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THE GALAXIES OF NONSTANDARD ENLARGEMENTS OF INFINITE AND TRANSFINITE GRAPHS: II

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Abstract — This report is an improvement of a prior report (Report 813). It sharpens the principal theorems (Theorems 4.2 and 11.2 of Report 813) while simplifying their proofs. There are also several minor changes involving clarifications and corrections of misprints.

The Abstract of the prior report remains the same as follows: The galaxies of the nonstandard enlargements of connected, conventionally infinite graphs as well as of connected transfinite graphs are defined, analyzed, and illustrated by some examples. It is then shown that any such enlargement either has exactly one galaxy, its principal one, or it has infinitely many galaxies. In the latter case, the galaxies are partially ordered by their “closeness” to the principal galaxy. If an enlargement has a galaxy different from its principal galaxy, then it has a two-way infinite sequence of galaxies that are totally ordered according to that “closeness” property. There may be many such totally ordered sequences.

Key Words: Nonstandard graphs, enlargements of graphs, transfinite graphs, galaxies in nonstandard graphs, graphical galaxies.

1 Introduction

In this work we extend the idea of galaxies in the hyperreal line \( ^*\mathbb{R} \) to nonstandard enlargements of conventionally infinite graphs and also of transfinite graphs. We stipulate henceforth that every graph considered herein is connected. Since graphs have structures much different from that of the real line \( \mathbb{R} \), the enlargements of graphs have properties not possessed by \( ^*\mathbb{R} \). The graphical galaxies of those enlargements comprise one aspect of that distinctive complexity. We will show that that any such enlargement has either one galaxy or infinitely many of them. Moreover, just as \( ^*\mathbb{R} \) contains images of the real numbers,
called the standard hyperreals, as well as hyperreals that are nonstandard, so too may the enlargement \( *G \) of a graph \( G \) contain "hypernodes," some of which are images of nodes of \( G \) and others of which are nonstandard hypernodes. In addition, there are "hyperbranches" incident to pairs of hypernodes; some of these hyperbranches are images of branches of \( G \), but there may be others that are not.

The galaxies graphically partition \( *G \) in the sense that every hypernode belongs to exactly one galaxy, and so too does every hyperbranch. There is a unique galaxy, which we refer to as the "principal galaxy," that contains the standard hypernodes and possibly nonstandard hypernodes as well. In the event that there are infinitely many galaxies, those galaxies are partially ordered according to how "close" they are to the principal galaxy. In fact, if there is a galaxy different from the principal galaxy, then there is a two-way infinite sequence of galaxies that are totally ordered according to their "closeness" to the principal galaxy. There may be many such totally ordered sequences, but a galaxy in one such sequence may not be comparable to a galaxy in another sequence according to that "closeness" property.

We speak of "conventionally infinite" graphs to distinguish them from transfinite graphs of ranks 1 or higher [5, Chapter 2], [6, Chapter 2]. Sections 2 through 4 herein are devoted to the enlargements of conventionally infinite graphs. The results for such enlargements extend to enlargements of transfinite graphs, but in more complicated ways. We show this in Sections 5 through 11, but only for transfinite graphs of rank 1. Results for transfinite graphs of still higher ranks are obtained similarly but in still more complicated ways and with additional complexity in the symbols. For the sake of brevity, the latter results are not included herein, but they may be found in [7] as well as in the archive www.arxiv.org in the category "mathematics" under "Zemanian."

Our notations and terminology follow the usual conventions of nonstandard analysis. \( \mathbb{N} = \{0, 1, 2, \ldots \} \) is the set of natural numbers, and \( \mathcal{N} \) is the set of hypernaturals. The standard hypernaturals (i.e., can be identified with) the natural numbers. Also, \( (a_n) \) or \( (a_n : n \in \mathbb{N}) \) or \( (a_0, a_1, a_2, \ldots) \) denotes a sequence whose elements can be members of any set, such as the set \( X \) of nodes in a conventional graph \( G = \{X, B\} \), where \( B \) is the set of branches, a branch being a two-element set of nodes. On the other hand, \( [a_n] \) denotes an
equivalence class of sequences, where two sequences \( (a_n) \) and \( (b_n) \) are taken to be equivalent if \( \{n: a_n = b_n\} \in \mathcal{F} \), where \( \mathcal{F} \) is any chosen and fixed free ultrafilter.\(^1\) \( \mathcal{F} \) will be so fixed throughout this work. The \( a_n \) appearing in \( [a_n] \) are understood to be the elements of any one of the sequences in the equivalence class. At times, we will use the more specific notation \( [(a_0, a_1, a_2, \ldots)] \). More generally, we adhere to the notations and terminology appearing in [3].

The ordinals are denoted in the usual way: \( \omega \) is the first transfinite ordinal. With \( \tau \in \mathbb{N} \), the product \( \omega \cdot \tau \) is the sum of \( \tau \) terms, each being \( \omega \).

2 The Nonstandard Enlargement of a Graph

Throughout Sections 2 to 4, we assume that the conventionally infinite graph \( G \) is connected and has infinitely many nodes. The definition of a nonstandard graph that we use herein is given in [6, Section 8.1], a special case of which is the “enlargement” of a graph \( G \).

Let us define the enlargement \( ^*G \) of \( G \) here as well in order to remove any need for referring to [6]. \( G = \{X, B\} \) is now taken to be a conventional connected graph having an infinite set \( X \) of nodes and therefore an infinite set of branches as well, each branch being a two-element set of nodes. Thus, there are no parallel branches (i.e., multiple branches). \( \mathcal{F} \) will denote a chosen and fixed free ultrafilter. \( x = [x_n] \) denotes an equivalence class of sequences of nodes as stated in the Introduction. Specifically, \( [x_n] \) and \( [x'_n] \) are in the same equivalence class \( x \) if \( \{n: x_n = x'_n\} \in \mathcal{F} \). \( x \) will be called a hypernode.\(^2\) Thus, the set of all sequences of nodes from \( G \) is partitioned into hypernodes. \( ^*X \) denotes the set of hypernodes. If all the elements of one of the representative sequences \( (x_n) \) for a hypernode \( x = [x_n] \) are the same node (i.e., \( x_n = x \) for all \( n \)), then \( x = [x] \) can be identified with \( x \); in