma_i = \bigcap \Gamma_i, \Gamma_i = \bigcup_{\nu \in \omega} \bigcap \Gamma_i \) for \( i = 0, 1, 2 \) and \( \Gamma_\gamma = \bigcup_{\nu \in \gamma} \Gamma_\gamma. \)

Remark. (i) \( gn(\lambda) \) and \( de(\lambda) \) depend only on \( ls(\lambda) \), or in other words, \( gn(\lambda + n) = gn(\lambda) \) and \( de(\lambda + n) = de(\lambda) \).

(ii) If \( gn(\lambda) = 1 \), then \( de(\lambda) = ls(\lambda) \).

If \( 1 < \nu = gn(\lambda) \), then \( \eta < \nu \) implies \( \alpha_\nu(\omega^{\nu(\lambda)}) = ls(\lambda) \). Hence \( ls(\lambda) = \alpha_\nu(\mu) \) where \( \mu \in \Phi_\nu \) by Theorem 2, and \( \mu = de(\lambda) \).

Therefore \( de(\lambda) \) is defined for any \( \lambda < \beta^v \), and \( de(\lambda) \in \Phi_{gn(\lambda)}^v \) in general.

Especially if \( \nu = gn(\lambda) > 1 \), then \( \omega^{\nu(\lambda)} = ls(\lambda) \) and hence \( \alpha_\nu(de(\lambda)) = ls(\lambda) \). Since \( \alpha_\nu \) is increasing, \( de(\lambda) < ls(\lambda) \).

(iii) If \( \eta < \nu = gn(\lambda) \), then especially \( 1 < \nu \) and \( ls(\lambda) = \omega^{\nu(\lambda)} \). Hence \( ls(\lambda) = \alpha_\eta(\omega^{\nu(\lambda)}) = \alpha_\eta(ls(\lambda)) \).

(iv) In general \( \lambda = \alpha_{gn(\lambda)}(de(\lambda)) + fr(\lambda) \).

Lemma 1.11. (i) \( gn(de(\lambda)) = gn(\lambda) \). (ii) \( cf(de(\lambda)) = cf(ls(\lambda)) \).

Proof. (i) If \( gn(\lambda) = 1 \), then \( de(\lambda) = ls(\lambda) \) and \( gn(de(\lambda)) = gn(ls(\lambda)) = gn(\lambda) \). If \( gn(\lambda) = \nu > 1 \), then by Remark (ii) above, \( de(\lambda) < ls(\lambda) \). Assume \( gn(de(\lambda)) = \eta > \nu \), then by Remark (iii) above, \( de(\lambda) = \alpha_\eta(de(\lambda)) = ls(\lambda) \) contradictirly. Hence \( gn(de(\lambda)) \leq gn(\lambda) \) in general.

(ii) is a consequence of Theorem 3 and \( de(\lambda) \in \Phi_{gn(\lambda)}^v \).

Lemma 1.12. If \( \xi > 0 \), then the least \( \gamma \)-number \( \mu \) such that \( cf(\mu) = \beta \) and \( \mu > \xi \) is \( \xi \omega_\beta \).

Proof. Let \( \xi \) be the least number with \( \mu \leq \xi \). \( \xi < \mu \) implies \( 1 < \xi \). If \( fr(\xi) \geq 1 \) (i.e., \( \xi \) is an isolated number), then \( \xi(\xi - 1) < \mu \) and \( \mu = \xi(\xi - 1) + \theta \) where \( 0 < \theta \leq \xi < \mu \) contradicting that \( \mu \) is a \( \gamma \)-number (see (b) in Lemma 1.10). Hence \( \xi \) is a limit number, and necessarily \( \mu = \xi \). If \( \xi < \omega \) then \( cf(\mu) = cf(\xi) < \beta \). Hence \( \xi \omega_\beta \) is obviously a \( \gamma \)-number with \( cf(\xi \omega_\beta) = \beta \) and \( \xi \omega_\beta > \xi \).

Corollary. In order that \( \mu \) is a \( \gamma \)-number such that \( \mu > 1 \) and \( cf(\mu) = \beta \) it is necessary and sufficient that \( \mu = \omega^v_\xi \) for an \( \xi \) which is either an isolated number or a limit number with \( cf(\xi) = \beta \).

In general any \( \lambda \in \Gamma^v \) is represented as

\[ \lambda = \alpha_\nu(\xi + \xi) + n, \]

where \( \nu = gn(\lambda), \xi = \gamma(de(\lambda)) \) and \( n = fr(\lambda) \). (Then \( \xi \) is uniquely determined).

Especially if \( \lambda \in \Gamma^v \), then \( de(\lambda) \) is not a \( \gamma \)-number, and hence \( 0 < \xi < de(\lambda) \) and \( 0 < \xi < de(\lambda) \).
If $\lambda \in \Gamma^2$, then $de(\lambda)$ is a $\gamma$-number and $\xi = de(\lambda)$ and $\zeta = 0$. Furthermore, since $cf(de(\lambda)) = cf(ls(\lambda)) = \beta$ by Lemma 1.11, (ii), it follows from Corollary of Lemma 1.12 that $de(\lambda) = \omega^\mu$ and $\lambda$ is represented as

$$\lambda = \alpha_s(\omega^\mu) + n,$$

where $\nu = gn(\lambda)$, $n = fr(\lambda)$ and $\mu$ is either an isolated number or a limit number with $cf(\mu) = \beta$.

**Definition 4.** When $\lambda \in \Gamma^1$ or $\lambda \in \Gamma^2$, the right side of (1) or (2) respectively is called the canonical decomposition of $\lambda$.

**Remark.** (i). When $\lambda \in \Gamma^1$, since $0 < \xi < de(\lambda)$ and $0 < \xi < de(\lambda)$ in (1), we have $\alpha_s(\xi) < \alpha_s(de(\lambda)) = ls(\lambda)$ and $\alpha_s(\xi) < ls(\lambda)$. Furthermore since $cf(ls(\lambda)) = \beta$, we have $\alpha_s(\xi) + \omega < ls(\lambda)$.

(ii). When $\lambda \in \Gamma^2$, since $\nu = gn(\lambda)$ in (2), $\mu < ls(\lambda)$.

If further $\mu$ is an isolated number, then $cf(\omega^\mu) = 0$ and $cf(\omega^\mu) = \beta$, hence $\omega^\mu < \omega^\delta$ and consequently $\omega^\mu < \omega^\delta \leq ls(\lambda)$. If $\mu$ is a limit number with $cf(\mu) = \beta$, then $\omega^\mu = \mu$. (Indeed putting $\mu = \omega^\delta \cdot \theta$ where $0 \leq \theta < \omega^\omega$, $\theta$ is necessarily 0. Hence $\omega^\mu = \omega^\mu \cdot \delta = \omega^\omega \cdot \delta = \mu$). Hence in either case $\omega^\mu < ls(\lambda)$.

This Remark (i) and (ii) will be recalled in Principle 1 later.

**Lemma 1.13.** If $\lambda = \alpha_s(\mu) + \omega$, then the least number $\xi$ in $\Gamma^1_\gamma \cup \Gamma^2_\gamma$ greater than $\lambda$ is $\alpha_s(\omega^\mu + \omega)$.

**Proof.** $\xi \in \Gamma^1_\gamma$ implies $ls(\xi) = \alpha_s(\delta)$ for a $\delta \in \Phi^1$. Since $\lambda < \xi$, $\mu < \delta$. Put $\delta = \mu + \xi$. If $\xi < \omega^\delta$, then $cf(ls(\xi)) = cf(\delta) = cf(\xi) < \beta$ contradicting $\xi \notin \Gamma^\gamma$. Hence $\xi \geq \omega^\delta$ and $\xi$ is of the form $\alpha_s(\mu + \xi) + n$. But among numbers of this form, $\xi = \alpha_s(\mu + \omega^\delta)$ is the least number and obviously contained in $\Gamma_\gamma^1 \cup \Gamma_\gamma^2$. (Especially if $\mu \geq \omega^\delta$, then $\xi \in \Gamma^1_\gamma$).

**Lemma 1.14.** If $\lambda = \alpha_s(\omega^\delta)^+ + \omega$, then the least number $\xi$ in $\Gamma_\gamma^2 \cup \Gamma_{\gamma + 1}$ greater than $\lambda$ is $\alpha_s(\omega^\mu + 1)$.

**Proof.** If $\xi \in \Gamma_{\gamma + 1}$, then $ls(\xi) = \alpha_s(\omega^\mu + \omega^\delta)$. Hence $\xi \in \Gamma_{\gamma}^2 \cup \Gamma_{\gamma + 1}$ implies that $ls(\xi)$ is of the form $\alpha_s(\omega^\nu)$ where $\nu < \xi$ implies $\mu < \delta$. Hence $\xi \in \Gamma_\gamma^2 \cup \Gamma_{\gamma + 1}$ and $\lambda < \xi$ imply that $\xi$ is of the form $\alpha_s(\omega^\mu + 1) + n$ where $\nu \geq 1$. But among numbers of this form, $\xi = \alpha_s(\omega^\mu + 1)$ is the least number and contained in $\Gamma_\gamma^2$.

**Chapter II. Main Theorems**

In this chapter, we shall introduce central notions and state Main Theorems. Finally a brief orientation of the proof of Theorem A is mentioned.
1. Ramified sets and relation

**Definition 5.** A ramified set \( X \) (which is called "un tableau ramifié" in [4]) is a partially ordered set which satisfies the following condition: for any \( x \in X \) the set \( \{ a \in X, a <^x \} \) is a well-ordered subset of \( X \).

By definition the following is obvious.

**Lemma 2.1.** (i). A subset of a ramified set is also a ramified set with the original order-relation. (ii). A ramified set satisfies the descending chain condition (see [2], p. 37). (iii). A totally ordered ramified set is a well-ordered set. Conversely a well-ordered set is a ramified set.

In this paper capital Latin letters, as well as these with suffixes, are used to denote ramified sets or their subsets. Especially \( W \) denotes a well-ordered set. \( W_\lambda \) is the set of all \( \xi <^\lambda \) with the natural order between them. Small Latin letters stand for elements of ramified sets or mappings into ramified sets (mostly from ramified sets), except \( i, k, m \) and \( n \) which are finite numbers. Especially \( f, g \) or \( h \) is used to denote a mapping of a ramified set into another (occasionally in itself). Capital German letters are used to denote families or sequences of ramified sets (or their subsets).

Concerning ramified sets we shall settle terminologies and notations followingly.

**Definition 6.** (i). For \( x \in X \), \( \text{Lb}(x \mid X) \), or simply \( \text{Lb}(x) \) (in the case where \( x \) is contained in a definite set or it is apparent what set \( X \) is referred to), denotes the set of all \( a \in X \) with \( a <^x \).

\( \text{Lb}'(x \mid X) \), or simply \( \text{Lb}'(x) \), denotes \( \text{Lb}(x \mid X) \cup \{ x \} \). (Lower bounds of \( x \)).

(ii). \( \text{Ub}(x \mid X) \), or simply \( \text{Ub}(x) \), denotes the set of all \( a \in X \) with \( a >^x \).

\( \text{Ub}'(x \mid X) \) or \( \text{Ub}'(x) \) denotes \( \text{Ub}(x \mid X) \cup \{ x \} \). (Upper bounds of \( x \)).

(iii). \( \tau(x \mid X) \), or simply \( \tau(x) \), denotes the order-type, which is an ordinal number, of \( \text{Lb}(x \mid X) \).

(iv). A subset \( Y \) of \( X \) is called a cut of \( X \) if \( y \in Y, x \in X \) and \( x <^y \) imply \( x \in Y \).

(v). \( \text{Seg}_\tau(X) \), \( \text{Lay}_\tau(X) \) and \( \text{Csg}_\tau(X) \) denote the sets \( \{ x \mid x \in X, \tau(x) <^\omega \} \), \( \{ x \mid x \in X, \tau(x) =^\omega \} \) and \( \{ x \mid x \in X, \tau(x) \geq^\omega \} \) respectively.

(vi). Let \( Y \) be a cut of \( X \). \( \text{Exp}_\tau(Y \mid X) \), or simply \( \text{Exp}_\tau(Y) \), denotes the subset of \( X \) which consists of all \( y \in Y \) and all \( x \in \text{Csg}_\tau(X) \) such that \( \text{Lb}(x \mid X) \wedge \text{Seg}_\tau(X) \) is entirely included in \( Y \).

By definition we have obviously
Lemma 2.2.  (i). If \( x \in Y \subseteq X \), then \( Lb(x; Y) = Lb(x; X) \cap Y \). Similar equalities hold for \( Lb' \), \( Ub \) and \( Ub' \).  (ii). If \( x < y \), then \( \tau(y; X) = \tau(x; X) + 1 + \tau(y; Ub(x)) \).

Concerning \( Exp_v(Y; X) \) we have

Lemma 2.3. Let \( Y \) be a cut of \( X \).  (i). \( Exp_v(Y) \) is a cut of \( X \).  (ii). \( Exp_v(Seg_v(X)) = X \).  (iii). \( Y \subseteq Exp_v(Y) \).  (iv). If \( Z \) is a cut of \( Y \), then \( Exp_v(Z; X) \subseteq Exp_v(Y; X) \), \( Exp_v(Z; Y) = Exp_v(Z; X) \cap Y \) and \( Exp_v(Exp_v(Z; Y); X) = Exp_v(Z; X) \).  (v). If \( Z \) is a cut of \( X \), then \( Exp_v(Y \cup Z) = Exp_v(Y) \cup Exp_v(Z) \).  (vi). \( x \in Exp_v(Y) \cap Csg_v(X) \), if and only if the type of \( Lb(x) \cap Y \) is not less than \( \omega^v \).  (vii). If \( x \) is a minimal element of \( X - Exp_v(Y) \), then \( x \in Seg_v(X) \).  (viii). \( Exp_v(Exp_v(Y)) = Exp_v(Y) \).

Proof. We shall show only (vii) and (viii), since the others are trivial.

(vii). Assume \( \tau(x) \geq \omega^x \). Since \( x \in X - Exp_v(Y) \), the type of \( Lb(x) \cap Y \) is less than \( \omega^x \). Hence there exists an \( a \in Lb(x) - Y \) such that \( \tau(a) < \omega^x \). Since \( x \) is minimal within \( X - Exp_v(Y) \), \( a \in Exp_v(Y) \). But by definition, \( a \in Exp_v(Y) - Y \) implies \( a \in Csg_v(X) \) contradicting \( \tau(a) < \omega^x \). Hence \( x \in Seg_v(X) \).

(viii). \( Exp_v(Exp_v(Y)) \supset Eq_v(X) \) follows from (iii) and (iv). Assume that \( D = Eq_v(Exp_v(Y)) - Eq_v(Y) \) is not void, and let \( x \) be a minimal element in \( D \). Since \( x \) is minimal in \( X - Eq_v(Y) \), \( \tau(x) < \omega^x \), while putting \( Z = Eq_v(Y) \), \( x \in Eq_v(Z) - Z \) implies \( x \in Csg_v(X) \) contradictirly. Hence \( D \) is void and \( Eq_v(Exp_v(Y)) = Eq_v(Y) \).

Remark 1. By (iii), (iv), (v) and (viii) of Lemma 2.3 the operation \( Eq_v \) on cuts of a ramified set satisfies the conditions of the so-called “finite-additive closure operation”.

Remark 2. In most cases where we are concerned with several ramified sets, each of them is a subset of one of them, for instance \( X \). Then, when we write simply \( Ub(x) \), \( \tau(x) \), \( Eq_v(Z) \) etc., it means \( Ub(x; X) \), \( \tau(x; X) \), \( Eq_v(Z; X) \) etc. respectively, and according to Lemma 2.1 (i) and Lemma 2.2 (iv), if \( Y \) is a subset or a cut of \( X \), then \( Ub(x; Y) \), \( Eq_v(Z; Y) \) etc. are mostly expressed by \( Ub(x) \cap Y \), \( Eq_v(Z) \cap Y \) etc. respectively.

Definition 7. Let \( X \) be a non-void ramified set. \( X \) is called resoluble if for any non-void subset \( Y \) of \( X \), there exists a \( y \in Y \) such that \( Ub(y) \cap Y \) is totally ordered. (Of course a void set is regarded as a totally ordered set). If \( X \) is not resoluble, then it is called irresoluble. If for any \( x \in X \), \( Ub(x) \) is not totally ordered, then \( X \) is called perfectly irresoluble.
For convenience a void set is regarded as resoluble and (perfectly) irresoluble in the same time.

For a subset $Y$ of $X$, let $J(Y)$ denote the set of all $y \in Y$ such that $\cup b(y) \cap Y$ is not totally ordered. Put $J_0(X) = X$, $J_{\xi+1}(X) = J(J_\xi(X))$ for any $\xi$ and $J_\xi(X) = \bigcap_{\xi < \xi} J_\xi(X)$ for a limit number $\xi$. If $J_{\xi+1}(X) \subseteq J_\xi(X)$ for any $\xi < \lambda$, then $\lambda$ can not exceed the potency of $X - J_\lambda(X)$. Hence there exists a $\lambda$, whose potency does not exceed $\overline{X}$, such that $J_{\lambda+1}(X) = J_\lambda(X)$. Put $K(X) = J_\lambda(X)$ for such a $\lambda$, then $J(K(X)) = K(X)$, $K(X)$ is perfectly irresoluble. If a subset $Y$ of $X$ is not included in $K(X)$, then there exists the least number $\xi$ such that $J_\xi(X)$ does not include $Y$. $\xi$ is not a limit number or otherwise $Y \subseteq J_\xi(X)$ contradictrily. Put $\xi = \xi + 1$, then $Y \subseteq J_\xi(X)$. Let $y$ be any element in $Y - J_\xi(X)$, then since $y \in J_\xi(X) - J_\xi(X)$, $\cup b(y) \cap Y - \cup b(y) \cap J_\xi(X)$ is totally ordered, i.e., $Y$ is not perfectly irresoluble. Hence $K(X)$ is the largest (in the sense of inclusion) perfectly irresoluble subset of $X$, which we shall call the perfectly irresoluble part of $X$. Similarly we can see that $X$ is resoluble if and only if $K(X)$ is void. In general $X - K(X)$ is always resoluble, which we shall call the resoluble part of $X$.

Summing up we have

**Theorem 4.** Any ramified set $X$ is uniquely decomposed into the union of its perfectly irresoluble part and resoluble part. $X$ is resoluble if and only if its perfectly irresoluble part is void.

**Corollary.** A subset of resoluble ramified set is also resoluble.

**Definition 8.** (i). A mapping $f$ (many-to-one in general) which maps $X$ into $Y$ is called increasing if $a < b$ implies $f(a) < f(b)$ for any $a$ and $b$ in $X$.

(ii). If there exists an increasing mapping of $X$ into $Y$, then $X$ is called smaller than $Y$ and $Y$ is called larger than $X$; in symbol $X \sim Y$. If $X \sim Y$ and $Y \sim X$, then $X$ is called equivalent to $Y$; in symbol $X \sim Y$. $X \sim Y$ and $X \sim Y$ denote the negations of $X \sim Y$ and $X \sim Y$ respectively.

(iii). A one-to-one increasing mapping of $X$ onto whole $Y$ with an increasing inverse is called an isomorphism of $X$ to $Y$. If there exists an isomorphism of $X$ to $Y$, then $X$ is called isomorphic to $Y$; in symbol $X = Y$. $X \equiv Y$ denotes the negation of $X \equiv Y$.

(iv). For an increasing mapping $f$ of $X$ into $Y$ and a subset $Z$ of $X$, $f(Z)$ denotes the set $\{f(x) | x \in Z\}$. $f$ is called reduced if $f(Z)$ is a cut of $Y$ for any cut $Z$ of $X$.

(v). $\kappa(X)$ denotes the least ordinal number $\xi$ such that $W_{\xi} \sim X$. 

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*Ramified Sets*
Lemma 2.4. Let $f$ be an increasing mapping of $X$ into $Y$. Then,
(i) $\tau(f(x)) \geq \tau(x)$ for any $x \in X$, (ii) $f$ is reduced if and only if $\tau(f(x)) = \tau(x)$ for any $x \in X$.

Proof. (i). Since $\text{Lb}(x)$ is a well-ordered set and $f$ is increasing, $\text{Lb}(x)$ is isomorphic to $f(\text{Lb}(x))$ which is a subset of $\text{Lb}(f(x))$. Hence the order-type $\tau(x)$ of $\text{Lb}(x)$ does not exceed the type $\tau(f(x))$ of $\text{Lb}(f(x))$ by a well-known theorem on well-ordered sets. Hence $\tau(x) \leq \tau(f(x))$.

(ii). Assume that there exists an $x \in X$ such that $\tau(f(x)) > \tau(x)$. Let $x$ be such a minimal element (see Lemma 2.1 (ii)). Since $\tau(f(x)) > \tau(x)$, there exists a unique element $b$ such that $\tau(b) = \tau(x)$ and $b < f(x)$. If $a < x$, then $\tau(f(a)) = \tau(a) < \tau(x) = \tau(b)$ and hence $f(a) = b$. Hence there is no element $a \in \text{Lb}'(x)$ such that $f(a) = b$. $\text{Lb}'(x)$ is a cut of $X$, while since $f(\text{Lb}'(x))$ contains $f(x)$ and does not contain $b < f(x)$, $f(\text{Lb}'(x))$ is not a cut of $Y$. Hence $f$ is not reduced.

Conversely assume $\tau(f(x)) = \tau(x)$ for any $x \in X$, and let $Z$ be a cut of $X$. If $b < f(z)$ where $z \in Z$, then, since $\tau(b) < \tau(f(z)) = \tau(z)$, there exists an $a < z$ such that $\tau(a) = \tau(b)$. Since $\tau(f(a)) = \tau(a) = \tau(b)$ and both $f(a)$ and $b$ are contained in $\text{Lb}(f(x))$, $f(a)$ coincides with $b$. Since $Z$ is a cut of $X$, $a \in Z$ and $b \in f(Z)$. Hence $f(Z)$ is a cut of $Y$ and $f$ is reduced.

Lemma 2.5. If $X \preceq Y$, then there exists a reduced increasing mapping of $X$ into $Y$.

Proof. $X \preceq Y$ implies the existence of an increasing mapping $g$ of $X$ into $Y$. For any $x \in X$, since $\tau(x) \leq \tau(g(x))$ by Lemma 2.4 (i), an element $f(x)$ of $Y$ is uniquely determined by $x$ in such a way that $f(x) \leq g(x)$ and $\tau(f(x)) = \tau(x)$. If $x < x'$ where $x, x' \in X$, then $f(x) \leq g(x) < g(x')$, and hence $f(x)$ and $f(x')$ are contained in $\text{Lb}'(g(x'))$. Since $\text{Lb}'(g(x'))$ is well-ordered and $\tau(f(x')) = \tau(x) < \tau(x') = \tau(f(x'))$, we have $f(x) < f(x')$ and $f$ is increasing. Further $f$ is reduced by Lemma 2.4 (ii), and our lemma is proved.

Corollary. If $X \preceq Y$, then $\text{Seg}_< (X) \preceq \text{Seg}_< (Y)$ and $\text{Csg}_< (X) \preceq \text{Csg}_< (Y)$.

It is easily seen that the relation $\preceq$ is a quasi-ordering between ramified sets and the relation $\sim$ is an equivalence relation (see [2], p. 4).

Theorem 5. (i). If $\kappa(X) = \mu + 1$, then $X \sim W_\mu$. (ii). If $\kappa(X) < \kappa(Y)$, then $X \preceq Y$.

Proof. (i). By the definition of $\kappa(X)$, $W_\mu \preceq X$.

For any element $x \in X$, $\tau(x) < \mu$, since $W_{\mu+1} \preceq \text{Lb}'(x)$. Put $f(x) = \tau(x)$ for any $x \in X$, then obviously $f$ is an increasing mapping of $X$ into $W_\mu$. Hence $X \preceq W_\mu$, which shows $X \sim W_\mu$.

(ii). Put $\mu = \kappa(X)$. Since $\mu < \kappa(Y)$, $W_\mu \preceq Y$ and there exists an
increasing mapping \( g \) of \( W_\mu \) into \( Y \). Similarly as the above, the mapping \( f \) of \( X \) such that \( f(x) = \tau(x) \) for any \( x \in X \) is an increasing mapping of \( X \) into \( W_\mu \). Since \( gf \) is an increasing mapping of \( X \) into \( Y \), \( X \preceq Y \). If \( Y \preceq X \), then \( W_\mu \preceq X \) contradicting \( \kappa(X) = \mu \). Hence \( X \preceq Y \).

We shall say that \( X \) is comparable with \( Y \) if either \( X \preceq Y \) or \( Y \preceq X \).

**Corollary.** If \( \kappa(X) \) is an isolated number, then \( X \) is comparable with any \( Y \).

### 2. Main Theorems

**Definition 9.** Let \( \omega_\beta \) be a fixed regular initial number greater than \( \omega_\alpha \) as we assumed in Chapter 1, § 1.

(i). \( \mathcal{R}_\beta \) denotes the family of all ramified sets with potencies less than \( \kappa_\beta \).

(ii). \( \mathcal{E}_\beta \) denotes the family of all resolvable ramified sets in \( \mathcal{R}_\beta \).

(iii). \( [\mathcal{R}_\beta] \) denotes the family of all equivalence classes of sets \( X \in \mathcal{R}_\beta \).

(iv). A class \( \mathcal{K} \) in \( [\mathcal{R}_\beta] \) is called resolvable if it contains a resolvable set. The family of all resolvable classes in \( [\mathcal{R}_\beta] \) is denoted by \( \mathcal{E}_\beta \).

(v). For \( \mathcal{K} \) and \( \mathcal{Y} \) in \( [\mathcal{R}_\beta] \), \( \mathcal{K} \preceq \mathcal{Y} \) means that there exists an \( X \in \mathcal{K} \) and a \( Y \in \mathcal{Y} \) such that \( X \preceq Y \).

**Remark 1.** \( [\mathcal{E}_\beta] \) is not defined as the family of all equivalence classes of sets in \( \mathcal{E}_\beta \). But it is not a matter of much difference, and \( [\mathcal{E}_\beta] \) may be taken for such a family without any modification in the succeeding mention.

**Remark 2.** Since the relation \( \preceq \) between ramified sets is a quasi-ordering, it is an order-relation between classes in \( [\mathcal{R}_\beta] \). It is obvious that if \( \mathcal{K} \preceq \mathcal{Y} \) for \( \mathcal{K} \) and \( \mathcal{Y} \) in \( [\mathcal{R}_\beta] \), then \( X \preceq Y \) for any \( X \in \mathcal{K} \) and \( Y \in \mathcal{Y} \).

**Lemma 2.6.** \( X \in \mathcal{R}_\beta \) implies \( \kappa(X) < \omega_\beta \).

Proof. Since \( \omega_\beta \) is regular and \( X \prec \kappa_\beta \), numbers \( \tau(x) \) with \( x \in X \), which are obviously less than \( \omega_\beta \), are not cofinal to \( \omega_\beta \). Hence putting \( \xi = \sup_{x \in X} \tau(x), \xi < \omega_\beta \) and \( W_{\xi+1} \preceq X \), i.e., \( \kappa(X) \leq \xi + 1 < \omega_\beta \).

Our main purpose of this paper is to prove the following:

**Main Theorem A.** (i). The family \( [\mathcal{E}_\beta] \) of resolvable classes is well-ordered by \( \preceq \). (ii). A resolvable ramified set is comparable with any other ramified set (resolvable or not).

**Main Theorem B.** Continuum Hypothesis (see [2], p. 45 or [8]) implies that, (i) there exist ramified sets which are not comparable with each other,
and, (ii) there exists a sequence of ramified sets \( X_i \), \( i=1,2,\ldots \) such that
\[ X_{i+1} \supseteq X_i \text{ for any } i < \omega. \]

Of course examples to confirm Theorem B can not be obtained within the confines of resoluble ramified sets as far as Theorem A is valid. Theorem B will be proved in Chapter IV, §2, while hereafter up to the end of Chapter III, we shall exclusively discuss about Theorem A.

Speaking of only Theorem A, (ii), it seems to be proved rather easily by induction on the least number \( \xi \) with which \( J_\xi(X) \) vanishes for a resoluble ramified set \( X \) (see the mention above Theorem 4). But by this induction the proof of Theorem A, (i) seems at least as laborious as the discussion we shall proceed henceforth.

In this paper, in order to prove Theorem A, we shall construct a certain sequence \( \mathcal{R} = \{ N_\lambda | \lambda < \beta^2 \} \) of sets \( N_\lambda \in \mathcal{S}_\beta \) starting from \( N_0 = 0 \), and show that

C) for any \( \delta < \omega_\beta \), there exists a \( \lambda < \beta^3 \) with \( \kappa(N_\lambda) \geq \delta \), and

D) each \( N_\lambda \) satisfies the following D.1), D.2) and D.3):

D.1) \( N_\mu \uparrow N_\lambda \) for any \( \mu < \lambda \).

D.2) If \( X \in \mathcal{S}_\beta \) and \( X \not\equiv N_\mu \) for any \( \mu < \lambda \), then \( N_\lambda \equiv X \).

D.3) \( N_\lambda \) is comparable with any \( X \in \mathcal{S}_\beta \).

Note that

**Lemma 2.7.** If a \( N_\lambda \) in \( \mathcal{R} \) satisfies D.1) and D.2') mentioned below, then \( N_\lambda \) satisfies D.2) and D.3).

D.2'). If \( X \in \mathcal{S}_\beta \) and \( X \not\equiv N_\mu \) for any \( \mu < \lambda \), then \( N_\lambda \equiv X \).

Proof. It is obvious that \( N_\lambda \) satisfies D.2). Let \( X \) be any set in \( \mathcal{S}_\beta \). If there exists a \( \mu < \lambda \) with \( X \equiv N_\mu \), then by D.1) \( X \equiv N_\lambda \). If \( X \not\equiv N_\mu \) for any \( \mu < \lambda \), then \( N_\lambda \equiv X \) by D.2'). Hence \( N_\lambda \) is comparable with \( X \), and \( N_\lambda \) satisfies D.3).

**Remark.** Hereafter, when we say that a set in \( \mathcal{R} \), for instance \( N_\xi \), satisfies D.1), D.2), D.3) or D.2'), it means that \( N_\xi \) satisfies it in which \( \lambda \) is replaced by \( \xi \).

Before we actually construct this sequence \( \mathcal{R} \), we shall assume that there exists a sequence \( \mathcal{R} \) which satisfies C) and D), and consider the consequence of its existence.

**Lemma 2.8.** If a sequence \( \mathcal{R} \) of \( N_\lambda \in \mathcal{S}_\beta \) with \( N_0 = 0 \) satisfies C) and D), then for any \( X \in \mathcal{S}_\beta \), there exists a \( \lambda < \beta^2 \) such that \( X \sim N_\lambda \).

Proof. Since \( \kappa(X) < \omega_\beta \), there exists a \( \lambda < \beta^3 \) such that \( \kappa(X) < \kappa(N_\lambda) \), which implies \( X \sim N_\lambda \) by Theorem 5, (ii). Let \( \lambda \) be the least number such that \( X \sim N_\lambda \). If \( \lambda = 0 \), then \( N_\lambda = 0 \) and hence \( X = 0 \), i.e., \( X \equiv N_0 \). If \( \lambda > 0 \), then \( X \not\equiv N_\mu \) for any \( \mu < \lambda \), which implies \( N_\lambda \equiv X \) by D.2). Hence \( X \sim N_\lambda \).
Corollary. \([\mathcal{S}_\beta]\) is well-ordered by \(\prec\) (Theorem A, (i)).

Proof. The order-type of \([\mathcal{S}_\beta]\) is same as the type of sequence \(R\) by the lemma above, i.e., \([\mathcal{S}_\beta]\) is well-ordered by \(\prec\) in the type \(\beta^3\).

Lemma 2.9. Any \(X \in \mathcal{S}_\beta\) is comparable with any \(Y \in \mathcal{R}_\beta\).

Proof. By Lemma 2.2, there exists a \(\lambda \prec \beta^3\) with \(X \sim N_\lambda\). By D.3), \(N_\lambda\) is comparable with any \(Y \in \mathcal{R}_\beta\). Hence \(X\) is also comparable with \(Y\).

Corollary. The existence of \(R\) for any regular number \(\omega_\beta > \omega_0\), which satisfies C) and D), implies Theorem A, (ii).

Proof. For any ramified sets \(X\) and \(Y\), there exists sufficiently large regular number \(\omega_\beta > \omega_0\) such that \(X\) and \(Y\) are contained in \(\mathcal{R}_\beta\). Especially if \(X\) is resoluble, then \(X \in \mathcal{S}_\beta\). Hence \(X\) is comparable with \(Y\) by the lemma above.

Thus Theorem A is proved if a certain sequence \(\mathcal{R}\) of \(N_\lambda \in \mathcal{S}_\beta\) with \(N_\lambda = \emptyset\) satisfies C) and D) (associating to every regular number \(\omega_\beta > \omega_0\)).

Now we shall consider the construction of \(\mathcal{R}\), and for this purpose we shall define several operations on ramified sets.

**Definition 10.** (i). Let \(\Lambda\) be a set of indecies, or especially a set of ordinal numbers, and assume that a ramified set \(X_\lambda\) is assigned to each \(\lambda \in \Lambda\). \(\bigvee_{\lambda \in \Lambda} X_\lambda\) or simply \(\bigvee X_\lambda\) (or occasionally \(\bigvee X_\lambda\), etc.), denotes the set of all pairs \((\lambda, x)\) with \(\lambda \in \Lambda\) and \(x \in X_\lambda\), where \((\lambda, x) \prec (\mu, y)\) holds if and only if \(\lambda = \mu\) and \(x \prec y\) within \(X_\lambda\).

For a subset \(Y\) of \(X_\lambda\), the set \(\{ (\lambda, x) | x \in Y \}\) is denoted by \((\lambda, Y)\).

(ii). For an ordinal number \(\lambda\) and a ramified set \(X\), \(W_\lambda + X\) denotes the set which consists of all \(\mu \in W_\lambda\) and all terms \(\lambda + x\) with \(x \in X\), where the order-relation preserves original meaning within \(W_\lambda\), \(\mu \prec \lambda + x\) for any \(\mu \in W_\lambda\) and \(x \in X\), and \(\lambda + x \prec \lambda + y\) if and only if \(x \prec y\) within \(X\).

For a subset \(Y\) of \(X\) the set \(\{ \lambda + x | x \in Y \}\) is denoted by \(\lambda + Y\).

(iii). For ramified sets \(X\) and \(Y\) and an ordinal number \(\nu \prec \omega_\beta\), the ramified product \(X \odot Y\) is a set which consists of all \(x \in X\) and pairs \((x, y)\) with \(x \in \text{Seg}(X)\) and \(y \in Y\), where order within \(X\) preserves original meaning, \(x \prec (x', y)\) if and only if \(x \leq x'\) within \(X\), and \((x, y) \prec (x', y')\) if and only if \(x = x'\) and \(y < y'\) within \(Y\).

For a subset \(Z\) of \(Y\), the set \(\{ (x, z) | z \in Z \}\) is denoted by \((x, Z)\).

**Remark 1.** \(\bigvee X_\lambda\) and \(W_\lambda + X\) are called a cardinal sum and an ordinal sum respectively in [2] or [3]. But the first term of \(W_\lambda + X\) is restricted to a well-ordered set in order that the resultant be a ramified set.

**Remark 2.** In \(W_\lambda + X\), the notation \(\lambda + x\) is used only to denote a term, and the signature \(+\) has no special meaning. But when \(X = W_\lambda\) and
\[ x = \mu \in W_\xi, \lambda + \mu \text{ is taken for the usual sum of ordinal numbers. Thus we have} \]

\[ W_\lambda + W_\xi = W_{\lambda + \xi}, \]

not only the equivalency of both sides.

**Lemma 2.10.** \( \bigvee_\Lambda X_\lambda, W_\lambda + X \text{ and } X \odot_\gamma Y \text{ are ramified sets, and if } X_\lambda \text{ (for any } \lambda \in \Lambda), X \text{ and } Y \text{ are resoluble, then } \bigvee_\Lambda X, W_\lambda + X \text{ and } X \odot_\gamma Y \text{ are resoluble.} \)

We omit the proof since it is obvious.

**Lemma 2.11.** If \( X_\lambda \prec Y \) for any \( \lambda \in \Lambda \), then \( \bigvee_\Lambda X_\lambda \prec Y. \)

Proof. For any \( \lambda \in \Lambda \) there exists an increasing mapping \( f_\lambda \) of \( X_\lambda \) into \( Y \). Put \( f((\lambda, x)) = f_\lambda(x) \) for any \( \lambda \in \Lambda \) and \( x \in X_\lambda \), then obviously \( f \) is an increasing mapping of \( \bigvee_\Lambda X_\lambda \) into \( Y \) and \( \bigvee_\Lambda X_\lambda \prec Y. \)

**Corollary.** Let \( X_\lambda \) and \( Y_\nu \) be ramified sets assigned to each \( \lambda \in \Lambda \) and \( \nu \in \nu' \) respectively. If for any \( \lambda \in \Lambda \) there exists a \( \nu' \in \nu' \) such that \( X_\lambda \prec Y_{\nu'} \), then \( \bigvee_\Lambda X_\lambda \prec \bigvee_\nu Y_{\nu'}. \)

Further the following lemma is easily seen and we omit the proof.

**Lemma 2.12.** (i) If \( X \prec X' \) and \( Y \prec Y' \), then \( W_\lambda + X \prec W_\lambda + X' \) and \( X \odot_\gamma Y \prec X' \odot_\gamma Y'. \)

(ii) Putting \( A = \text{Lay}_\nu(X), \operatorname{Csg}_\nu(X) = \bigvee_{a \in A} \text{Ub}'(a). \)

(iii) \( X \prec W_\nu + Y, \text{ if and only if } \operatorname{Csg}_\nu(X) \prec Y. \)

(iv) \( \bigvee_{\lambda \in \Lambda} X_\lambda \odot_\gamma Y = \bigvee_{\lambda \in \Lambda} (X_\lambda \odot_\gamma Y). \)

(v) \( \kappa(\bigvee_{\lambda \in \Lambda} X_\lambda) = \sup_{\lambda \in \Lambda} \kappa(X_\lambda). \) If \( \max(\kappa(X), \kappa(Y), \omega^\nu) \leq \omega^\nu, \) then \( \kappa(X \odot_\gamma Y) \leq \omega^\nu. \)

(vi) \( \operatorname{Csg}_{\nu}(\bigvee_{\lambda \in \Lambda} X_\lambda) \sim \bigvee_{\lambda \in \Lambda} \operatorname{Csg}_{\nu}(X_\lambda). \) If \( X \prec Y \) and \( \eta \leq \nu, \) then \( \operatorname{Csg}_{\nu}(X \odot_\gamma Y) = \operatorname{Csg}_{\nu}(X) \).

(vii) If \( Z \) is a cut of \( X \), then \( \operatorname{Exp}(Z; X \odot_\gamma Y) = \operatorname{Exp}(Z; X). \) If \( Z \) is a cut of \( \bigvee_{\lambda \in \Lambda} X_\lambda \), then \( \operatorname{Exp}(Z; \bigvee_{\lambda \in \Lambda} X_\lambda) = \bigvee_{\lambda \in \Lambda} \operatorname{Exp}(Z \odot_\gamma X_\lambda; X_\lambda). \)

**Lemma 2.13.** If \( \eta \) is an isolated number less then \( \omega^\nu, \) then \( W_\eta + X \prec W_\eta \odot_\gamma X. \)

Proof. \( W_\eta \) has a greatest number \( \xi \), and \( \xi \in \text{Seg}_\nu(W_\eta). \) The mapping \( f \) such that \( f(\mu) = \mu \) for \( \mu \in W_\eta \) and \( f(\eta + x) = (\xi, x) \) for \( x \in X \) is obviously an increasing mapping of \( W_\eta + X \) into \( W_\eta \odot_\gamma X. \) Conversely the mapping \( g \) such that \( g(\mu) = \mu \) for \( \mu \in W_\eta \), and \( g((\mu, x)) = \eta + x \) for any \( \mu \in W_\eta \) and \( x \in X \) is an increasing mapping of \( W_\eta \odot_\gamma X \) into \( W_\eta + X. \) Hence \( W_\eta + X \prec W_\eta \odot_\gamma X. \)

**Corollary.** \( W_\eta + X \prec W_\eta \odot_\gamma X \) for any \( \nu \) with \( 0 \prec \nu \prec \omega_\beta. \)
Lemma 2.14. If $Y$ is not void, then $X \odot_v (Y \odot_v Z) \sim (X \odot_v Y) \odot_v Z$.

Proof. Here temporarily let $x$, $y$ and $z$ denote elements in $X$, $Y$ and $Z$ respectively and $x'$ and $y'$ denote elements in $\text{Seg}_v(X)$ and $\text{Seg}_v(Y)$ respectively. $X \odot_v (Y \odot_v Z)$ consists of all terms $x$, $(x', y)$ and $(x', (y', z))$ while $(X \odot_v Y) \odot_v Z$ consists of all terms $x$, $(x', y)$, $((x', y'), z)$ and $(x', z)$. (remark that $(x', y) \in \text{Seg}_v(X \odot_v Y)$ if and only if $y \in \text{Seg}_v(Y)$). The mapping $f$ such that $f(x) = x$, $f((x', y)) = (x', y)$ and $f((x', (y', z))) = ((x', y'), z)$ is an increasing mapping of $X \odot_v (Y \odot_v Z)$ into $(X \odot_v Y) \odot_v Z$. Let $y_0$ be any element in $\text{Seg}_v(Y)$. The mapping $g$ which is the inverse of $f$ in the range of $f$ and $g((x', z)) = (x', (y_0, z))$, is an increasing mapping of $(X \odot_v Y) \odot_v Z$ into $X \odot_v (Y \odot_v Z)$ and hence we have our equivalency.

Lemma 2.15. If $X$ is not void and $\eta < \omega^\gamma$, then $W_\eta + (X \odot_v Y) \sim (W_\eta + X) \odot_v Y$.

Proof. We use notations $x$, $y$, $x'$ and $y'$ with same meaning in the proof of Lemma 2.14, and $\mu$ as an element in $W_\eta$. $W_\eta + (X \odot_v Y)$ consists of all terms $\mu$, $\eta + x$ and $\eta + (x', y)$ while $(W_\eta + X) \odot_v Y$ consists of all terms $\mu$, $\eta + x$, $(\eta + x', y)$ and $(\mu, y)$. $W_\eta + (X \odot_v Y) \odot_v (W_\eta + X) \odot_v Y$ is obvious. Let $x_0$ be any element in $\text{Seg}_v(X)$, then the mapping $f$ such that $f(\mu) = \mu$, $f(\eta + x) = \eta + x$, $f((\eta + x', y)) = \eta + (x', y)$ and $f((\mu, y)) = \eta + (x_0, y)$ is an increasing mapping of $(W_\eta + X) \odot_v Y$ into $W_\eta + (X \odot_v Y)$. Hence we have our equivalency.

We assume that for any limit number $\lambda < \beta^\gamma$, a set $\Lambda_\lambda$ of ordinal numbers $\mu < \lambda$ is selected by axiom of choice, so that $\Lambda_\lambda = \text{asc}(\lambda)$ and $\Lambda_\lambda$ is cofinal to $\lambda$. For an isolated number $\lambda$ put $\Lambda_\lambda = \Lambda_{\text{Is}(\lambda)}$. Besides, put $\sigma_\xi = \omega$ if $\text{cf}(\text{Is}(\xi)) = \beta$ and $\sigma_\xi = 0$ if $\text{cf}(\text{Is}(\xi)) < \beta$. $N_\lambda$ in $\mathbb{N}$ is inductively defined along the following principle.

PRINCIPLE 1. Put $N_0 = 0$ and $N_n = W_n$.

Case $\lambda \in \Gamma^0$. Then put
$$N_\lambda = W_{\text{tr}(\lambda)} + (\bigvee_{\lambda \in \Lambda_\lambda} N_{\mu}).$$

Case $\lambda \in \Gamma^1$. Let $\lambda = \alpha \odot (\xi + \zeta) + n$ be the canonical decomposition of $\lambda$ (see Definition 4), and put
$$N_\lambda = N_{\alpha \odot \xi} \odot_v N_{\alpha \odot \xi + \sigma_\xi} \odot_v N_{\alpha \odot \xi + \sigma_\xi + n}.$$

Case $\lambda \in \Gamma^2$. Let $\lambda = \alpha \odot (\omega_\xi) + n$ be the canonical decomposition of $\lambda$. If $\xi$ is a limit number (and necessarily $\text{cf}(\xi) = \beta$), then put
$$N_\lambda = W_{\omega_\xi} + N_{\xi + n}.$$

If $\xi$ is an isolated number $\zeta + 1$, then put
$$N_\lambda = W_{\omega_\xi} + N_{\omega_\xi + \sigma_\xi + n}.$$
REMARK 1. According to Remark below Definition 4, the index attached to each $N$ which appears in the right sides of four formulae in Principle 1 is surely less than $\lambda$, and the definition of $N_\lambda$ is inductive.

REMARK 2. Let $\lambda$ be a limit number in $\Gamma^\alpha$. Of course the set $N_\lambda$ itself, as well as $N_{\lambda+n}$, is determined depending on the choice of $\Lambda_\lambda$, but it is easily seen that, under the assumption that $N_\mu$ with any $\mu<\lambda$ satisfies D.1, the equivalence class which contains $N_\lambda$ is determined independently of the choice of the sequence $\Lambda_\lambda$ cofinal to $\lambda$. (Refer to Corollary of Lemma 2.11).

Referring to Lemma 2.10, we can see that any $N_\lambda$ is contained in $\Theta_\beta$. For $\lambda=\alpha_\nu(\omega_\beta)$, $N_\lambda=W_\omega+X_0=W_\omega'$, and $\nu(N_\lambda)=\omega_\nu+1$, from which it follows that $\mathcal{R}$ satisfies C). Therefore in proving Main Theorem A, it is remained only to prove that each $N_\lambda$ in $\mathcal{R}$ satisfies D.1), D.2) and D.3). Next chapter is devoted to this proof.

CHAPTER III. PROOF OF MAIN THEOREM A

In this chapter we shall show that any $N_\lambda\in\mathcal{R}$ satisfies D.1), D.2) and D.3) to complete the proof of Main Theorem A. First we prepare some lemmas on $N_\lambda$ ($\S$ 1), and next discuss about $N_\lambda$ for each case $\lambda\in\Gamma^0$, $\lambda\in\Gamma^1$ and $\lambda\in\Gamma^2$ in $\S$ 2, $\S$ 3 and $\S$ 4 respectively.

1. Preliminaries on $N_\lambda$

Lemma 3.1. If $\lambda\in\Gamma^0_1\cup\Gamma^2_1$ and $\eta<\omega_\nu$,

$$W_\eta+N_\lambda \sim N_\lambda.$$ (4)

Proof. If $\lambda/\in\Gamma^2_1$, then $N_\lambda$ is of the form $W_\omega'+X$ where $\eta<\omega_\nu\leq\omega_\nu'$. Since $W_\eta+W_\omega'=W_\omega+X_0=W_\omega'$, we have (4) trivially. Especially (4) is true for $\lambda=\alpha_\nu(\omega_\beta)$ which is the least number in $\Gamma^0_1\cup\Gamma^2_1$ (see Lemma 1.13). Assume $\lambda'\in\Gamma^1_1$ and (4) is true for any $\lambda/\in\Gamma^0_1\cup\Gamma^2_1$ with $\lambda<\lambda'$. Let $\lambda'=\alpha_\nu(\xi'+\xi)+n$ be the canonical decomposition of $\lambda'$, and then $N_{\lambda'}=N_{\alpha_\nu(\xi')}\cap N_{\alpha_\nu(\xi')+\sigma}\in\cap N_{\alpha_\nu(\xi')+\sigma}$. Since $\xi'$ is a limit number with $cf(\xi')=\beta$, $\alpha_\nu(\xi')+n/\in\Gamma^0_1\cup\Gamma^2_1$ and by assumption $W_\eta+N_{\alpha_\nu(\xi')+n_0} \sim N_{\alpha_\nu(\xi')+n}$ which is not void. Hence by Lemma 2.15, $W_\eta+N_{\lambda'}=W_\eta+(N_{\alpha_\nu(\xi')+n}\cap N_{\alpha_\nu(\xi')+\sigma}) \sim N_{\alpha_\nu(\xi')+n}\cap N_{\alpha_\nu(\xi')+\sigma}=N_\lambda'$, and (4) is proved for $\lambda'=\lambda'$.

Corollary. If $\lambda/\in\Gamma^1_1$, then $W_1+N_\lambda \sim N_\lambda$.

Assume $2\leq\nu<\omega_\beta$, and letting $\mu=\xi+\xi'$ be the $\varphi$-decomposition of $\mu$ (see Definition 2, (ii)), $\xi'=\varphi(\mu)>0$. Now we define $ta_a(\mu)$ (tail of $\mu$) by
\[ \text{Lemma 3.2.} \] Under the same assumption as above, putting \( t_a(\mu) = \varepsilon \),

\[ N_{\alpha(\mu)} + n = W_\varepsilon + N_{\alpha(\varepsilon) + \sigma_\varepsilon + n}. \]

Proof. We shall prove (5) only for the case \( \nu = \eta + 1 \), since the proof for the case that \( \nu \) is a limit number is similarly obtained.

\[ \alpha(\xi + 1) = \alpha(\omega_\xi + 1) \in \Gamma_\eta, \]

and hence \( N_{\alpha(\xi) + n} = W_\omega + N_{\alpha(\xi) + \sigma_\xi + n} \)

(since \( \omega \alpha(\xi) = \alpha(\xi) \); refer to Corollary 2 of Theorem 1), which shows (5) for \( \xi = 1 \). Assume that (5) is true for \( \xi = k + 1 \).

\[ \alpha(\xi + k + 1) = \alpha(\omega_\xi + k + 1) \in \Gamma_\eta \]

and \( N_{\alpha(\xi + k + 1) + n} = W_\omega + W_{\omega_\xi + k} + N_{\alpha(\xi + \sigma_\xi + n)} \)

which shows (5) for \( \xi = k + 1 \). Hence (5) is proved by induction on \( \xi \).

Corollary. If \( 2 \leq \nu < \omega_\beta, \mu > 0, \varphi_\delta(\mu) = 0 \) and \( t_a(\mu) = \varepsilon \), then

\[ N_{\alpha(\mu)} + n = W_\varepsilon + n. \]

In proving that \( N_\lambda \) satisfies D. 1, D. 2) and D. 3), it is assumed that \( N_\xi \) with any \( \xi < \lambda \) satisfies them. In the following three lemmas, which are used to prove that \( N_\lambda \) satisfies D. 1, D. 2) and D. 3), especially D. 1) is assumed for \( N_\xi \) with any \( \xi < \lambda \), and under this assumption, for a limit number \( \xi \in \Gamma_\omega \) with \( \xi \leq \lambda \) and for any sequence \( \Delta_\xi \) of ordinal numbers less than and cofinal to \( \xi \), \( \lambda' \xi N_\mu \sim \lambda' \xi N_\mu \sim N_\xi \), as we remarked below Principle 1.

\[ \text{Lemma 3.3.} \] If \( \xi \) is a \( \gamma \)-number greater than 1 and \( 0 < \xi < \xi_\omega \), then putting \( \lambda = \xi + \sigma_\xi + \xi \),

\[ N_\lambda \sim N_\xi \circ_1 N_{\xi + \sigma_\xi}. \]

Proof. If \( \xi \) is a finite number greater than 0, then \( N_{\xi + \sigma_\xi} \xi = W_\xi + N_{\xi + \sigma_\xi} \)

by Corollary of Lemma 2.13, and (7) is proved for finite numbers \( \xi \). Now assume that \( \omega \leq \xi < \xi_\omega \) and \( N_{\xi + \sigma_\xi + \mu} \sim N_\mu \circ_1 N_{\xi + \sigma_\xi} \)

for any \( \mu \) with \( 0 < \mu < \xi \).

In the case \( \xi \in \Gamma_\omega \), \( N_\lambda = W_n + \lambda \lambda N_\mu \) where \( n = \text{fr}(\lambda) \), and referring to the remark above,

\[ N_\lambda \sim W_n + \bigvee_{\mu \in \lambda_\xi} N_{\xi + \sigma_\xi + \mu} \]

\[ \sim W_n + \bigvee_{\mu \in \lambda_\xi} (N_\mu \circ_1 N_{\xi + \sigma_\xi}) \]

(by assumption),

\[ \sim W_n + (\bigvee_{\mu \in \lambda_\xi} N_\mu) \circ_1 N_{\xi + \sigma_\xi} \]

(by Lemma 2.12, (iv)).
and (7) is proved for \( \zeta \in \Gamma^0 \).

If \( \zeta \in \Gamma^1 \cup \Gamma^2 \) and accordingly \( \text{cf}(\lambda(\zeta)) = \beta \), then \( \lambda \in \Gamma^1 \) and \( \gamma(\lambda) = \xi \), and (7) immediately follows from the definition of \( N_\lambda \).

**Lemma 3.4.** Assume that \( \xi \) is a \( \gamma \)-number not less than \( \omega^\beta \), \( 0 < \xi < \xi_\omega \) and \( 2 < \nu < \omega^\beta \), then putting \( \lambda = \alpha(\xi + \zeta) + n \),

\[
N_\lambda \sim N_{N(\xi) + n} \cup_{\nu} N_{N(\xi) + \sigma_{\xi}} \tag{8}
\]

except where \( n = \varphi^*(\xi) = 0 \).

Proof. Since \( \xi \in \Phi_i \), \( \varphi^*(\xi + \zeta) = \varphi^*(\zeta) \). Hence putting \( \xi = \text{ta}(\zeta) \), \( \xi = \text{ta}(\xi + \zeta) \).

If \( \varphi^*(\xi) = 0 \), then \( \varphi^*(\xi + \zeta) = \zeta \). In this case, excepting where \( n = 0 \),

\[
N_\lambda \sim W_\xi + N_{N(\xi) + \sigma_{\xi} + n} \tag{by (5)}
\]

\[
\sim W_\xi + W_n + N_{N(\xi) + \sigma_{\xi}} \tag{by assumption},
\]

\[
W_{n + m} \cup_{\nu} N_{N(\xi) + \sigma_{\xi}} \tag{by Lemma 2.15},
\]

\[
N_{N(\xi) + n} \cup_{\nu} N_{N(\xi) + \sigma_{\xi}} \tag{by (6)},
\]

and we have (8).

Assume \( \varphi^*(\xi) > 0 \) and \( N_{N(\xi) + \theta} \sim N_{N(\xi) + n} \cup_{\nu} N_{N(\xi) + \sigma_{\xi}} \) for any \( \theta \) such that \( 0 < \theta < \xi \) with similar exceptions. We distinguish three cases.

Case 1. Putting \( \varphi^*(\xi) = \delta \), \( \text{cf}(\delta) < \beta \).

In this case, since \( \varphi^*(\xi + \zeta) = \xi + \delta \),

\[
N_\lambda \sim W_\xi + N_{N(\xi) + \theta + n} \tag{by (5) and \( \text{cf}(\delta) < \beta \)}
\]

\[
\sim W_\xi + W_n + \left( \bigvee_{\theta \in \Lambda_{\delta}} N_{N(\xi) + \theta + 1} \right) \tag{by \( \text{cf}(\delta) < \beta \) and \( \delta = 0 \)}
\]

\[
W_{n + m} + \left( \bigvee_{\theta \in \Lambda_{\delta}} (N_{N(\xi) + \theta + 1} \cup_{\nu} N_{N(\xi) + \sigma_{\xi}}) \right) \tag{by assumption},
\]

\[
(W_{n + m} + \left( \bigvee_{\theta \in \Lambda_{\delta}} N_{N(\xi) + \theta + 1} \right) \cup_{\nu} N_{N(\xi) + \sigma_{\xi}} \tag{by Lemma 2.15},
\]

\[
(W_\xi + N_{N(\xi) + \theta + n}) \cup_{\nu} N_{N(\xi) + \sigma_{\xi}} \tag{by (5)},
\]

and we have (8).

Case 2. \( \xi \) is a limit number with \( \text{cf}(\xi) = \beta \) (then necessarily \( \xi \in \Phi_i \)).

In this case, \( \lambda \in \Gamma^1 \) and \( \gamma(\xi + \zeta) = \xi \). Hence (8) follows from the definition of \( N_\lambda \).

Case 3. Letting \( \delta + \eta \) be the \( \varphi_* \)-decomposition of \( \zeta \), \( \text{cf}(\delta) = \beta \) and \( \eta > 0 \).
In this case,
\[ N \sim W + N_{\alpha \nu + \xi} + \omega \]
\[ \sim W + N + \left( \bigvee_{k<\omega} N_{\alpha \nu + \xi + k} \right) \]
\[ \sim W + \left( \bigvee_{k<\omega} N_{\alpha \nu + \xi + k} \right) \cup \left( N_{\alpha \nu + \xi + \sigma} \right) \]
\[ \sim \left( \bigvee_{k<\omega} N_{\alpha \nu + \xi + k} \right) \cup \left( N_{\alpha \nu + \xi + \sigma} \right) \]
\[ \sim \left( \bigvee_{k<\omega} N_{\alpha \nu + \xi + k} \right) \cup \left( N_{\alpha \nu + \xi + \sigma} \right) \]
\[ \sim N_{\alpha \nu + \xi + \sigma} \cup N_{\alpha \nu + \xi + \sigma} \]
(by (5)),

and we have (8).

Hence for any possible case concerning \( \zeta \) we have (8) and the proof is completed.

**Corollary.** Assume that \( \xi \) is a \( \gamma \)-number not less than \( \omega \beta \), \( 0<\nu<\omega \beta \), \( \omega \leq \xi < \xi \omega \) and \( \zeta \in \Phi^\lambda \). Put \( \lambda = \xi + \sigma + \xi + \sigma \) if \( \nu = 1 \), and \( \lambda = \alpha \xi + \sigma \) if \( \nu > 1 \), then
\[ N \sim N_{\alpha \nu + \xi} + \sigma \]
\[ \sim N_{\alpha \nu + \xi} + \sigma \]
\[ \sim N_{\alpha \nu + \xi} + \sigma \]
\[ \sim N_{\alpha \nu + \xi} + \sigma \]
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\[ \sim N_{\alpha \nu + \xi} + \sigma \]
\[ \sim N_{\alpha \nu + \xi} + \sigma \]

(by assumption),

(by Lemma 2.12, (iv)),

(by Lemma 2.15),

(by (5)),

and we have (8).

Hence for any possible case concerning \( \zeta \) we have (8) and the proof is completed.

**Corollary.** Assume that \( \xi \) is a \( \gamma \)-number not less than \( \omega \beta \), \( 0<\nu<\omega \beta \), \( \omega \leq \xi < \xi \omega \) and \( \zeta \in \Phi^\lambda \). Put \( \lambda = \xi + \sigma + \xi + \sigma \) if \( \nu = 1 \), and \( \lambda = \alpha \xi + \sigma \) if \( \nu > 1 \), then
\[ N \sim N_{\alpha \nu + \xi} + \sigma \]
\[ \sim N_{\alpha \nu + \xi} + \sigma \]
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\[ \sim N_{\alpha \nu + \xi} + \sigma \]

(by (5)),

and we have (8).

Hence for any possible case concerning \( \zeta \) we have (8) and the proof is completed.

**Remark.** Assume that \( \lambda \) is a limit number in \( \Gamma^\nu \), and let \( \lambda = \alpha \xi + \sigma \) be the canonical decomposition of \( \lambda \). Put \( \Psi_\lambda = \{ \mu \mid \omega \leq \mu < \xi \} \) if \( \nu = 1 \), \( \Psi_\lambda = \{ \mu \mid \omega < \mu < \xi \} \) if \( \nu \) is an isolated number greater than 1 and \( \Psi_\lambda = \{ \mu \mid \nu < \mu < \xi \} \) if \( \nu \) is a limit number. Then the numbers \( \alpha \xi + \sigma \) with \( \mu \in \Psi_\lambda \) are cofinal to \( \lambda \). For \( \nu = 1 \), \( \Psi_\lambda \) is defined so that \( \mu \in \Psi_\lambda \) implies \( \xi + \sigma + \mu = \xi + \mu \). Hence it follows from Lemmas 3.3 and 3.4 that in general \( \mu \in \Psi_\lambda \) implies
\[ N \sim N_{\alpha \nu + \xi + \sigma} \cup N_{\alpha \nu + \xi + \sigma} \]
\[ \sim N_{\alpha \nu + \xi + \sigma} \cup N_{\alpha \nu + \xi + \sigma} \]
\[ \sim N_{\alpha \nu + \xi + \sigma} \cup N_{\alpha \nu + \xi + \sigma} \]
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\[ \sim N_{\alpha \nu + \xi + \sigma} \cup N_{\alpha \nu + \xi + \sigma} \]

This Remark is the foundation of the proof that \( N \) with a limit number \( \lambda \in \Gamma^\nu \) satisfies D. 1), D. 2) and D. 3).

We shall say that a ramified set \( X \) satisfies condition E.\( \nu \) if there exists no maximal totally ordered subset of \( X \) whose type is less than \( \omega \nu \).

**Lemma 3.5.** If \( \lambda = \alpha \xi + \theta \) where \( \omega \beta \leq \mu < \beta \) and \( 0 \leq \theta < \omega \beta \), then there exists a \( N \in \mathcal{E}_\beta \) such that \( N \sim N \) and \( N \) satisfies E.\( \nu \).

Proof. If \( \mu = \omega \beta \) and \( \theta = n < \omega \), then \( N = W + n \) which itself is a totally ordered set with type \( \omega + n \geq \omega \nu \) and satisfies E.\( \nu \).
Assume that $\mu$ and $\theta$ where $0 \leq \theta < \omega_\beta$ are given and that for any $\theta'$ with $0 \leq \theta' < \theta$, putting $\lambda' = \alpha_\xi(\mu) + \theta'$, there exists a $N'_{\lambda'} \in \mathfrak{F}_\beta$ such that $N'_{\lambda'} \sim N'_{\lambda'}$ and $N'_{\lambda'}$ satisfies $E_\nu$. Put $N'_{\lambda'} = W_{f(\theta')} + \sqrt{N_{a_{\xi}(\mu') + 2' + \theta'}}$, obviously $N'_{\lambda'} \sim N_{\lambda'}$. Since every maximal totally ordered subset $A$ of $N_{\lambda'}$ has a from $W_{f(\lambda') + (\theta', A')}$ where $\theta' \in \lambda'_\theta$ and $A'$ is a maximal totally ordered subset of $N_{a_{\xi}(\mu) + \lambda'}$, $A = f(\theta) + A' \geq \omega_\nu$. Hence $N_{\lambda'}$ satisfies $E_\nu$.

Hence in order to prove our lemma, we need to consider only the case $\theta = n < \omega$.

Assume $\omega_\beta < \mu < \beta^\chi$ and that for any $\mu'$ with $\omega_\beta \leq \mu' < \mu$ and $\theta'$ with $0 \leq \theta' < \omega_\beta$, putting $\lambda = \alpha_\xi(\mu) + \theta'$, there exists a $N'_{\lambda'} \in \mathfrak{F}_\beta$ such that $N_{\lambda'} \sim N'_{\lambda'}$ and $N'_{\lambda'}$ satisfies $E_\nu$). Put $\theta = n < \omega$. We distinguish five cases.

Case 1. $\mu \in \Phi'_\xi$.

Put $\varphi'_\xi(\mu) = \xi$ and $\tau_\xi(\mu) = \xi$ where $\mu \in \Phi'_\xi$ implies $\xi > 0$. Put $N'_{\lambda'} = W_{\xi} + N_{a_{\xi}(\xi) + \xi + n}$, then by (5), $N_{\lambda'} \sim N_{\lambda'}$. Since any maximal totally ordered subset $A$ of $N_{\lambda'}$ has a form $W_{\xi} + A'$ where $A'$ is a maximal totally ordered subset of $N_{a_{\xi}(\xi) + \xi + n}$, the type $A$, as well as $A'$, is not less than $\omega_\nu$, i.e., $N_{\lambda'}$ satisfies $E_\nu$.

Case 2. $\mu \in \Phi'_\xi$ and $\text{cf}(\mu) < \beta$.

In this case, the sequence $\Lambda'_\xi = \{ \alpha_\xi(\mu) | \omega_\beta \leq \mu' < \mu, \mu' \in \Lambda_\mu \}$ is cofinal to $\text{ls}(\lambda) = \alpha_\xi(\mu)$. Put $N'_{\lambda'} = N_{\mu} + N_{a_{\xi}(\xi) + \xi + n}$, then by (5), $N_{\lambda'} \sim N_{\lambda'}$ and $N_{\lambda'}$ satisfies $E_\nu$) similarly as we saw in the case $\omega \leq \theta < \omega_\beta$.

Case 3. $\mu \in \Phi'_\xi$, $\text{cf}(\mu) = \beta$ and $\mu = \alpha_\xi(\mu) = \text{ls}(\lambda)$.

In this case $\mu \in \Gamma'_\nu$ where $\nu' > \nu$. Put $N'_{\lambda'} = W_{\nu'} + N_{\lambda'}$, then by Lemma 3.1, $N_{\lambda'} \sim N_{\lambda'}$. Since any maximal totally ordered subset of $N_{\lambda'}$ includes $W_{\nu'}$, $N_{\lambda'}$ satisfies $E_\nu$.

Case 4. $\mu \in \Phi'_\xi$, $\text{cf}(\mu) = \beta$, $\mu < \alpha_\xi(\mu)$ and $\mu$ is not a $\gamma$-number.

In this case $\lambda \in \Gamma'_\chi$ and putting $\mu = \xi + \zeta$ where $\xi = \gamma(\mu)$ and $N_{\lambda'} = N_{\alpha_{\xi}(\xi) + n} \cap N_{a_{\xi}(\xi) + \xi}$, we have $N_{\lambda'} \sim N_{\lambda'}$. Since any maximal totally ordered subset of $N_{\lambda'}$ is either included in $N_{a_{\xi}(\xi) + n}$ or of the form $\text{lb}(x; N_{a_{\xi}(\xi) + n}) + A'$ where $x \in \text{Seg}(N_{a_{\xi}(\xi) + n})$ and $A'$ is a maximal totally ordered subset of $(x, N_{a_{\xi}(\xi) + \xi})$, $N_{\lambda'}$ satisfies $E_\nu$.

Case 5. $\mu \in \Phi'_\xi$, $\text{cf}(\mu) = \beta$, $\mu < \alpha_\xi(\mu) = \text{ls}(\lambda)$ and $\mu$ is a $\gamma$-number.

In this case $\lambda \in \Gamma'_\nu$ and $N_{\lambda'}$ is of a form $W_{\nu'} + X$. Hence $N_{\lambda'}$ itself satisfies $E_\nu$.

Thus in any case we can inductively find a $N'_{\lambda'}$ required, and we complete the proof.

2. Case $\lambda \in \Gamma''$

By the aid of preliminary lemmas shown in §1, we shall prove that for any $\lambda < \beta^\chi$,
Proposition 1. $N_\lambda$ satisfies D. 1), D. 2) and D. 3).

As we have seen in Lemma 2.8 and 2.9 and their Corollaries, if we complete the proof of Proposition 1 for any $\lambda<\beta^0$, then Main Theorem A is also proved. In proving Proposition 1 for a $\lambda<\beta^0$, it is assumed that any $N_\xi$ with $\xi<\lambda$ satisfies Proposition 1 in which $\lambda$ is replaced by $\xi$, and hence Lemma 3.3 and 3.4 can be applied on any $N_\lambda'$ with $\lambda'<\lambda$ without any restriction. Occasionally for some $\lambda$ we can show

Proposition 2. $N_\lambda$ satisfies D. 1) and D. 2') (see Lemma 2.7), and as we noticed in Lemma 2.7, Proposition 2 implies Proposition 1.

Proposition 2 trivially holds for $N_\mu$ with $n<\omega$. We shall show that any $N_\lambda$ with $\lambda\in\Gamma^0$ satisfies Proposition 2.

Proof of Proposition 2 for a limit number $\lambda\in\Gamma^0$.

Assume $\mu<\lambda$. Let $\xi$ be the least number in $\Lambda_\lambda$ such that $\mu<\xi$, then by assumption D.1) on $N_{\xi}$, $N_\mu\sim N_\xi$. By the definition of $N_\lambda$, it includes a subset isomorphic to $N_\xi$. Hence $N_\mu\sim N_\xi\sim N_\lambda$ and $N_\lambda$ satisfies D. 1).

Let $X$ be a set in $\frak{R}_\beta$ such that $X\not\approx N_\mu$ for any $\mu<\lambda$. By assumption D. 3) on $N_\mu$ with $\mu<\lambda$, $N_\mu\sim X$. Hence $N_\lambda=\bigvee_{\lambda_\lambda} N_\mu\sim X$ by Lemma 2.11, and $N_\lambda$ satisfies D. 2').

Lemma 3.6. Let $\lambda$ be a limit number in $\Gamma^0$. If $X$ has the least element and $X\not\approx N_\lambda$, then there exists a $\mu<\lambda$ such that $X\approx N_\mu$.

Proof. Let $a$ be the least element of $X$ and $f$ be an increasing mapping of $X$ into $N_\lambda$, then there exists a $\mu\in\Lambda_\lambda$ such that $f(a)\in(\mu, N_\mu)$, and $X=\text{Ub}'(a)$ is entirely mapped into $(\mu, N_\mu)$ which is isomorphic to $N_\mu$, i.e., $X\not\approx N_\mu$.

Corollary. If $\lambda$ is a limit number in $\Gamma^0$ and $a\in N_\lambda$, then there exists a $\mu<\lambda$ such that $\text{Ub}'(a)\not\approx N_\mu$.

Lemma 3.7. Let $\lambda$ be a limit number in $\Gamma^0$. If $\mu<\lambda$, then $W_1+N_\mu\not\approx N_\lambda$.

Proof. If $\mu\in\Gamma^0$, then $W_1+N_\mu=N_{\mu+1}$ by definition. If $\mu\in\Gamma^0\cup\Gamma^\infty$, then $W_1+N_\mu\sim N_\mu$ by Lemma 3.1. Hence our lemma follows from D. 1) on $N_\lambda$.

Corollary. Let $\lambda$ be a limit number in $\Gamma^0$. If $N_\lambda\not\approx W_1+X$, then $N_\lambda\not\approx X$.

Proof. Since $W_1+N_\mu\not\approx N_\lambda\sim W_1+X$, $N_\mu\not\approx X$ for any $\mu<\lambda$. Hence $N_\lambda\not\approx X$.

Proof of Proposition 2 for an isolated number $\lambda=\lambda'+1\in\Gamma^0$. 

Ramified Sets
Put $\xi = \text{ls}(\lambda') = \text{ls}(\lambda)$, $n = \text{fr}(\lambda')$ then $N_{\lambda'} = W_n + N_\xi$ and $N_\lambda = W_n + \{n\} + N_\xi$.

First we shall show $N_{\lambda'} \cong N_\lambda$. $N_\lambda \cong N_{\lambda'}$ is obvious. Assume $N_{\lambda'} \cong N_\lambda$, and let $\tau$ be an increasing mapping of $N_{\lambda'}$ into $N_\lambda$, then $\tau(f(n)) \geq \tau(n) = n$. Hence there exists an $a \in N_\xi$ such that $f(n) = n + a$, and $f$ maps $\text{Ub}(n; N_\lambda)$ into $\text{Ub}(n + a; N_{\lambda'})$ which is isomorphic to $\text{Ub}(a; N_\xi)$. Since $\text{Ub}(n; N_\lambda) \equiv N_\xi$, we have $N_\xi \cong \text{Ub}(a; N_\xi)$ contradicting Corollary of Lemma 3.6. Hence $N_{\lambda'} \not\cong N_\lambda$ and $\mu \leq \lambda'$ implies $N_\mu \not\cong N_\lambda$ by D.1) on $N_{\lambda'}$. Hence $N_\lambda$ satisfies D.1).

Assume $X \in \mathfrak{B}_\lambda$, and $X \not\cong N_{\lambda'}$ (and accordingly $X \not\cong N_\mu$ for any $\mu \leq \lambda'$ by assumption D.1) on $N_{\lambda'}$). Let $Y$ denote the set of all $y \in X$ such that $\tau(y) = n$. If $\text{Ub}'(y) \not\cong N_\xi$ for any $y \in Y$, then similarly to Lemma 2.11, we have $X \not\cong W_n + N_\xi = N_{\lambda'}$ contradicting $X \not\cong N_{\lambda'}$. Hence there exists a $y \in Y$ such that $\text{Ub}'(y) \not\cong N_\xi$. By assumption D.3) on $N_\xi$, $N_\xi \cong \text{Ub}'(y) = \{y\} + \text{Ub}(y)$. Hence $N_\xi \cong \text{Ub}(y)$ by Corollary of Lemma 3.7, and $N_\lambda = W_n + N_\xi \cong \text{Ub}(y) + \text{Ub}(y) \subset X$ which shows that $N_\lambda$ satisfies D.2').

3. Case $\lambda \in \Gamma'$

In this section we shall show that for any $\lambda \in \Gamma'$ Proposition 1 holds and for some cases Proposition 2 also holds. In order to show it, we prepare a definition of a notation.

**Definition 11.** We shall say that an $x \in X$ supports $Y$ if $Y \cong \text{Ub}(x; X)$. Spt$(X; Y)$ denotes the set of all $x \in X$ which support $Y$. Let $\mathcal{Y} = \{Y_\lambda; \lambda \in \Lambda\}$ be a family of ramified sets. Spt$(X; \mathcal{Y})$ or Spt$(X; Y_\lambda, \lambda \in \Lambda)$ (or occasionally Spt$(X; Y_\lambda, \lambda \in \Lambda)$ etc.) denotes the set of all $x \in X$ which supports every $Y_\lambda \in \mathcal{Y}$. Exp$(\text{Spt}(X; \mathcal{Y}))$ is denoted by $\text{Spt}^\ast(X; \mathcal{Y})$ and Seg$(\text{Spt}(X; \mathcal{Y}))$ is denoted by $\text{Spt}_v(X; \mathcal{Y})$.

**Remark.** Let $Z$ be a subset of $X$. In general Spt$(Z; Y)$ does not agree with Spt$(X; Y) \cap Z$. If $x \in \text{Spt}(Z; Y)$, then $Y \cong \text{Ub}(x; Z)$, while $x \in \text{Spt}(X; Y) \cap Z$ implies $Y \cong \text{Ub}(x; X)$. Hence we can assert only Spt$(Z; Y) \subset \text{Spt}(X; Y) \cap Z$.

The following is obvious.

**Lemma 3.8.** (i) Spt$(X; \mathcal{Y})$ is a cut of $X$ (and hence Exp$(\text{Spt}(X; \mathcal{Y}))$ can be defined).

(ii) If $X \cong X'$ then Spt$(X; \mathcal{Y}) \cong \text{Spt}(X'; \mathcal{Y})$ and similar relations hold for $\text{Spt}^\ast$ and $\text{Spt}_v$.

(iii) If for any $Y \in \mathcal{Y}$ there exists a $Y' \in \mathcal{Y}'$ such that $Y \cong Y'$, then Spt$(X; \mathcal{Y}) \subset \text{Spt}(X; \mathcal{Y}')$, and especially if $Y \cong Y'$ then Spt$(X; Y) \subset \text{Spt}(X; Y)$. Similar inclusions hold for $\text{Spt}^\ast$ and $\text{Spt}_v$. 

(iv). For a family \( \{X'_\lambda; \lambda \in \Lambda'\} \), \( \operatorname{Spt}(\bigvee_{X'_\lambda; \lambda \in \Lambda'}; Y) \sim \bigvee_{X'_\lambda; \lambda \in \Lambda'} \operatorname{Spt}(X'_\lambda; Y) \). Similar equivalencies hold for \( \operatorname{Spt}' \) and \( \operatorname{Spt} \).

**Lemma 3.9.** If \( y \in Y \) implies \( Y \cong \operatorname{Ub}(y) \), then \( \operatorname{Spt}'(X \circ Y; Y) = X \).

Proof. For any \( x \in \operatorname{Seg}_v(X) \), \( \operatorname{Ub}(x; X \circ Y) \) include the subset \( (x, Y) \) isomorphic to \( Y \), and \( x \in \operatorname{Spt}(X \circ Y; Y) \). Hence \( \operatorname{Seg}_v(X) \cong \operatorname{Spt}(X \circ Y; Y) \) and \( X \circ \operatorname{Spt}'(X \circ Y; Y) \). On the other hand, for any \( x \in \operatorname{Seg}_v(X) \) and \( y \in Y \), \( \operatorname{Ub}((x, y); X \circ Y) \equiv \operatorname{Ub}(y; Y) \), and \( (x, y) \) does not support \( Y \) by assumption, i.e., \( \operatorname{Spt}(X \circ Y; Y) \subset X \). Hence \( \operatorname{Spt}'(X \circ Y; Y) \subset X \) by Lemma 2.1, (vi) and we have the lemma.

**Lemma 3.10.** \( \operatorname{Spt}'(X \circ Y; Y) \cong Y \cong X \).

Proof. If \( \operatorname{Spt}(X; Y) \) is void, then \( \operatorname{Spt}'(X; Y) \) and \( \operatorname{Spt}(X; Y) \circ Y \) are void and the inequality is trivial. Assume that \( \operatorname{Spt}(X; Y) \) is not void. Since \( x \in \operatorname{Spt}(X; Y) \) implies \( Y \cong \operatorname{Ub}(x) \), there exists an increasing mapping \( f_x \) of \( Y \) into \( \operatorname{Ub}(x) \) for any \( x \in \operatorname{Spt}(X; Y) \). Put \( f(x) = x \) for any \( x \in \operatorname{Spt}'(X; Y) \) and \( f((x, y)) = f_x(y) \) for any \( x \in \operatorname{Spt}_v(X; Y) \) and any \( y \in Y \), then obviously \( f \) is an increasing mapping of \( \operatorname{Spt}'(X; Y) \circ Y \) into \( X \) and the lemma is proved.

**Lemma 3.11.** If \( Y \) is comparable with any \( X' \in \mathfrak{R}_3 \), and \( Z \) satisfies \( \mathfrak{E}_2 \) (see Lemma 3.5), then for any \( X \in \mathfrak{R}_3 \), \( \operatorname{Spt'}(X; Y) \cong Z \) implies \( X \cong Z \circ Y \).

Proof. Let \( g \) be a reduced increasing mapping of \( \operatorname{Spt}'(X; Y) \) into \( Z \) and \( M \) be the set of all minimal elements of \( X - \operatorname{Spt}'(X; Y) \). \( a \in M \) implies \( \tau(a) \cong \omega^* \) by Lemma 2.3 (vii), and \( \operatorname{Lb}(a) \subset \operatorname{Spt}(X; Y) \). Since \( g \) is reduced, the type of the set \( \operatorname{Lb}(\operatorname{Lb}(a)) \) is equal to \( \tau(a) \) which is less than \( \omega^* \). Hence by \( \mathfrak{E}_2 \) on \( Z \), \( \operatorname{Lb}(a) \) is not maximal totally ordered subset of \( Z \), and there exists an \( a' \in Z \) such that \( \tau(a') = \tau(a) \) and \( \operatorname{Lb}(a') = \operatorname{Lb}(a) \). Let \( g' \) be the extension of \( g \) such that \( g'(a) = a' \) for any \( a \in M \). Since \( a \in M \) implies \( Y \cong \operatorname{Ub}(a) \), \( \operatorname{Ub}(a) \cong Y \) by assumption on \( Y \). Let \( f_a \) be an increasing mapping of \( \operatorname{Ub}(a) \) into \( Y \) for any \( a \in M \). \( X \) is decomposed into a union \( \bigcup_{a \in M} \operatorname{Ub}(a) \cup (M \cup \operatorname{Spt}(X; Y)) \). Let \( f \) be a mapping of \( X \) into \( Z \circ Y \) such that \( f(a) = g'(a) \) for \( M \cup \operatorname{Spt}(X; Y) \) and \( f(b) = (g'(a), f_a(b)) \) for \( b \in \operatorname{Ub}(a) \) where \( a \in M \), then obviously \( f \) is increasing and \( X \cong Z \circ Y \).

**Lemma 3.12.** Assume \( \lambda \in \Gamma^* \) and let \( \lambda = \alpha_3(\xi + \zeta) + n \) be the canonical decomposition of \( \lambda \), then

(i). \( \lambda \cong X \) implies \( \lambda \cong \lambda \cong \lambda \cong \lambda \cong \lambda \).

(ii). \( X \cong \lambda \) implies \( \lambda \cong \lambda \cong \lambda \cong \lambda \).
(iii) $\text{Spt}^\vee(X; N_{a\langle \xi \rangle + \sigma_\xi}) \cong N_{a\langle \xi \rangle + n}$ implies $X \cong N_\lambda$.
(iv) $N_{a\langle \xi \rangle + n} \overset{\text{Spt}^\vee}{\cong} X; N_{a\langle \xi \rangle + \sigma_\xi}$ implies $N_\lambda \propto X$.

Proof. (i). Since $\alpha_\xi + \sigma_\xi \in \Gamma^0$, $a \in N_{a\langle \xi \rangle + \sigma_\xi}$ implies $N_{a\langle \xi \rangle + \sigma_\xi} \cong \text{Ub}(a)$ by Corollary of Lemma 3.6. Hence $\text{Spt}^\vee(N_{\lambda}; N_{a\langle \xi \rangle + \sigma_\xi}) = N_{a\langle \xi \rangle + n}$ by Lemma 3.9. Hence (i) follows from 3.8 (ii).

(ii). Since $\omega_\beta \leq \zeta < \beta^*$, there exists a $N_{a\langle \zeta \rangle + n} \in \mathcal{E}_\beta$ which is equivalent to $N_{a\langle \xi \rangle + n}$ and satisfies $E_\gamma$ by Lemma 3.5. By Lemma 3.11, $\text{Spt}^\vee(X; N_{a\langle \xi \rangle + \sigma_\xi}) \cong N_{a\langle \xi \rangle + n} \sim N_{a\langle \xi \rangle + n}$ implies $X \propto N_{a\langle \xi \rangle + n} \circ \gamma N_{a\langle \xi \rangle + \sigma_\xi} \sim N_\lambda$.

(iii) is a consequence of (i) and (ii).

(iv) follows from Lemma 3.10 and Lemma 2.12 (i).

Now referring to the remark below Lemma 3.4, we shall obtain the Proof of Proposition 1 for $\lambda \in \Gamma^0$. (Besides let $\lambda = \alpha_\xi (\xi + \zeta) + n$ be the canonical decomposition of $\lambda$. Proposition 2 holds for $\lambda$ if Proposition 2 in which $\lambda$ is replaced by $\theta = a\langle \zeta \rangle + n$. In brackets of the following proof, we shall consider about this case.)

Let $\lambda = \alpha_\xi (\xi + \zeta) + n$ be the canonical decomposition of $\lambda$. First we shall show that $N_\lambda$ satisfies D.1).

Case $n = \text{fr}(\lambda) = 0$. If $\mu \prec \lambda = \alpha_\xi (\xi + \zeta)$, then there exists a $\psi \in \Psi_\lambda$ such that $\mu \prec \alpha_\xi (\xi + \psi)$ (see the remark bellow Lemma 3.4), and by assumption D.1) on $N_{a\langle \xi \rangle + \psi}$. Since $N_{a\langle \xi \rangle + \psi} \propto N_{a\langle \xi \rangle + \xi}$, $N_{a\langle \xi \rangle + \psi} = N_{a\langle \xi \rangle + \xi} \circ \gamma N_{a\langle \xi \rangle + \sigma_\xi} \cong N_{a\langle \xi \rangle + \xi} \circ \gamma N_{a\langle \xi \rangle + \sigma_\xi} = N_\lambda$ by Lemma 2.12, (i). Hence $N_\mu \cong N_\lambda$ and $N_\lambda$ satisfies D.1).

Case $n = \text{fr}(\lambda) > 0$. It suffices to show $N_{a\langle \xi \rangle + \xi + n} \cong N_{a\langle \xi \rangle + \xi + n} \cdot \text{Spt}^\vee(N_{a\langle \xi \rangle + \xi + n-1} \circ N_{a\langle \xi \rangle + \sigma_\xi} = N_{a\langle \xi \rangle + \xi + n} \cong N_{a\langle \xi \rangle + n}$ by Lemma 3.9 and assumption D.1) on $N_{a\langle \xi \rangle + n}$. Hence $N_{a\langle \xi \rangle + \xi + n-1} \cong N_\lambda$ by Lemma 3.12, (iii) and $N_\lambda$ satisfies D.1).

Next we shall show that $N_\lambda$ satisfies D.2) (resp. D.2') in the case where $N_{a\langle \xi \rangle + n}$ satisfies D.2'). Assume $X \in \mathcal{E}_\beta$ (resp. $X \in \mathcal{F}_\beta$) and that $X \not\propto N_\mu$ for any $\mu \prec \lambda$.

Case $n = \text{fr}(\lambda) = 0$. By assumption D.3) on $N_\mu$ with $\mu \prec \lambda$, $N_\mu \propto X$ for any $\mu \prec \lambda$. Especially for any $\psi \in \Psi_\lambda$, $N_{a\langle \xi \rangle + \psi} \propto X$ and hence $N_{a\langle \psi \rangle} = \text{Spt}^\vee(N_{a\langle \xi \rangle + \psi} ; N_{a\langle \xi \rangle + \sigma_\xi} \propto \text{Spt}^\vee(X; N_{a\langle \xi \rangle + \sigma_\xi})$ by Lemma 3.9 and Lemma 3.8 (ii). Hence $N_{a\langle \xi \rangle} \propto \text{Spt}^\vee(X; N_{a\langle \xi \rangle + \sigma_\xi})$ by assumption D.2) (resp. D.2') on $N_{a\langle \xi \rangle}$. Hence $N_\lambda = N_{a\langle \xi \rangle} \circ \gamma N_{a\langle \xi \rangle + \sigma_\xi} \cong X$ by Lemma 3.12 (iv) and $N_\lambda$ satisfies D.2) (resp. D.2')).

Case $n = \text{fr}(\lambda) > 0$. It suffices to show that $X \not\propto N_{a\langle \xi \rangle + \xi + n-1}$ implies $N_{a\langle \xi \rangle + \xi + n-1} \propto X$. By Lemma 3.12 (ii), $X \not\propto N_{a\langle \xi \rangle + \xi + n-1}$ implies $\text{Spt}^\vee(X; N_{a\langle \xi \rangle + \sigma_\xi}) \not\propto N_{a\langle \xi \rangle + \xi + n-1}$ which implies $N_{a\langle \xi \rangle + n} \propto \text{Spt}^\vee(X; N_{a\langle \xi \rangle + \sigma_\xi})$ by assumption D.2) (resp. D.2') on $N_{a\langle \xi \rangle}$. Hence $N_\lambda \propto X$ by Lemma 3.12 (iv).
Finally we shall show that $N_\lambda$ satisfies D. 3). Assume $X \in R_\beta$. By assumption D. 3) on $N_{\alpha_\xi+n}$, either $Sp_t(X; N_{\alpha_\xi+n}) \supseteq N_{\alpha_\xi+n}$ or $N_{\alpha_\xi+n} \supseteq Sp_t(X; N_{\alpha_\xi+n})$ holds, hence either $X \supseteq N_\lambda$ or $N_\lambda \supseteq X$ holds accordingly by Lemma 3.12, (iii) and (iv), and $N_\lambda$ satisfies D. 3).

4. Case $\lambda \in \Gamma^2$

We distinguish three cases. First we shall consider the case $\lambda = \alpha_\xi(\omega_\beta) + n$, next the case $\lambda = \alpha_\xi(\omega_\beta+1) + n$, and finally the case $X = \alpha_\xi(\omega_\beta) + n$ where $\xi$ is a limit number with $\text{cf}(\xi) = \beta$ and $\xi < \text{Is}(\lambda)$.

Lemma 3.13. Assume $X \in R_\beta$, $\lambda \in \Gamma^2$, $\text{fr}(\lambda) = 0$ and that any $N_\mu$ with $\mu < \lambda$ satisfies D. 1). Put $Y = Sp_t(X; N_\mu, \mu < \lambda)$, then there exists a $\xi < \lambda$ such that for any $x \in X$, $N_\xi \supseteq \text{Ub}(x)$ implies $x \in Y$.

Proof. If $x \in X - Y$, then there exists a $\xi(x) < \lambda$ such that $N_{\xi(x)} \not\supseteq \text{Ub}(x)$. Since $X < R_\beta$ and $\text{cf}(\lambda) = \beta$, numbers $\xi(x)$ with $x \in X - Y$ are not cofinal to $\lambda$. Hence there exists a $\xi < \lambda$ such that $\xi(x) < \xi$ and accordingly $N_{\xi(x)} \supseteq N_\xi$ for any $x \in X - Y$. Then $x \in X$ and $N_\xi \supseteq \text{Ub}(x)$ imply $x \in Y$.

Proof of Proposition 1 for $\lambda = \alpha_\xi(\omega_\beta)$. (fr(\lambda) = 0).

$\lambda$ is the least number in $\Gamma^1 \cup \Gamma^2$ (see Lemma 1.13), i.e., $\mu < \lambda$ implies $\mu \in \Gamma^1 \cup \bigcup_{\alpha_\xi} \Gamma_\beta$. Hence applying Lemma 2.12, (v), we can inductively see that $\mu < \lambda$ implies $\kappa(N_\mu) \leq \omega^\gamma$, while $\kappa(N_{\alpha_\xi(\omega_\beta)}) = \omega^\gamma + 1$. Hence by Theorem 5, $\mu < \lambda$ implies $N_\mu \supseteq N_\lambda$, i.e., $N_\lambda$ satisfies D. 1).

Assume $X \in R_\beta$ and $X \supseteq N_\lambda$ for any $\mu < \lambda$, then by assumption D. 3) on $N_\mu$, $N_\mu \supseteq X$ for any $\mu < \lambda$. Put $Y = Sp_t(X; N_\mu, \mu < \lambda)$, then by Lemma 3.13, there exists a $\xi < \lambda$ such that $x \in X$ and $N_\xi \supseteq \text{Ub}(x)$ imply $x \in Y$. Since ordinal numbers $\alpha_\xi(\theta)$ where $\theta \in \Phi_\xi$ and $\theta < \omega_\beta$ are cofinal to $\lambda = \alpha_\xi(\omega_\beta)$, we may assume that $\xi = \alpha_\xi(\theta)$ where $\theta \in \Phi_\xi$ and $\theta < \omega_\beta$ without loss of generality. Then $\text{cf}(\xi) = \text{cf}(\theta) < \beta$ by Theorem 3 and accordingly $\xi \in \Gamma^0$ and $\sigma_\xi = 0$. Now we shall show that

(a). for any $\varepsilon < \omega^\gamma$ and $y \in Y$, $W_\varepsilon + N_\xi \supseteq \text{Ub}(y; X)$.

If $\nu = 1$, then since $\xi$ is a limit number in $\Gamma^0$, $W_\nu + N_\xi \supseteq N_{\xi+n} \supseteq \text{Ub}(y)$ for any $n < \omega$.

Next assume $\nu \geq 2$. If $\nu = \eta + 1$, then let $\xi$ be the least finite number such that $\varepsilon < \omega^\eta \cdot \xi$ and put $\nu' = \omega^\eta \cdot \xi$. If $\nu$ is a limit number, then let $\xi$ be the least number such that $\varepsilon < \omega^\xi$ and put $\nu' = \omega^\xi$. In either case put $\mu = \theta + \xi$, then $\theta + \xi$ is the $\rho_\nu$--decomposition of $\mu$, $\nu < \omega_\beta$ and $\varepsilon < \nu'$ = $= \text{ta}_\nu(\mu)$ (see the mention above Lemma 3.2). Hence by Lemma 3.2, $W_\varepsilon + N_\xi \supseteq W_{\nu'} + N_\xi = N_{\alpha_\xi(\mu)} \supseteq \text{Ub}(y)$.

Hence Assertion (a) is proved for any $\nu$ with $0 < \nu < \omega_\beta$. Next we shall show that
(b). For any \( \varepsilon \) with \( 0 < \varepsilon < \omega^\nu \) and \( y \in Y \), there exists a \( z \in \text{Ub}(y) \cap Y \) such that \( \tau(z; \text{Ub}(y)) = \varepsilon \).

Indeed, \( W_{\omega+1} + N_x \cong \text{Ub}(y) \) by (a) above. Let \( f \) be a reduced increasing mapping of \( W_{\omega+1} + N_x \) into \( \text{Ub}(y) \), then \( f \) maps \( \varepsilon \in W_{\omega+1} \) onto a \( z \in \text{Ub}(y) \). Since \( N_x \cong \text{Ub}(\varepsilon; W_{\omega+1} + N_x) \), \( N_x \cong \text{Ub}(z) \) which implies \( z \in Y \) by assumption on \( x \). Since \( f \) is reduced, \( \tau(z; \text{Ub}(y)) = \tau(\varepsilon; W_{\omega+1}) = \varepsilon \) and (b) is proved.

Similarly as the above, \( Y \) itself includes a subset isomorphic to \( W_{\omega+1} + N_x \) for any \( \varepsilon < \omega^\nu \) and especially \( Y \) is not void. Since \( \text{XG@} \), i.e., \( X \) is resoluble, there exists a \( y \in Y \) such that \( \lambda \text{Jb}(y) \cap Y \) is a well-ordered subset of \( Y \). Since for any \( \varepsilon < \omega^\nu \), there exists a \( z \in \text{Ub}(\varepsilon; W_{\omega+1} + N_x) \) which implies \( z \in Y \) by assumption on \( \xi \). Since \( f \) is reduced, \( \tau(z; W_{\omega+1}) = \tau(\xi; W_{\omega+1}) = \xi \) and (b) is proved.

It follows from Corollary of Theorem 5 that \( N_\lambda \) satisfies D.3).

By the way we shall show:

Lemma 3.14. If either \( \nu \) is an isolated number or a limit number with \( \text{cf}(\nu) = 0 \), then \( N_\lambda \) with \( \lambda = \alpha_\nu(\omega_\beta) \) satisfies D.2'). (Hence Proposition 2 holds for \( \lambda \).

Proof. In either case \( \text{cf}(\omega^\nu) = 0 \) and there exists a countable (strictly) ascending sequence \( \varepsilon_1, \varepsilon_2, \ldots \), \( \varepsilon_m, \ldots \) cofinal to \( \omega^\nu \).

Assume \( X \in \mathfrak{R}_\beta \) and \( X \neq N_\mu \) for any \( \mu < \lambda \). It is all the same as (b) in the proof above that for any \( y \in Y = \text{Spt}(X; N_\mu, \mu < \lambda) \) and \( \varepsilon < \omega^\nu \), there exists a \( z \in \text{Ub}(y) \cap Y \) such that \( \tau(z; \text{Ub}(y)) = \varepsilon \). Especially \( Y \) itself is not void. Let \( y_1 \) be an element in \( Y \) such that \( \tau(y_1; X) = \varepsilon_1 \), and after we have a \( y_m \in Y \), let \( y_{m+1} \) be the element in \( \text{Ub}(y_m) \cap Y \) such that \( \tau(y_{m+1}; X) = \varepsilon_{m+1} \), then we have a sequence \( y_1, y_2, \ldots, y_m, \ldots \) of elements in \( Y \) such that \( y_m < y_{m+1} \) for any \( m < \omega \) and \( \tau(y_m; X) = \varepsilon_m \). Let \( W \) be a maximal totally ordered subset of \( X \), which contains every \( y_m, m < \omega \), then since for any \( \varepsilon < \omega^\nu \), \( W \) contains a \( w \) such that \( \tau(w) = \varepsilon \), the type of \( W \) is at least \( \omega^\nu \). Hence \( N_\lambda \cong W_{\omega^\nu} \cap X \) and \( N_\lambda \) satisfies D.2'), and the proof is completed.

Proof of Proposition 2 for \( \lambda = \alpha_\nu(\omega_\beta) + n \) with \( n > 0 \).

\( \kappa(N_\lambda) = \kappa(W_{\omega^\nu+n}) = \omega^\nu + n + 1 \) while \( \kappa(N_{\omega^\nu+n-1}) = \omega^\nu + n \).

Hence \( N_{\omega^\nu+n-1} \cong N_{\omega^\nu+n} \cong N_\lambda \) by Theorem 5 and \( N_\lambda \) satisfies D.1).

Assume \( X \in \mathfrak{R}_\beta \) and \( X \neq N_{\omega^\nu+n-1} \). Then since \( \kappa(N_{\omega^\nu+n-1}) = \omega^\nu + n \) is an isolated number, \( \omega^\nu + n < \kappa(X) \), i.e., \( \omega^\nu + n + 1 \leq \kappa(X) \). Hence by definition of \( \kappa(X) \), \( N_\lambda = W_{\omega^\nu+n} \cap X \), and \( N_\lambda \) satisfies D.2').

Next we shall consider the case \( \lambda = \alpha_\nu(\omega_\beta + 1) \) where \( \xi > 0 \).

Put \( \xi' = \omega_\beta \) and \( \sigma_\nu = \sigma_\nu' \), i.e., \( \sigma_\nu = 0 \) if \( \xi \) is a limit number with \( \text{cf}(\xi') < \beta \) and \( \sigma_\nu = \omega \) otherwise.

Lemma 3.15. Put \( \varepsilon = \alpha_\xi(\omega_\beta) + \sigma_\xi \), then \( \text{Csg}_\xi(N_\varepsilon) \sim N_{\omega_\beta + \sigma_\xi} \).
Proof. Case 1. \( \zeta = \theta + 1 \).

In this case \( \sigma_\zeta = \omega \), \( \sigma_\zeta = \sigma_\theta \) and \( N_{\alpha_v(\omega_\theta^\xi)+n} = W_\omega \cdot N_{\omega_0 + \sigma_\theta + n} \). Hence \( \text{Csg}_\zeta(N_{\alpha_v(\omega_\theta^\xi)+n}) = N_{\omega_0 + \sigma_\theta + n} \). Since \( N_{\alpha_v(\omega_\theta^\xi)+n} \sim \bigvee_{n<\omega} N_{\alpha_v(\omega_\theta^\xi)+n} \) by Remark 2 below Principle 1, \( \text{Csg}_\zeta(N_{\alpha_v(\omega_\theta^\xi)+\sigma_\zeta} \sim \bigvee_{n<\omega} \text{Csg}_\zeta(N_{\alpha_v(\omega_\theta^\xi)+n}) \sim \bigvee_{n<\omega} N_{\omega_0 + \sigma_\theta + n} \sim N_{\omega_0 + \sigma_\theta + n + \theta} = N_{\omega_0 + \sigma_\theta + n + \sigma_\theta} = N_{\omega_0 + \sigma_\theta + n + \sigma_\theta + n} \) by Lemma 2.12, (vi).

Case 2. \( \zeta \) is a limit number with \( \text{cf}(\zeta) = \beta \) and \( \zeta = \alpha_v(\omega_\beta^\xi) \).

In this case \( \sigma_\zeta = \sigma_\xi = \omega_\beta \). \( \omega_\zeta = \xi \) and \( N_{\alpha_v(\omega_\beta^\xi)+n} = W_\omega \cdot N_{\zeta + m} \). Hence \( \text{Csg}_\zeta(N_{\alpha_v(\omega_\beta^\xi)+\sigma_\zeta} \sim \bigvee_{n<\omega} N_{\zeta + n} \).

Case 3. \( \zeta \) is a limit number with \( \text{cf}(\zeta) = \beta \) and \( \zeta < \alpha_v(\omega_\beta^\xi) \).

In this case \( \sigma_\zeta = \omega \), \( \omega_\zeta = \xi \) and \( N_{\alpha_v(\omega_\beta^\xi)+n} = W_\omega \cdot N_{\zeta + n} \). Hence \( \text{Csg}_\zeta(N_{\alpha_v(\omega_\beta^\xi)+\sigma_\zeta} \sim \bigvee_{n<\omega} N_{\zeta + n} \sim N_{\zeta + n} \).

Case 4. \( \zeta \) is a limit number with \( \text{cf}(\zeta) < \beta \).

In this case \( \sigma_\zeta = \omega_\beta^\xi = 0 \), \( \omega_\zeta = \xi \) and \( N_{\alpha_v(\omega_\beta^\xi)+n} = W_\omega \cdot N_{\xi + n} \). Hence \( \text{Csg}_\zeta(N_{\alpha_v(\omega_\beta^\xi)+\sigma_\zeta} \sim \bigvee_{n<\omega} N_{\xi + n} \sim N_{\xi + n} \).

Lemma 3.16. If \( \alpha_v(\omega_\beta^\xi) + \sigma_\zeta \leq \xi < \alpha_v(\omega_\beta^\xi + 1) \), then \( \text{Csg}_\zeta(N_\xi) = N_{\omega_0 + \sigma_\xi} \).

Proof. \( \alpha_v(\omega_\beta^\xi + 1) \) is the least number in \( \Gamma_\beta^\xi \cdot \cup \Gamma_\beta^\xi \cdot \beta \) greater than \( \omega_\beta^\xi + \sigma_\zeta \). By Lemma 1.14, i.e., \( \xi \in \Gamma_\beta^\xi \cdot \cup \Gamma_\beta^\xi \cdot \beta \). By Lemma 3.15 the equivalency is true for \( \xi = \alpha_v(\omega_\beta^\xi) + \sigma_\zeta \). Hence we can inductively prove our equivalency referring to Lemma 1.12 (vi).

Lemma 3.17. Assume that \( X \in \mathfrak{H}_\beta \) and \( N_\mu = N_\mu \cdot \times X \cdot \times \mu < \lambda = \alpha_v(\omega_\beta^\xi + 1) \). Put \( Y' = \text{Spt}(X; \mu, \mu < \lambda) \) and \( Y = \text{Exp}(Y'; X) = \text{Spt}(X; N_\mu, \mu < \lambda) \), then for any \( y \in Y \cap \text{Seg}(X) \), \( N_{\alpha_v(\omega_\beta^\xi)+\sigma_\xi} \cdot \times \text{Ub}(y) \cdot \cap Y \).

Proof. By Lemma 3.12, there exists a \( \xi' \cdot \times \lambda \) such that \( x \in X \) and \( N_{\xi'} \cdot \times \text{Ub}(x) \cdot \cap Y' \). Without loss of generality we may assume \( \xi' = \alpha_v(\xi') + \sigma_\xi \) where \( \xi \) is a \( \gamma \)-number such that \( \omega_\beta^\xi < \xi < \omega_\beta^\xi + 1 \) (remark that if \( \xi < \omega_\beta^\xi + 1 \), then \( \xi \omega < \omega_\beta^\xi + 1 \) and \( \xi \omega \) is a \( \gamma \)-number). Put \( \theta = \xi + \sigma_\xi + \omega_\beta^\xi + \sigma_\zeta \) if \( \nu = 1 \), and \( \theta = \alpha_v(\xi + \omega_\beta^\xi + \sigma_\xi) \) if \( \nu \geq 2 \), then by Corollary of Lemma 3.4, \( N_{\theta} \cdot \times N_{\alpha_v(\omega_\beta^\xi)+\sigma_\zeta} \cdot \times \alpha_v(\xi^\beta + \sigma_\zeta) \cdot \times \alpha_v(\xi^\zeta + \sigma_\zeta) \cdot \times \) of which we shall denote the right side by \( Y \). If \( y \in Y \cdot \cap \text{Seg}(X) \cdot \cap Y' \), then since \( \theta < \lambda \), \( N_{\theta} \cdot \times \text{Ub}(y) \cdot \times Y \) exists and there exists a reduced increasing mapping of \( Y \) into \( \text{Ub}(y) \). If \( s \in \text{Seg}_s(\alpha_v(\omega_\beta^\xi)+\sigma_\zeta) \), then since \( N_{\alpha_v(\omega_\beta^\xi)+\sigma_\zeta} \cdot \times \text{Ub}(a; Z) \cdot \times \text{Ub}(f(a); \text{Ub}(y)) \), \( f(a) \in Y' \) by the definition of \( \xi' \). Hence \( f \) maps \( \text{Seg}_s(\alpha_v(\omega_\beta^\xi)+\sigma_\zeta) \) entirely into \( \text{Ub}(y) \cdot \cap Y' \).
Hence $f$ maps $N_{\alpha_\upsilon(\omega_\beta^\zeta)+\sigma_\zeta}$ into $\text{Ub}(y)\cap\text{Exp}(Y')=\text{Ub}(y)\cap Y$ (refer to Lemma 2.12, (vii)) and $N_{\alpha_\upsilon(\omega_\beta^\zeta)+\sigma_\zeta}\sim\text{Ub}(y)\cap Y$.

**Lemma 3.18.** *If $X$ is comparable with any set in $\mathcal{R}_\beta$, then $W_{\omega^\zeta}+X$ is comparable with any $Y \in \mathcal{R}_\beta$.***

Proof. If $\text{Ub}'(a) \sim X$ for any $a \in \text{Lay}_\nu(Y)$, then $Y \sim W_{\omega^\zeta}+X$ by Lemmas 2.12, (iii). If there exists an $a \in \text{Lay}_\nu(Y)$ such that $\text{Ub}'(a) \not\sim X$, then $X \sim \text{Ub}'(a)$ by assumption on $X$. Since $\text{Lb}(a)=W_{\omega^\zeta}$, $W_{\omega^\zeta}+X \sim \text{Lb}(a) \cup \text{Ub}'(a) \subset Y$. Hence in either case $W_{\omega^\zeta}+X$ is comparable with $Y$.

**Proof of Proposition 1 for $\lambda=\alpha_\upsilon(\omega_\beta^\zeta)$**. (fr($\lambda$)=0).

If $\mu<\lambda$, then there exists an $\varepsilon$ such that $\mu<\varepsilon$ and $\alpha_\upsilon(\omega_\beta^\zeta)+\sigma_\zeta \leq \varepsilon<\lambda$. Since $\text{Csg}_\upsilon(N_\mu) \sim N_{\omega_\beta^\zeta}+\sigma_\zeta$ by Lemma 3.16, $N_\mu \sim W_{\omega^\zeta}+N_{\omega_\beta^\zeta}+\sigma_\zeta=N_\lambda$ by Lemma 2.12 (ii). Hence $N_\mu \sim N_\lambda \sim N_\lambda$ by assumption D.1) on $N_\mu$ and $N_\lambda$ satisfies D.1).

Assume $X \in \mathcal{R}_\beta$ and $X \not\sim N_\mu$ for any $\mu<\lambda$. Put $Y=\overline{\text{Spt}}(X; N_\mu, \mu<\lambda)$, then it follows from Lemma 3.16 that for any $y \in Y \cap \text{Seg}_\upsilon(X)$, $N_{\alpha_\upsilon(\omega_\beta^\zeta)+\sigma_\zeta} \sim \text{Ub}(y)$ and $Y$ is not void. Hence $Y \cap \text{Seg}_\upsilon(X)$ is not void. Since $X \in \mathcal{R}_\beta$ and $X$ is resolvable, there exists a $y \in Y \cap \text{Seg}_\upsilon(X)$ such that $\text{Ub}(y) \cap Y \cap \text{Seg}_\upsilon(X)$ is totally ordered. Put $Z=\text{Ub}(y) \cap Y$, then since $N_{\alpha_\upsilon(\omega_\beta^\zeta)+\sigma_\zeta} \sim Z \cap \text{Seg}_\upsilon(X)=W_{\omega^\zeta}$ and $N_{\omega_\beta^\zeta} \sim \text{Csg}_\upsilon(N_{\alpha_\upsilon(\omega_\beta^\zeta)+\sigma_\zeta}) \sim Z \cap \text{Csg}_\upsilon(X)$. Hence $N_\lambda = W_{\omega^\zeta} + N_{\omega_\beta^\zeta} + \sigma_\zeta \sim W_{\omega^\zeta} + (Z \cap \text{Csg}_\upsilon(X))=Z \subset X$ and $N_\lambda$ satisfies D.1).

It follows from Lemma 3.18 that $N_\lambda$ satisfies D.3).

**Proof of Proposition 2 for $\lambda=\alpha_\upsilon(\omega_\beta^{\zeta+1})$**. (fr($\lambda$)=0). (Besides it can be proved that if Proposition 2 holds for $\lambda=\zeta$, then Proposition 2 also holds for $\lambda=\alpha_\upsilon(\omega_\beta^\zeta)$. In brackets of the following proof we shall consider this case).

If $\mu<\lambda$, then there exists a $\theta<\zeta$ such that $\mu<\alpha_\upsilon(\omega_\beta^{\theta+1})$. Since
\[ \omega^\beta + \sigma_\delta < \omega^\xi = \zeta, \quad N_\mu \cong N_{\alpha, (\omega^\beta + 1)} = W_\omega^\nu + N_{\omega + \sigma_\delta} \cong W_\omega^\nu + N_\xi = N_\lambda \text{ and } N_\lambda \text{ satisfies D. 1).} \]

Assume \( X \in \mathfrak{g} \) (resp. \( X \in \mathfrak{r} \) if \( N_\lambda \) satisfies D. 2')) and \( X \not\preceq N_\mu \) for any \( \mu < \lambda \). Put \( A = \text{Lay}_\omega(X) \). If for any \( a \in A \) there exists a \( \xi(a) < \zeta \) such that \( \text{Ub}'(a) \cong N_{\xi(a)} \), then the numbers \( \xi(a), \) \( a \in A \), are not cofinal to \( \zeta \) since \( \overline{X} < \mathfrak{u}_3 \), and \( \text{cf}(\zeta) = \beta \). Hence there exists a \( \xi' < \xi \) with \( \xi(a) < \xi' \) for any \( a \in A \). Without loss of generality we may assume that \( \xi' \) has a form \( \xi' = \omega^\zeta + \sigma_\ell \) where \( \xi < \zeta \). Then since \( \exists \bigvee_{a \in A} \text{Ub}'(a) \equiv \text{Csg}_\omega(X) \cong N_{\omega + \sigma_\ell} \), \( X \preceq W_\omega^\nu + N_{\omega + \sigma_\ell} = N_{\alpha, (\omega^\beta + 1)} \) while \( \alpha_\zeta(\omega^\beta + 1) < \lambda \) contradicting assumption. Hence there exists an \( a \in A \) such that \( \text{Ub}'(a) \not\preceq N_\xi \) for any \( \xi < \zeta \). By assumption D. 2) (resp. D. 2')) on \( N_\zeta \), \( N_\xi \cong \text{Ub}'(a) \). Hence \( N_\lambda \cong W_\omega^\nu + \text{Ub}'(a) = \text{Lb}(a) \cup \text{Ub}'(a) \subset X \) and \( N_\lambda \) satisfies D. 2) (resp. D. 2')).

It follows from Lemma 3.18 that \( N_\lambda \) satisfies D. 3).

**Proof of Proposition 1 for** \( \lambda = \alpha_\zeta(\omega_\delta^\beta + 1) + n \) where \( \zeta < \lambda \) and \( n > 0 \). (Besides, under assumption that \( N_{\zeta+n} \) satisfies D. 2'), Proposition 2 holds for \( \lambda \).

**Proof for D. 1) and D. 2) (resp. D. 2'))** are obtained almost samely as the case \( \lambda = \alpha_\zeta(\omega_\delta^\beta + 1) + n \) where \( \zeta > 0 \) and \( n > 0 \). For D. 3), refer to Lemma 3.18.

Now we complete the proof that \( N_\lambda \in \mathfrak{g} \) satisfies Proposition 1 in any case, and as we noticed at the head of \$2 \$ of this chapter, the proof of Theorem A is also completed.

**Remark.** It will be worth to notice that for most \( \lambda < \beta^\mu \), Proposition 2 is satisfied, i.e., \( N_\lambda \) satisfies D. 1) and D. 2'). Indeed by a careful study of proofs in this chapter, we can see that \( \lambda = \alpha_\zeta(\omega_\delta^\beta + 1) \) is the only case where we can not assert Proposition 2 for \( \lambda < \beta^\mu \) even under the assumption that any \( N_\zeta \) in \( \mathfrak{g} \) which is refered to define \( N_\lambda \) satisfies D. 1) and D. 2'). Even for \( \lambda = \alpha_\zeta(\omega_\delta^\beta + 1) \), if \( \zeta = 0 \) and \( \nu \) is either an isolated number or a limit number with \( \text{cf}(\nu) = 0 \), then D. 2') also holds (Lemma 3.14).

This remark will be recalled in the appendix at the end of this paper.

**Chapter IV. Proof of Main Theorem B**

In \$1 \$ we shall define an operation—the ramified power—of ramified sets. It is, in a sense, a limit operation of repeated ramified products. Applying it we shall find a ramified set \( S_\zeta \) for any \( \nu \) and \( \zeta \) with \( 0 < \nu < \omega_\beta \) and \( \zeta < \beta^\mu \), which is situated by the order \( \cong \) at the least upper bound of sets \( N_\mu \) with \( \mu < \alpha_\zeta(\omega_\delta^\beta + 1) \) within \( \mathfrak{h}_\beta \). In \$2 \$ we shall find sets which are examples to confirm Theorem B, (i) or (ii).
1. The sets $S^n_\nu$

**Definition 12.** Let $P_n(X)$ denote the set of all sequences $p = \{p(1), p(2), \ldots, p(n)\}$ of length $n$ such that $p(k) \in \text{Seg}_\nu(X)$ for $k = 1, 2, \ldots, n$ and $p(n) \in X$. The ramified power $X^{\oplus_\nu}$ of $X$ is the set $\bigcup_{n=0}^{\infty} P_n(X)$ within which we have $p < p'$ for $p \in P_n(X)$ and $p' \in P_{n'}(X)$, if and only if

- either $n < n'$, $p(k) = p'(k)$ for any $k \leq n - 1$ and $p(n) \leq p'(n)$,
- or $n = n'$, $p(k) = p'(k)$ for any $k \leq n - 1$ and $p(n) < p'(n)$.

For $p \in P_n(X)$, $\text{Dig}(p)$ (digitation of $p$) denotes the set of all $p' \in P_{n+1}(X)$ such that $p'(k) = p(k)$ for any $k \leq n$. (If $p(n) \in \text{Csg}_\nu(X)$, then $\text{Dig}(p)$ is void.) $\text{len}(p)$ denotes the number $n$ such that $p \in P_n(X)$.

The set $P_n(X)$ and $\text{Dig}(p)$ for $p \in X^{\oplus_\nu}$ are considered as a ramified subset of $X^{\oplus_\nu}$. If $\text{Dig}(p)$ is not void, i.e., $p(\text{len}(p)) \in \text{Seg}_\nu(X)$, then obviously $\text{Dig}(p)$ is isomorphic to $X$. It is easily seen that a ramified power of a ramified set is always a ramified set and if $X \subseteq X^{\oplus_\nu}$ for any $\nu$ with $0 < \nu < \omega_\alpha$. Further if $\kappa(X) \supseteq \omega_\nu$, then $X^{\oplus_\nu}$ is irresoluble. The following is obvious, and we omit the proof.

**Lemma 4.1.** (i). $\tau(p; X^{\oplus_\nu}) < \omega^{\nu}$ if and only if $\tau(p(\text{len}(p)); X) < \omega^{\nu}$.

(ii). $\text{Csg}_\nu(P_n(X)) = P_n(X) \cap \text{Csg}_\nu(X^{\oplus_\nu})$.

(iii). $\bigcup_{n \leq n} P_n(X)$ is a cut of $X^{\oplus_\nu}$, and $\text{Exp}_\nu(\bigcup_{n \leq n} P_n(X)) = \bigcup_{n \leq n} P_n(X)$.

**Corollary 1.** $\text{Csg}_\nu(X^{\oplus_\nu}) \sim \text{Csg}_\nu(X)$.

**Corollary 2.** If $\kappa(X) > \omega^\nu$, then $\kappa(X^{\oplus_\nu}) = \kappa(X)$.

**Corollary 3.** $X^{\oplus_\nu} \bowtie W_\omega \cup \text{Csg}_\nu(X)$.

**Lemma 4.2.** $P_n(X) \sim X$.

Proof. Obviously $P_1(X) \equiv X$. If $n = m + 1$ where $m > 0$, then $P_n(X)$ is the union of all $\text{Dig}(q)$ where $q \in P_m(X)$. Since $p \in \text{Dig}(q)$, $p' \in \text{Dig}(q')$ and $q = q'$ for $q$ and $q'$ in $P_m(X)$ imply that $p$ and $p'$ are disordered, $P_n(X) = \bigcup_{q \in P_m(X)} \text{Dig}(q)$. Since $\text{Dig}(q) \sim X$ for $q \in P_m(X) \cap \text{Seg}_\nu(X^{\oplus_\nu})$ and $\text{Dig}(q) = \emptyset$ for $q \in P_m(X) \cap \text{Csg}_\nu(X^{\oplus_\nu})$, $P_n(X) \sim X$.

**Lemma 4.3.** If $p \in \text{Seg}_\nu(X^{\oplus_\nu})$, then $\text{Ub}(p) \sim X^{\oplus_\nu}$.

Proof. $\text{Ub}(p) \bowtie X^{\oplus_\nu}$ is obvious. Put $n = \text{len}(p)$. $p \in \text{Seg}_\nu(X^{\oplus_\nu})$ implies $p(n) \in \text{Seg}_\nu(X)$ (see Lemma 4.1 (i)). For $q \in X^{\oplus_\nu}$, put $f(q) = q'$ where $q'(k) = p(k)$ for $k \leq n$ and $q'(n + k) = q(k)$ for $k \leq \text{len}(q)$, then it is easily seen that $f$ is an increasing mapping of $X^{\oplus_\nu}$ into $\text{Ub}(p)$ and $X^{\oplus_\nu} \bowtie \text{Ub}(p)$.

**Corollary 1.** If $\eta \leq \nu$ then $X^{\oplus_\eta \oplus_\nu} \sim X^{\oplus_\nu}$.

**Corollary 2.** If $\eta < \omega^\nu$ then $W_\omega + X^{\oplus_\nu} \sim X^{\oplus_\nu}$.
Now we shall find a set \( S_\xi \in \mathfrak{R}_\beta \) which is situated by the order relation \( \prec \) at the least upper bound of sets \( N_\mu \) with \( \mu < \alpha_\xi(\omega_\beta^{\xi+1}) \) within \( \mathfrak{R}_\beta \). (\( N_{\alpha_\xi(\omega_\beta^{\xi+1})} \) is the least upper bound of them within \( \mathfrak{R}_\beta \)). It was already seen that if either \( \nu \) is an isolated number or a limit number with \( \text{cf}(\nu) = 0 \), then \( N_{\alpha_\xi(\omega_\beta^{\xi+1})} \) is the least upper bound of sets \( N_\mu \) with \( \mu < \alpha_\xi(\omega_\beta) \) within \( \mathfrak{R}_\beta \) (Lemma 3.14).

If \( \nu \) is a limit number with \( \text{cf}(\nu) > 0 \) (where \( \beta \) is assumed greater than 1), then put \( S_\beta^{\nu} = N_{\alpha_\xi(\omega_\beta^{\xi+1})} \). In general (i.e., \( \nu \) is any number with \( 0 < \nu < \omega_\beta \)), if \( \zeta > 0 \), then put \( S_\zeta = N_{\alpha_\xi(\omega_\beta^{\xi+1})} \). And we shall show that a proposition similar to Proposition 2 for \( N_\lambda \) with \( \lambda = \alpha_\xi(\omega_\beta^{\xi+1}) \) holds for \( S_\zeta \).

**Remark.** If \( \nu \) is a limit number with \( \text{cf}(\nu) > 0 \), then \( \alpha_\xi(\nu) = \sup_{\mu < \xi} \alpha_\xi(\mu) \) and hence \( N_{\alpha_\xi(\nu)} \sim \bigvee_{\mu < \mu_\xi} N_{\alpha_\xi(\omega_\beta^{\xi+1})} = \bigvee_{\mu \in \mathfrak{R}_\beta} W_\mu^\nu \). Hence \( \alpha_\xi(\nu) \) is the least number among numbers \( \zeta \) with \( \kappa(N_\zeta) = \omega^\nu \). Similarly when \( \zeta > 0 \) (and \( \nu \) is any number), \( \alpha_\xi(\omega_\beta^{\xi+1}) + \sigma_\xi^\nu \) is the least number among numbers \( \zeta \) with \( \text{Csg}_\xi(N_\zeta) \sim N_{\alpha_\xi(\omega_\beta^{\xi+1})} \).

Besides, Proposition 2 for above \( \lambda \) does not hold.

Hereafter until the end of this section, when we say \( \zeta = 0 \), we automatically assume that \( \nu \) is a limit number with \( \text{cf}(\nu) > 0 \). (When \( \zeta > 0 \), this restriction is omitted).

**Lemma 4.4.** Put \( \lambda = \alpha_\xi(\omega_\beta^{\xi+1}) \). (i). If \( \mu < \lambda \) then \( N_\mu \ll S_\zeta \).

(ii). If \( X \in \mathfrak{R}_\beta \) and \( X \ll N_\mu \) for any \( \mu < \lambda \), then \( S_\zeta \ll X \).

**Proof.** Put \( \delta = \alpha_\xi(\nu) \) if \( \zeta = 0 \) and \( \delta = \alpha_\xi(\omega_\beta^{\xi+1}) + \sigma_\xi^\nu \) if \( \zeta > 0 \). \( \lambda \) is the least number greater than \( \delta \) within \( 1^\nu_{\mathfrak{R}_\beta} \cup 1^\nu_{\mathfrak{R}_\beta} \cup 1^\nu_{\mathfrak{R}_\beta} \) (see Lemma 1.14). Hence \( \delta < \mu < \lambda \) implies \( \mu \in 1^\nu_{\mathfrak{R}_\beta} \cup \bigcup_{\eta \leq \nu} 1^\eta_{\mathfrak{R}_\beta} \cup \bigcup_{\eta > \nu} 1^\eta_{\mathfrak{R}_\beta} \).

(i). Of course \( \mu \leq \delta \) implies \( N_\mu \ll N_{\delta} \ll S_\zeta \). Assume \( \delta < \mu < \lambda \) and \( N_\theta \ll S_\zeta \) for any \( \theta < \mu \), and we shall show \( N_\mu \ll S_\zeta \).

Case \( \mu \in 1^\nu_{\mathfrak{R}_\beta} \). In this case \( N_\mu \ll S_\zeta \) follows from D.2' on \( N_\mu \) immediately.

Case \( \mu \in \bigcup_{\eta \leq \nu} 1^\eta_{\mathfrak{R}_\beta} \). Let \( \mu = \alpha_\eta(\xi + \theta + n) \) be the canonical decomposition of \( \mu \). By assumption \( N_{\alpha_\eta(\xi + \theta + n)} \ll S_\zeta \) and \( N_{\alpha_\eta(\xi + \sigma_\theta^\eta)} \ll S_\zeta \). Hence by Corollary 1 of Lemma 4.3 and \( \eta \leq \nu \), \( N_\mu = N_{\alpha_\eta(\theta + n)} \circ N_{\alpha_\eta(\xi + \sigma_\theta^\eta)} \ll S_\zeta \).

Case \( \mu \in \bigcup_{\eta > \nu} 1^\eta_{\mathfrak{R}_\beta} \). Let \( \mu = \alpha_\eta(\omega_\beta^{\eta} + n) \) be the canonical decomposition of \( \mu \). Put \( \theta' = \theta \) if \( \theta \) is a limit number with \( \text{cf}(\theta) = \beta \) and \( \theta' = \omega(\theta - 1) + \sigma_\theta \) if \( \theta \) is an isolated number. By assumption \( N_{\theta' + n} \ll S_\zeta \). Since \( \eta < \nu \), \( N_\mu = W_\theta^{\eta + n} + W_{\theta'}^{n} + S_\zeta \). Hence \( N_\mu \ll S_\zeta \) for any \( \mu < \lambda \), and hence \( N_\mu \ll N_{\mu + 1} \ll S_\zeta \) which proves (i).
(ii). Assume $X \in \mathcal{R}_s$ and $X \not\sim N_\mu$ for any $\mu < \lambda$. By D.3 on $N_\mu$, $N_\mu \sim X$ for any $\mu < \lambda$. Put \( Y = \text{Spt}(X; N_\mu, \mu < \lambda) \) then for any $y$ in $Y \cap \text{Seg}_s(X)$, $N_\delta \sim \text{Ub}(y) \cap Y$ (refer to the proof of Proposition 1 for $\lambda = \alpha_\nu(\omega_\rho)$ in the case $\zeta = 0$ or to Lemma 3.17 in the case $\zeta > 0$). Especially $N_\delta \sim Y$.

Let $f_1$ be a reduced increasing mapping of $P_1(N_\delta)$, which is equivalent to $N_\delta$ by Lemma 4.2, into $Y$, and assume that $f_1$ is extended to a reduced increasing mapping $f_n$ of \( \bigcup_{k \leq n} P_1(N_\delta) \) into $Y$. Put $A_n = P_1^m(N_\delta) \cap \text{Seg}_s(S_\delta^\nu)$, then $P_1^m(N_\delta) = \bigcup_{a \leq n} \text{Dig}(a)$. Put $y = f_n(a)$ for $a \in A_n$, then $y \in \text{Seg}_s(X) \cap Y$. Since \( \text{Dig}(a) \equiv N_\delta \sim \text{Ub}(y) \cap Y \), there exists a reduced increasing mapping $g_n \equiv \text{Dig}(a)$ into $\text{Ub}(y) \cap Y$. Put $f_{n+1}(x) = g_n(x)$ for $x \in \text{Dig}(a)$ and $a \in A_n$ and $f_{n+1}(x) = f_n(x)$ for $x \in \bigcup_{k \leq n} P_1(N_\delta)$, then $f_{n+1}$ is an extension of $f_n$ and a reduced increasing mapping of $\bigcup_{k \leq n} P_1(N_\delta)$ into $Y$. Finally put $f(x) = f_n(x)$ for $x \in P_1^m(N_\delta)$, then $f$ is an extended increasing mapping of $S_\delta^\nu$ into $Y \subset X$. Hence $S_\delta^\nu \sim X$ and (ii) is proved.

**Corollary.** $S_\delta^\nu$ is comparable with any $X \in \mathcal{R}_s$.

Hence $S_\delta^\nu$ is the least upper bound of sets $N_\mu$ with $\mu < \alpha_\nu(\omega_\rho^{\gamma+1})$ within $\mathcal{R}_s$ as we noticed. Moreover,

**Lemma 4.5.** \( S_\delta^\nu \equiv N_\nu \) where $\lambda = \alpha_\nu(\omega_\rho^{\gamma+1})$.

Proof. Let $\delta$ be the same number defined in the proof of previous lemma.

Case $\zeta = 0$. It suffices to show $\kappa(S_\delta) = \omega^\nu$, since $N_\nu = W_\nu \sim$ and $\kappa(N_\lambda) = \omega^\nu + 1$ (see Theorem 5). Of course $\kappa(S_\delta) \leq \kappa(N_\delta) = \omega^\nu$.

Let $W$ be a maximal totally ordered subset of $S_\delta$. If there exist a $p \in W$ and a $n \leq \omega$ such that $\text{Ub}'(p) \cap W \subset P_1^m(N_\delta)$, then let $p$ be such a least element. If $n = 1$ then $W \subset P_1^m(N_\delta) \sim N_\delta$ and $W \not\sim \kappa(N_\delta) = \omega^\nu$. If $n > 1$, then $p$ is contained in a $\text{Dig}(q)$ where $q \in P_1^m(N_\delta)$, and obviously $\tau(p) = \tau(q) + 1$. Since $\text{Dig}(q)$ is not void, $\tau(q) < \omega^\nu$ while the type of $\text{Ub}'(p) \cap W$ is less than $\kappa(P_1^m(N_\delta)) = \kappa(N_\delta) = \omega^\nu$. Hence $\bar{W} = \tau(q) + 1 + \text{Ub}'(p) \cap W < \omega^\nu$.

If for any $n \leq \omega$, there exists a $p_n$ in $P_1^m(N_\delta) \cap W$, then let $p_n$ be such a least element. Similarly as the above $\tau(p_n; N_\delta \sim \omega^\nu) \leq \omega^\nu$ for any $n \leq \omega$. But there is no $w \in W$ such that $p_n < w$ for any $n \leq \omega$, and numbers $\tau(p_n; N_\delta \sim \omega^\nu)$ with $n \leq \omega$ are cofinal to $\bar{W}$. By assumption $\nu$ is a limit number with $\text{cf}(\nu) > 0$, and $\text{cf}(\omega^\nu) = \text{cf}(\nu) > 0$. Hence the number $\bar{W}$, to which a countable sequence of numbers less than $\omega^\nu$ is cofinal, is less than $\omega^\nu$. 

Hence $W \subseteq N_\omega^{\omega^\chi}$ implies $W \subseteq \omega^\chi$ and $\kappa(N_\omega^{\omega^\chi}) = \omega^\chi$ which is to be proved.

Case $\chi > 0$. Since $\text{Csg}_\chi(S_\chi^0) = \text{Csg}_\chi(N_\chi^0) = N_{\omega^\chi + \sigma^\chi} = \text{Csg}_\chi(N_\chi)$ (see Corollary 1 of Lemma 4.1), $S_\chi^0 \approx W_{\omega^\chi} + N_{\omega^\chi + \sigma^\chi} = N_\chi$ (Lemma 2.12, (iii)).

Assume $N_\chi \propto S_\chi^0$ and let $f$ be a reduced increasing mapping of $N_\chi$ into $S_\chi^0$. Let $a$ be any element in $\text{Lay}_\chi(N_\chi)$, then $f(a)$ falls onto a $p \in P^\chi_n(N_\chi)$, and $f$ maps the subset $W_{\omega^\chi}$ of $N_\chi = W_{\omega^\chi} + N_{\omega^\chi + \sigma^\chi}$ into $\bigcup P^\chi_k(N_\chi)$. Hence $f(N_\chi) \subset \text{Exp}_\chi(f(W_{\omega^\chi})) \subset \text{Exp}_\chi(\bigcup P^\chi_k(N_\chi); N_\chi^{\omega^\chi}) = \bigcup P^\chi_k(N_\chi)$ (see Lemma 4.1 (iii)). Besides there exists a $w \in W_{\omega^\chi}$ such that $f(w) \in P^\chi_n(N_\chi)$, or otherwise $f$ maps any element $w$ in $W_{\omega^\chi}$ into $\bigcup P^\chi_k(N_\chi)$ and $f(N_\chi) \subset \bigcup P^\chi_k(N_\chi)$ similarly as the above, contradicting $p = f(a) \in P^\chi_n(N_\chi)$.

Then $f$ maps $\text{Ub}'(w; N_\chi)$ entirely into $P^\chi_n(N_\chi)$ while $\text{Ub}'(w; N_\chi) = W_{\omega^\chi} + N_{\omega^\chi + \sigma^\chi} \sim N_\chi$ contradicting $P^\chi_n(N_\chi) \sim N_\chi \propto N_\chi$. Hence $S_\chi^0 \propto N_\chi$ which is to be proved.

In Chapter 3 we did not assert that Proposition 2 holds for $\chi = \alpha_\chi(\omega_\xi'^{+1})$ where either $\xi^* > 0$ or $\nu$ is a limit number with $\text{cf}(\nu) > 0$, but Lemmas 4.4 and 4.5 shows that surely it does not hold for such $\chi$.

Finally we add

**Lemma 4.6.** Assume $\chi > 0$ and an $X \in \mathfrak{X}_\chi$ satisfies the following conditions: (a) the potency of $\text{Lay}_\chi(X)$ is at most $\mathfrak{X}_\chi$, and (b) for any $a \in \text{Lay}_\chi(X)$, $\text{Exp}_\chi(\text{Lb}(a)) \propto N_{\alpha_\chi(\omega_\xi'^{+1}) + \sigma_\chi'}$; then $X \propto S_\chi^0$.

Proof. Put $\delta = \alpha_\chi(\omega_\xi'^{+1}) + \sigma_\chi'$ similarly as previous lemmas. Let $\mathfrak{U}$ be the family of all maximal totally ordered subsets $A$ of $\text{Seg}_\chi(X)$ such that $\text{Exp}_\chi(A) \cap \text{Lay}_\chi(X)$ is not void. Then the type of $A \in \mathfrak{U}$ is $\omega^\chi$. By (a), the potency of $\mathfrak{U}$ is at most $\mathfrak{X}_\chi$. Let $A_1, A_2, \ldots, A_n, \ldots (n < \omega)$ be a sequence which consists of all $A \in \mathfrak{U}$. Here we shall consider only the case $\mathfrak{U} = \mathfrak{X}_\chi$ and assume $A_k \propto A_n$ if $k \propto n$. For the case $\mathfrak{U} \propto \mathfrak{X}_\chi$, the sequence ceases at a $n < \omega$ and we can proceed the following proof with slight modifications.

Since $\text{Exp}_\chi(A_1) \propto N_\chi$, there exists a reduced increasing mapping $g_1$ of $\text{Exp}_\chi(A_1)$ into $P^\chi_1(N_\chi)$. Assume that $g_1$ is extended to a reduced increasing mapping $g_{n-1}$ of $\bigcup \text{Exp}_\chi(A_k)$ into $\bigcup P^\chi_k(N_\chi)$ where $n \geq 1$. Since $A_n - \bigcup A_k$ is not void (or otherwise $A_n$ coincides with an $A_k$ where $k < n$, for $n$ is finite, contradictorily), there exists a minimal element $a$ in it.

If $a$ is minimal within $X$, then let $b$ be any minimal element in $\bigcup A_k$. If $a$ is not minimal in $X$, then $\text{Lb}(a)$ is included in an $A_k$ where $k < n$. Since the type of $A_k$ is $\omega^\chi$ and $\tau(a) < \omega^\chi$, there exists uniquely
a \(b\) in \(A_k\) such that \(\tau(b) = \tau(a)\). In either case that \(a\) is minimal within \(X\) or not, we have a \(b \in \bigcup A_k\) such that \(Lb(b) = Lb(a)\). Since \(g_{n-1}\) is reduced, \(\tau(g_{n-1}(b)) = \tau(b) = \tau(a) < \omega\). Since \(\Exp(A_n) \cap \Ub(a) \cong N_\delta\), there exists a reduced increasing mapping \(g'\) of \(\Exp(A_n) \cap \Ub(a)\) into \(\Diag(g_{n-1}(b))\) which is isomorphic to \(N_\delta\). Put \(g_n(x) = g_{n-1}(x)\) for \(x \in \bigcup_{k < n} \Exp(A_k)\), \(g_n(a) = g_{n-1}(b)\) and \(g_n(x) = g_n'(x)\) for \(x \in \Exp(A_n) \cap \Ub(a)\), then \(g_n\) is an extension of \(g_{n-1}\) and a reduced increasing mapping of \(\bigcup_{k \leq n} \Exp(A_k)\) into \(\bigcup P_\delta(N_\delta)\).

Let \(M\) be the set of all minimal element of \(X - \bigcup \Exp(A_m)\), then similarly as the above, for any \(a \in M\) there exists a \(n < \omega\) and a \(b \in A_n\) such that \(Lb(a) = Lb(b)\). \(a \in M\) implies \(\kappa(\Ub'(a)) \leq \omega + 1\) while \(\kappa(\Exp(A_n) \cap \Ub'(b)) \geq \omega + 2\). Hence there exists a reduced increasing mapping \(h_a\) of \(\Ub'(a)\) into \(\Exp(A_n) \cap \Ub'(b)\).

Put \(f(x) = g_n(x)\) for \(x \in \Exp(A_n) \cap \bigcup A_k\) and \(f(x) = fh_a(x)\) for \(x \in \Ub'(a)\) and \(a \in M\), then \(f\) is a reduced increasing mapping of \(X\) into \(S'_\zeta\), and \(X \cong S'_\zeta\).

2. **Proof of Main Theorem B**

Now we shall intend to find examples to confirm Theorem B i) or ii).

**Definition 13.**

i). Put \(L = \bigcup_{3 \leq k < \omega} W_{\omega + k}\) and \(S = L \odot_1\).

ii). \(\mathcal{U}'\) denotes the family of all maximal totally ordered subsets of \(\Seg_x(S)\) and put \(\mathcal{U} = \mathcal{U}' - \{Lb(a) | a \in \Lay_x(S)\}\).

iii). Let \(t_A\) denote a term assigned to each \(A \in \mathcal{U}\) and put \(B = \{t_A | A \in \mathcal{U}\}\).

Put \(T = S \cup B\) where order within \(S\) preserves orginal relation and \(a < t_A\) holds if and only if \(a \in A\). \((t_A < x\) does not occur for any \(x \in T\). For any subset \(C\) of \(B\), \(S \cup C\) is regarded as a ramified subset of \(T\).

iv). A subset \(C\) of \(B\) is called **barren** if \(S \cup C \cong S\).

The followings are obvious and we omit the proofs.

**Lemma 4.7.**

(i). \(L \sim N_{\omega_3} + \omega\) and hence \(S \sim S_1\). Especially \(L \cong S\).

(ii). If \(A\) is a maximal totally ordered subset of \(S\), then either \(\bar{A} = \omega\) or \(\omega + 3 \leq \bar{A} < \omega \cdot 2\). (Remark that the type of any maximal totally ordered subset of \(L\) is at least \(\omega^3\)).

(iii). \(\bar{S} = \mathbb{R}\) and \(\bar{B} = 2^\mathbb{R}\).

(iv). For any \(A \in \mathcal{U}'\), \(\Exp(A; T) \cap \Lay_x(T)\) consists of one and only one element.

(v). If \(a_n \in P_\delta(L)\) and \(a_n < a_{n+1}\) for any \(n < \omega\), then the sequence

\[a_n < a_{n+1} < \cdots < a_m < \cdots\]
\{a_n|n<\omega\} uniquely determines a maximal totally ordered subset \(W\) of \(\text{Seg}_T(T)\) such that \(a_n\in W\) for any \(n<\omega\), and \(W\) is contained in \(\mathfrak{A}\).

(vi). If \(a\in\text{Seg}_T(T)\), then \(\text{Ub}(a)\sim T\). (See Lemma 4.3).

(vii). If \(C\subseteq B\) and \(C\subseteq\mathfrak{A}\), then \(C\) is barren. (See Lemma 4.6).

**Lemma 4.8.** \(S\cong T\).

Proof. \(S\cong T\) is obvious. Assume \(T\cong S\) and that there exists a reduced increasing mapping \(f\) of \(T\) into \(S\). Let \(a\) be any minimal element of \(T\) then \(f(a)\in P_1(L)\). Assume that an \(a_n\in T\) is already determined in such a way that \(\tau(a_n)<\omega\) and \(f(a_n)\in P_n(L)\). Since \(\text{Ub}(a_n)\sim T\) and \(P_n(L)\sim L\cong S\), \(\text{Ub}(a_n)\sim P_n(L)\) and \(f(\text{Ub}(a_n))\) is not included in \(P_n(L)\). Let \(a_{n+1}\) be a minimal element in \(\text{Ub}(a_n)\) which is mapped by \(f\) in \(\text{Ub}(f(a_n))-P(L)\), then obviously \(f(a_{n+1})\in P_{n+1}(L)\). Furthermore \(\tau(a_{n+1})<\omega\), or otherwise, since \(\text{Ub}(a_{n+1})\cap\text{Seg}_T(T)\) is mapped by \(f\) into \(\bigcup_{k=n}^\infty P_k(L)\), \(a_{n+1}\) is mapped in \(\text{Exp}(\bigcup_{k=n}^\infty P_k(L);S)=\bigcup_{k=n}^\infty P_k(L)\) contradictorily. Thus we have a sequence \(a_1, a_2, \ldots, a_n, \ldots (n<\omega)\) such that \(a_n\in\text{Seg}_T(T)\) and \(f(a_n)\in P_n(L)\) for any \(n<\omega\). By Lemma 4.7, (iv) and (v), there exists a \(t\in\text{Lay}_T(S)\) such that \(a_n\sim t\) for any \(n<\omega\). \(f(t)\in S\) and hence \(f(t)\) is contained in a \(P(t)\), but then since \(f(a_{n+1})\in P_{n+1}(L)\), \(f(a_{n+1})\) is not less than \(f(t)\), contradicting \(a_{n+1}\sim t\) and that \(f\) is increasing. Hence \(T\cong S\) and accordingly \(S\cong T\).

**Lemma 4.9.** If \(f\) is a reduced increasing mapping of \(T\) into itself, then the restriction \(f'\) of \(f\) on \(S\) is a reduced increasing mapping of \(S\) into itself. Conversely if \(f'\) is a reduced increasing mapping of \(S\) into itself, then there exists a unique reduced increasing mapping of \(T\) into itself which is an extension of \(f'\).

Proof. Assume that \(f\) is a reduced increasing mapping of \(T\) into itself, but there exists an \(x\in S\) such that \(f(x)\in B-T-S\), then \(f(x)\sim t_A\) for an \(A\in\mathfrak{A}\). Since \(f\) is reduced, \(\tau(x)=\tau(t_A)=\omega\). But by the definition of \(L\) and \(S\), for any \(x\in\text{Lay}_S(S)\), \(\text{Ub}(x)\) is not void, while \(\text{Ub}(t_A)\) is void, contradicting \(f(\text{Ub}(x))\subseteq\text{Ub}(t_A)\). Hence \(x\in S\) implies \(f(x)\in S\) and the restriction \(f'\) of \(f\) on \(S\) is a reduced increasing mapping of \(S\) into itself.

Conversely let \(f'\) be a reduced increasing mapping of \(S\) into itself. For any \(t_A\in B-T-S\), \(A=\text{Lb}(t_A)\in\mathfrak{A}\) and since \(f'\) is reduced, \(f'(A)\in\mathfrak{A}'\). By Lemma 4.7 (iv) there exists a unique element \(b_A\in\text{Exp}_S(f'(A);T)\cap\text{Lay}_S(T)\). Put \(f(t_A)=b_A\) and \(f(x)=f'(x)\) for \(x\in S\), then it is obvious that \(f\) is the unique reduced increasing mapping of \(T\) into itself, which is an extension of \(f'\).

**Corollary.** For any subsets \(C\) and \(D\) of \(B\) such that \(S\cup C\sim S\cup D\),
a reduced increasing mapping of \( S \cup C \) into \( S \cup D \) can be uniquely extended to a reduced increasing mapping of \( T \) into itself.

Now we shall introduce topology in \( \text{Lay}_T(T) \) and \( B \). For \( x \in \text{Seg}_T(T) \) put \( V_x = \text{Lay}_T(T) \cap \text{Ub}(x) \). If \( V_x \) intersect with \( V_{x'} \), then one is entirely included in the other, and if \( V_x \subset V_{x'} \), then \( x' \leq x \). Hence if the intersection of a family \( \{ V_{x_k} | k \leq n \} \) is not void, then the set \( \{ x_k | k \leq n \} \) is totally ordered. Let \( x \) be the greatest element of this set, then \( \bigcap_{k \leq n} V_{x_k} = V_x \).

Hence the family \( \{ V_x | x \in \text{Seg}_T(T) \} \), which will be denoted by \( \mathfrak{B} \), makes a basis of open sets, by which a topology is defined on \( \text{Lay}_T(T) \). Since \( \text{Seg}_T(T) \) is countable, \( \mathfrak{B} \) is countable. It is easy to see (or rather well-known) that the topological space \( \text{Lay}_T(T) \) thus defined is a totally disconnected Hausdorff space.

\( B \) is a topological subspace of \( \text{Lay}_T(T) \) with relative topology. Put \( V_x = B \cap V_x \) for \( x \in \text{Seg}_T(T) \), and \( \mathfrak{B} = \{ V_x | x \in \text{Seg}_T(T) \} \), then \( \mathfrak{B} \) is a basis of open sets of \( B \).

For a reduced increasing mapping \( f \) of \( T \), let \( f^r \) denote the restriction of \( f \) on \( \text{Lay}_T(T) \). Since \( f \) is reduced, \( f^r(\text{Lay}_T(T)) \subset \text{Lay}_T(T) \).

Lemma 4.10. If \( f \) is a reduced increasing mapping of \( T \) into itself, then \( f^r \) is a continuous mapping of \( \text{Lay}_T(T) \) into itself.

Proof. Assume \( b \in \text{Lay}_T(T), b' = f^r(b) \) and that \( V \) is an open set which contains \( b' \), then there exists a \( V_{x'} \in \mathfrak{B} \) such that \( b' \in V_{x'} \subset V \).

Let \( x \) be the unique element in \( \text{Lb}(b) \) such that \( \tau(x) = \tau(x') \). Since \( f \) is reduced, \( f(x) = x' \). Now \( b \in V_x \) and \( f^r(V_x) \subset V_{x'} \subset V \) which shows that \( f^r \) is a continuous mapping of \( \text{Lay}_T(T) \) into itself.

For a subset \( C \) of \( \text{Lay}_T(T) \), put \( \bar{C} = \bigcup_{b \in \mathfrak{B}} \text{Exp}(\text{Lb}(b)) \).

Lemma 4.11. If a subset \( C \) of \( \text{Lay}_T(T) \) is closed, then \( \text{Exp}_T(\bar{C}) = \bar{C} \).

Proof. Assume \( x \notin \bar{C} \). If \( \tau(x) < \omega \), then \( x \notin \text{Exp}_T(\bar{C}) \) by the definition of \( \text{Exp}_T \). If \( \tau(x) \geq \omega \), then let \( b \) be the unique element in \( \text{Lay}_T(T) \cap \text{Lb}^T(x) \). Of course \( b \notin \bar{C} \).

Since \( C \) is closed, there exists a \( V_y \in \mathfrak{B} \) such that \( b \in V_y \) and \( V_y \cap C = 0 \). Since \( x \in \text{Ub}(y) \) and \( \text{Ub}(y) \cap C = 0 \), \( x \notin \text{Exp}_T(\bar{C}) \) and hence \( \text{Exp}_T(\bar{C}) \subset \bar{C} \).

Lemma 4.12. In order that a subset \( C \) of \( B \) is barren, it is necessary and sufficient that \( C \) is a subset of a union of at most countable barren subsets of \( B \) which are closed within \( B \).

Proof. If \( C \) is barren, then there exists a reduced increasing mapping \( f^r \) of \( S \cup C \) into \( S \). \( f^r \) is uniquely extended to a reduced increasing mapping \( f \) of \( T \) into itself (see Corollary of Lemma 4.9). \( f \) maps every \( t \in C \) into \( \text{Lay}_T(S) \) which consists of countable elements \( b_1, b_2, \ldots, b_n, \ldots \).
Let \( C_n \) be the set of all \( t \in B \) such that \( f^n(t) = b_n \), then since \( f^r \) is continuous, each \( C_n \) is closed in \( B \). Since \( f(S \cup C_n) \subset S \), each \( C_n \) is barren, and hence \( C \) is a subset of the union of countable barren subsets \( C_n \) of \( B \) each of which is closed in \( B \).

Conversely assume that a subset \( C \) of \( B \) is included in a union \( C' \) of at most countable barren subsets \( C_n \) of \( B \), where each \( C_n \) is closed in \( B \). Let \( \bar{C}_n \) be the closure of \( C_n \) in \( \text{Lay}_i(T) \), then since \( C_n \) is closed in \( B \), \( \bar{C}_n \cap B = C_n \). Put \( C'' = \text{Lay}_i(S) \setminus \bigcup_{n<\omega} \bar{C}_n \), then \( C'' \) is at most countable.

Let \( \otimes \) be the family of all sets \( \bar{C}_n \) and all \( \{d\} \) where \( \{d\} \) is the set which consists of a single element in \( C'' \). Notice that any set \( D \) in \( \otimes \) is closed in \( \text{Lay}_i(T) \) and, since \( D \cap B \) is either void or coincidental with a \( C_n \) which is barren, \( D \cup S \subset S \).

\( \otimes \) contains at most countable sets (it can be proved that the potency of \( \otimes \) is not finite, but we need not use the fact here). Let \( D_1, D_2, \ldots \) be an arrangement of all sets in \( \otimes \) into a sequence, where repeats of same sets are admitted. \( \text{Lay}_i(S \cup C') = \bigcup_{n<\omega} D_n \), and \( S \cup C' = C' \cup \bigcup_{a \in \text{Lay}_i(S \cup C')} \text{Exp}_i(\text{Lb}(\alpha)) = \bigcup_{a \in \text{Lay}_i(S \cup C')} \bigcup_{s<\omega} \text{Exp}_i(\text{Lb}(\alpha)) = \bigcup_{s<\omega} D_n \).

Since \( D \subset D \cup S \subset S \), there exists a reduced increasing mapping \( f_i \) of \( \tilde{D}_i \) into \( S \). Assume that \( f_i \) is extended to a reduced increasing mapping \( f_n \) of \( \bigcup_{k \leq n} \tilde{D}_k \) into \( S \). Put \( E_n = \bigcup_{k \leq n} D_k \), then \( E_n = \bigcup_{k \leq n} \tilde{D}_k \). Since \( E_n \) is closed, \( \text{Exp}_i(E_n) = \tilde{E}_n \) by Lemma 4.11. Hence for any minimal element \( a \) of \( (S \cup C') \setminus \tilde{E}_n \), \( \tau(a) < \omega \) by Lemma 2.3 (vii). Let \( M_n \) be the set of all minimal elements of \( (S \cup C') \setminus \tilde{E}_n \), then \( (S \cup C') \setminus \tilde{E}_n \subset \bigcup_{a \in M_n} \text{Ub}^i(\alpha ; T) \). Put \( D_{n+1} = D_{n+1} \cap \text{Ub}^i(\alpha) \) for \( a \in M_n \) and let \( M_n \) be the set of all \( a \in M_n \) where \( D_{n+1, a} \) is not void. \( (M_n \) itself may be void). Then \( D_{n+1} = \bigcup_{a \in M_n} D_{n+1, a} \) and \( \tilde{D}_{n+1} \subset S \cup D_{n+1, a} \). If \( a \in M_n \), then since \( \tau(a) < \omega \), either \( \tau(a) = 0 \) or \( a \) has an immediate ascendant \( a' \) in \( E_n \). If \( \tau(a) = 0 \), then let \( g_{a} \) be any reduced increasing mapping of \( \tilde{D}_{n+1, a} \) into \( S \). If \( a \) has an immediate ascendant \( a' \) in \( E_n \), then since \( \tau(f_n(a')) < \omega \) and \( \text{Ub}(f_n(a')) \subset S \) by Lemma 4.3, we have a reduced increasing mapping \( g_{a} \) of \( \tilde{D}_{n+1, a} \cap \text{Ub}(a) \) into \( \text{Ub}(f_n(a')) \subset S \). Put \( f_{n+1}(x) = f_n(x) \) for \( x \in \tilde{E}_n \) and \( f_{n+1}(x) = g_{a}(x) \) for \( x \in \tilde{D}_{n+1, a} \cap \text{Ub}(a) \) and \( a \in M_n \), then as easily seen, \( f_{n+1} \) is a reduced increasing mapping of \( \bigcup_{k \leq n+1} \tilde{D}_k \) into \( S \). Finally put \( f(x) = f_n(x) \) for \( x \in \tilde{D}_n \), then \( f \) is a reduced increasing mapping of \( S \cup C' = \bigcup_{k \leq n} \tilde{D}_k \) into \( S \) and hence \( S \cup C' \subset S \), i.e., \( C' \) is barren. Hence the subset \( C \) of \( C \) is also barren.
Hereafter, until the end of this section, we assume continuum hypothesis. The following Lemma is essentially a consequence of Proposition \( P_* \) of [8].

**Lemma 4.13.** If a subset \( C \) of \( B \) is not barren, then there exists a subset \( D \) of \( C \) such that \( S \cong S \cup D \cong S \cup C \).

Proof. Let \( \mathfrak{C} \) be the family of all barren subsets of \( B \) which are closed in \( B \). Since the basis \( \mathfrak{S}' \) of open sets of \( B \) is countable, the potency of \( \mathfrak{C} \) is at most \( \mathfrak{K} \), by continuum hypothesis. Let \( \mathfrak{F} \) be the family of all reduced increasing mappings of \( S \cup C \) into itself, and \( \mathfrak{Y} \) be the family of all reduced increasing mappings of \( S \) into itself. As we have seen in Lemma 4.9 and its Corollary, there exists a one-to-one correspondence between all mappings in \( \mathfrak{F} \) and (not necessarily all) mappings in \( \mathfrak{Y} \) such that, if \( f \in \mathfrak{F} \) is corresponding to \( f' \in \mathfrak{Y} \), then \( f' \) is the restriction of \( f \) on \( S \). Since \( S = \mathfrak{K}_0 \), the potency of \( \mathfrak{Y} \) is at most \( \mathfrak{K} \), by continuum hypothesis. Hence the potency of \( \mathfrak{F} \) is also at most \( \mathfrak{K} \). Since \( C \) is not barren, it is not countable (see Lemma 4.7 (vii)), while the potency of \( B \) is \( 2^{\kappa_0} = \mathfrak{K} \) (see Lemma 4.7 (iii)). Hence \( \overline{\mathfrak{C}} = \mathfrak{K} \).

Let \( \{C_\alpha | \alpha < \omega_1 \} \) be a transfinite sequence formed of all sets in \( \mathfrak{C} \), \( \{f_\alpha | \alpha < \omega_1 \} \) be a transfinite sequence formed of all mappings in \( \mathfrak{F} \), and \( \{b_\alpha | \alpha < \omega_1 \} \) be a transfinite sequence formed of all elements in \( C \), where in the former two sequences, repeats of same terms (sets or mappings) are admitted if they are necessary, but since \( \overline{\mathfrak{C}} = \mathfrak{K} \), we may assume \( b_\alpha = b_\beta, f_\alpha = f_\beta \) if \( \alpha = \beta \). Put \( D_\xi = f_\xi(S \cup C) \cap B \). Since \( f_\xi \) is a reduced increasing mapping of \( S \cup C \) into itself, \( D_\xi \subset C \). \( D_\xi \) is not barren, or otherwise, there exists a reduced increasing mapping \( g \) of \( S \cup D_\xi \) into \( S \), and \( g f_\xi \) is a reduced increasing mapping of \( S \cup C \) into \( S \), contradicting that \( C \) is not barren.

Now we shall define two increasing sequence \( \{\lambda_\xi | \xi < \omega_1 \} \) and \( \{\mu_\xi | \xi < \omega_1 \} \) of ordinal numbers less than \( \omega_1 \), which satisfy following conditions: (i) if \( \eta < \xi \), then \( \mu_\eta < \lambda_\xi < \mu_\xi \), (ii) \( \lambda_\xi \in D_\xi \) and (iii) \( b_{\lambda_\xi} \in C - \bigcup \{C_\nu | \nu < \xi \} \).

Since \( D_\xi \) is not barren, it is not void. Let \( \lambda_0 \) be the least ordinal number such that \( b_{\lambda_0} \in D_\xi \), and put \( \mu_0 = \lambda_0 + 1 \). Assume that for an ordinal number \( \xi < \omega_1 \), sequences \( \{\lambda_\eta | \eta < \xi \} \) and \( \{\mu_\eta | \eta < \xi \} \) are already obtained. Let \( \zeta_\xi \) be the least ordinal number such that \( \mu_\eta < \zeta_\xi \) for any \( \eta < \xi \). Since the sequence \( \{\mu_\eta | \eta < \xi \} \) is not cofinal to \( \omega_1 \), \( \zeta_\xi < \omega_1 \), and \( \zeta_\xi = \mathfrak{K} \). Let \( E_\xi \) be the union of the set \( \{b_\nu | \nu < \zeta_\xi \} \) and all sets \( C_\nu \) with \( \nu < \zeta_\xi \). Since \( E_\xi \) is a union of at most countable barren sets which are closed in \( B \), \( E_\xi \) is also barren by Lemma 4.12. Since \( D_\xi \) is not barren, \( D_\xi - E_\xi \) contains more than countable elements. Let \( \lambda_\xi \) be the least ordinal
number such that \( b_{\lambda_{\xi}} \in D_{\xi} - E_{\xi} \), and \( \mu_{\xi} \) be the least ordinal number such that \( b_{\mu_{\xi}} \in D_{\xi} - E_{\xi} - \{ b_{\lambda_{\xi}} \} \), (remark \( D_{\xi} \subset C \)). Thus we can inductively define sequences \( \{ \lambda_{\xi} | \xi < \omega_1 \} \) and \( \{ \mu_{\xi} | \xi < \omega_1 \} \) which obviously satisfy (i), (ii) and (iii).

Let \( D \) be the set which consists of all \( b_{\mu_{\xi}} \) with \( \xi < \omega_1 \). Since no repeats of same elements are admitted in the sequence \( \{ b_{\nu} | \nu < \omega \} \), and there is no number common to both sequences \( \{ \lambda_{\xi} | \xi < \omega_1 \} \) and \( \{ \mu_{\xi} | \xi < \omega_1 \} \) by (i), \( D \) does not contains \( b_{\lambda_{\xi}} \) for any \( \xi < \omega_1 \).

We shall show \( S \models S \cup D \models S \cup C \). Since no \( \nu \) is repeated in the sequence \( \{ b_{\nu} | \nu < \omega \} \), and \( \xi \) is not common to both sequences \( \{ \lambda_{\xi} | \xi < \omega_1 \} \) and \( \{ \mu_{\xi} | \xi < \omega_1 \} \) by (i), \( D \) does not contain \( b_{\lambda_{\xi}} \) for any \( \xi < \omega_1 \).

Hence \( D \) is not barren and \( S \models S \cup D \). Next we shall show \( S \cup C \not\models S \cup D \). Assume on the contrary, that there exists a reduced increasing mapping \( f \) of \( S \cup C \) into \( S \cup D \). Since \( S \cup D \) is a subset of \( S \cup C \), \( f \) itself may be regarded as a reduced increasing mapping of \( S \cup C \) into itself. Hence \( f \) coincides with a \( f_{\xi} \) in \( \mathfrak{F} \). But \( b_{\lambda_{\xi}} \in f_{\xi}(S \cup C) \) by (ii), while \( b_{\lambda_{\xi}} \) is not contained in \( D \cup \text{Lay}_\nu(S) \), contradicting \( f_{\xi}(\text{Lay}_\nu(S \cup C)) \subset D \cup \text{Lay}_\nu(S) \). Hence \( S \cup C \not\models S \cup D \) and accordingly \( S \cup D \models S \cup C \).

Proof of Main Theorem B (ii).

The set \( B \) itself is not barren by Lemma 4.8. Hence putting \( D_0 = B \), we can inductively define a sequence \( D_0, D_1, \ldots \) of subsets of \( B \) such that \( S \models S \cup D_{n+1} \models S \cup D_n \) for any \( n < \omega \) by Lemma 4.13. Hence, putting \( X_n = S \cup D_n \), the sets \( X_n \), \( n < \omega \), satisfy the condition of Theorem B (ii).

Proof of Main Theorem B (i).

By Lemma 4.13, there exists a subset \( C \) of \( B \) such that \( S \models S \cup C \models T \). Let \( s_t \) be an element assigned to each \( t \in C \), and put \( E = \{ s_t | t \in C \} \) and \( U = S \cup C \cup E \) where each \( s_t \in E \) is maximal in \( U \) and we have \( x \leq s_t \) for \( x \in S \cup C \) and \( t \in C \) if and only if \( x \leq t \) within \( S \cup C \).

First assume \( U \sim T \), and let \( f \) be a reduced increasing mapping of \( U \) into \( T \). Since \( \tau(s) = \omega + 1 \) for any \( s \in E \) and \( \tau(t) = \omega \) for any \( t \in B \), any \( s \in E \) is not mapped by \( f \) (since \( f \) is reduced) on any \( t \in B \), i.e., \( f(s) \in S \). Since \( S \) is a cut of \( T \) and \( f(t) < f(s_t) \) for any \( t \in C \), \( C \) is mapped by \( f \) into \( S \). Finally \( f(S) \subset S \) by Lemma 4.9. Hence the restriction of \( f \) on \( S \cup C \) is a reduced increasing mapping of \( S \cup C \) into \( S \) contradicting \( S \models S \cup C \). Hence \( U \not\sim T \).

Next assume \( T \sim U \), and let \( g \) be a reduced increasing mapping of \( T \) into \( U \). Since \( g \) is reduced, any \( t \in B \) is not mapped on any \( s \in E \). Further by the definition of \( L \) and \( S \), any \( x \in S \) with \( \tau(x) = \omega + 1 \) is not
maximal within $T$ (see Lemma 4.7 (ii)), while $s \in E$ is maximal within $U$. Hence we have never $f(x) \in E$ for $x \in S$, and there is no element in $T$ which is mapped by $g$ into $E$. Hence $g$ maps $T$ entirely into the subset $S \cup C$ of $U$, contradicting $S \cup C \cong T$. Hence $T \not\approx U$.

Thus we have ramified sets $T$ and $U$ which are not comparable with each other, completing the proof of Main Theorem B (i).

**APPENDIX. Case $\beta=1$.**

Here we shall consider the special case $\beta=1$. Of course every statements hitherto mentioned holds unaffectedly, except these about $S_0$ (see Chapter 4, § 1) where we assumed $\beta>1$. Besides, in the case $\beta=1$, Main Theorem A can be fairly sharpened, and it will be proved that not only $[{\mathcal S}]$ is well-ordered by $\prec$, but also

**Theorem C.** $[{\mathcal R}]$ is well-ordered by $\prec$.

In order to prove this, we shall define a sequence $\mathcal{M} = \{M_\lambda | \lambda \prec 1^\ast\}$ such that each $M_\lambda$ satisfies

1. D. 1) $\eta < \lambda$ implies $M_\eta \cong M_\lambda$, and
2. D. 2') $X \in \mathcal{R}$, and $X \not\approx M_\eta$ for any $\eta < \lambda$ imply $M_\lambda \prec X$.

It is all the same as Lemma 2.8 and its Corollary that, under the assumption that $\mathcal{M}$ is already constructed, for any $X \in \mathcal{R}$, there exists a $\lambda \prec 1^\ast$ such that $X \sim M_\lambda$ and hence $[{\mathcal R}]$ is well-ordered by $\prec$ in the type $1^\ast$.

**Definition 14.** $\Delta_0$ and $\Delta_1$ denote sets of ordinal numbers less than $1^\ast$ such that:

In the case $\lambda \in 1^\ast$, always $\lambda \in \Delta_0$.

Assume that for any $\eta < \lambda$, it is decided whether $\eta \in \Delta_0$ or $\eta \in \Delta_1$.

In the case $\lambda \in 1^\ast$, letting $\lambda = \alpha_0(\xi + \zeta) + n$ be the canonical decomposition of $\lambda$, $\xi \in \Delta_0$ or $\lambda \in \Delta_1$ according as $\alpha_0(\xi) \in \Delta_0$ or $\alpha_0(\xi) \in \Delta_1$, respectively.

In the case $\lambda \in 1^{\ast \ast}$, letting $\lambda = \alpha_0(\omega^\mu) + n$ be the canonical decomposition of $\lambda$, we distinguish three cases:

- if $\mu = 1$, then $\lambda \in \Delta_0$,
- if $\mu$ is an isolated number greater than 1, then $\lambda \in \Delta_1$, and
- if $\mu$ is a limit number with $\text{cf}(\mu) = 1$, then $\lambda \in \Delta_0$ or $\lambda \in \Delta_1$, respectively.

Then any number less than $1^\ast$ is allotted to $\Delta_0$ or $\Delta_1$.

The sequence $\mathcal{M}$ is defined according to the following Principle.

**Principle II.**

If $\lambda \in \Delta_0$, then $M_\lambda = N_\lambda$. 


For $\lambda \in \Delta_1$, we distinguish four cases:
In the case that $\lambda$ is an isolated number $\lambda + 1$, then $M_\lambda = N_{\lambda'}$.

In the case $\lambda = \alpha_\xi((\omega_1^{\omega_1} + n)$ where $\xi > 0$, then $M_\lambda = S_{\xi}^0 = N_{\alpha_\xi(\omega_1^{\omega_1} + \xi^\omega)}$.

Assume that $\lambda$ is a limit number in $\Delta_1$ and for any $\eta < \lambda$, $M_\eta$ is already defined.

In the case $X$ is an isolated number $\lambda'$, then $M_\lambda = N_{\lambda'}$.

In the case $X = a^{\omega_1}$ where $\Gamma > 0$, then $M_\lambda = S_\omega^\omega = N_{\lambda'}(\omega_1 + \omega)$.

Assume that $X$ is a limit number in $\Delta_1$ and for any $\eta < \lambda$, $M_\eta$ is already defined.

In the case $X \in \Gamma_1$ letting $X = a^\omega(\xi + \zeta)$ be the canonical decomposition of $\lambda$, $M_\lambda = M_{a^\omega(\xi + \zeta)} N_{\omega(\xi + \zeta)}$.

In the case $X \in \Gamma_2$ and, letting $\lambda = \alpha_\xi(\omega_1^{\omega_1} + n$ be the canonical decomposition of $\lambda$, $\mu$ is a limit number with $\text{cf}(\mu) = 1$, then $M_\lambda = W_{\omega^\omega} + M_\mu$.

REMARK. In $\mathfrak{N}$, all sets $N_\lambda$ in $\mathfrak{G}$ are disposed retaining the original order within $\mathfrak{R}$, and for any limit number $\lambda$ in $\Delta_1$, a set $M_\lambda$, which is utterly new and not contained in $\mathfrak{N}$, is inserted. Remark that for any limit number $\lambda$, numbers $\eta < \lambda$ such that $M_\eta$ is cofinal to $\lambda$, and hence if $M_\lambda = N_{\lambda'}$ (either $\lambda = \lambda'$ or $\lambda = \lambda' + 1$), then $M_\lambda$ satisfies D.1) and D.2). Within $\mathfrak{N}$, then $M_\lambda$ satisfies them within $\mathfrak{M}$, reserving the case where $\lambda$ is next to a limit number in $\Delta_1$ for the proof mentioned later.

If $\lambda \in \Gamma_1$ and $\lambda = \alpha_\xi(\xi + \zeta) + n$ is the canonical decomposition of $\lambda$, then put $\theta(\lambda) = \alpha_\xi(\xi) + n$. If $\lambda \in \Gamma_2$ and $\alpha_\xi(\omega_1^{\omega_1} + n$ is the canonical decomposition of $\lambda$, where $\mu$ is a limit number with $\text{cf}(\mu) = 1$, then put $\theta(\lambda) = \mu + n$. $\lambda \in \Gamma_1 \cup \Gamma_2$ implies $\theta(\lambda) \in \Gamma_1 \cup \Gamma_2$. If further, either it is the case $\lambda \in \Gamma_1$ or the case $\lambda \in \Gamma_2$, and, letting $\alpha_\xi(\omega_1^{\omega_1} + n$ be the canonical decomposition of $\theta(\lambda)$, $\mu_i$ is a limit number, then we can define $\theta(\lambda) = \theta(\theta(\lambda))$. In general, putting $\theta^{k+1}(\lambda) = \theta(\theta^k(\lambda))$, we shall finally arrive at a number $m < \omega$ such that $\theta^m(\lambda) \in \Gamma_2$, and letting $\alpha_m(\omega_1^{\omega_1} + n$ be the canonical decomposition of $\theta^m(\lambda)$, $\mu_m$ is an isolated number. Then whether $\theta^m(\lambda) \in \Delta_0$ or $\theta^m(\lambda) \in \Delta_1$ is decided by $\theta^m(\lambda)$ itself; the former in the case $\mu_m = 1$ and the latter in the case $\mu_m > 1$. Put $\theta(\lambda) = \theta^m(\lambda)$ for such a final $m$, where $m = 0$ and $\theta(\lambda) = \lambda$, if $\lambda \in \Gamma_2$ and, letting $\lambda = \alpha_\xi(\omega_1^{\omega_1} + n$ be the canonical decomposition of $\lambda$, $\mu$ itself is an isolated number.

For $\lambda \in \Gamma_1 \cup \Gamma_2$ we have $\lambda \in \Delta_0$ or $\lambda \in \Delta_1$ according as $\theta(\lambda) \in \Delta_0$ or $\theta(\lambda) \in \Delta_1$, respectively.

Now we shall briefly show that any $M_\lambda$ in $\mathfrak{G}$ satisfies D.1) and D.2').

First assume $\lambda \in \Gamma_1 \cup \Gamma_2$. It was proved in each case for $\lambda < \omega_1$, that if $N_{\theta(\lambda)}$ satisfies D.1) and D.2'), then $N_{\theta(\lambda)}$ also satisfies D.1) and D.2'). Hence if $N_{\theta(\lambda)}$ satisfies D.1) and D.2'), then $N_\lambda$ satisfies them. Especially if $\theta(\lambda) \in \Delta_0$ then $\theta(\lambda) \in \Gamma_2$ and letting $\alpha_\xi(\omega_1^{\omega_1} + n$ be the canonical decomposition of $\theta(\lambda)$, it falls to $\mu = 1$. If $n = 0$, then since $\nu$ is either isolated number or a limit number with $\nu < \omega_1$, and accordingly $\text{cf}(\nu) = 0$, $N_{\theta(\lambda)}$
satisfies D.1) and D.2') by Lemma 3.14.

It is already seen that if \( \lambda = \alpha_\varsigma (\omega^\mu_n) + n \) where \( n > 0 \) and \( \mu \) is an isolated number (then \( \lambda \in 1^\nu \)), then \( N_\lambda \) satisfies D.1) and D.2') in any case.

If \( \lambda \in \Delta_0 \cap (1^\nu \cup 1^\omega) \), then \( \theta(\lambda) \in \Delta_0 \cap 1^\omega \). Hence \( N_{\theta(\lambda)} \), as well as \( N_\lambda \), satisfies D.1) and D.2').

Since \( \lambda \in 1^\nu \) (and accordingly \( \lambda \in \Delta_0 \)) implies that \( N_\lambda \) satisfies D.1) and D.2'), for any \( \lambda \in \Delta_0 \), \( M_\lambda \) satisfies D.1) and D.2') under assumption of induction (remark that \( \lambda \ll \omega^\nu_1 \) implies \( \lambda \in \Delta_0 \)).

Similarly for any isolated number \( \lambda \), \( N_\lambda \) is seen to satisfy D.1) and D.2'). For \( \lambda \in \Delta_1 \), if \( fr(\lambda) \geq 2 \), then, putting \( \lambda = \lambda + 1 \), \( M_\lambda = N_\lambda \) and \( fr(\lambda) > 0 \). Hence under assumption of induction, it follows from results on \( N_\lambda \) that \( M_\lambda \) satisfies D.1) and D.2') (About the mention above, see the remark at the end of Chapter III).

Now it remains the case where \( \lambda \in \Delta_1 \) and \( fr(\lambda) = 0 \) or 1.

First consider the case \( \theta(\lambda) = \lambda \), i.e., \( \lambda \in 1^\omega \) and letting \( \lambda = \alpha_\varsigma (\omega^\mu_n) + n \) be the canonical decomposition of \( \lambda \), \( \mu = \xi + 1 \) where \( \xi > 0 \).

Case \( n = 0 \). \( M_\lambda = S_\lambda = N_{\alpha_\varsigma (\omega^\mu_0) + \sigma^\xi_0} \). Then by Lemma 4.4 (i), \( \xi \ll \lambda \) implies \( N_\xi \cong M_\lambda \). Since the numbers \( \xi \ll \lambda \) with \( M_\xi = N_\xi \) are cofinal to \( \lambda \), it follows from assumption D.1) on \( M_\xi \) with \( \xi \ll \lambda \) that \( M_\lambda \) satisfies D.1). Similarly it follows from Lemma 4.4 (ii) that \( M_\lambda \) satisfies D.2').

Case \( n = 1 \). Since \( M_{\lambda - 1} = S_\xi \) and \( M_\lambda = N_{\alpha_\varsigma (\omega^\mu_{11})} \), it follows from Lemma 4.5 that \( M_{\lambda - 1} \cong M_\lambda \), i.e., \( M_\lambda \) satisfies D.1).

Assume \( X \in \mathfrak{N}_1 \), and \( X \not\in M_{\lambda - 1} \). Since \( \bar{X} \not\in \mathfrak{N}_1 \), \( X \) satisfies (a) of Lemma 4.6. Hence \( X \) does not satisfies (b) of Lemma 4.6, or otherwise, \( X \cong S_\xi = M_{\lambda - 1} \). Hence there exists an \( a \in \text{Lay}_v(X) \) such that \( \text{Exp}_v(Lb(a)) \neq N_{\alpha_\varsigma (\omega^\mu_1) + \sigma^\xi_1} \). By D.3) on \( N_{\alpha_\varsigma (\omega^\mu_1) + \sigma^\xi_1} \), \( N_{\alpha_\varsigma (\omega^\mu_1) + \sigma^\xi_1} \cong \text{Exp}_v(Lb(a)) \). Since \( \text{Exp}_v(Lb(a)) \not\cong \text{Exp}_v(Lb(a)) \), \( M_\lambda = W_{\omega^\nu} + N_{\omega^\mu_1 + \sigma^\xi_1} \cong \text{Exp}_v(Lb(a)) \). Therefore \( \lambda \in \Delta_1 \) with \( \theta(\lambda) = \lambda \), we have proved that \( M_\lambda \) satisfies D.1) and D.2').

For \( \lambda \in \Delta_1 \) with \( \theta(\lambda) \ll \lambda \), it is inductively proved that \( M_\lambda \) satisfies D.1) and D.2') all the same as we considered for \( N_\xi \not\in \mathfrak{N}_1 \).

Hence any \( M_\lambda \) with \( \lambda \ll 1^\nu \) satisfies D.1) and D.2') and this fact implies Theorem C as we noticed below it.

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Bibliography
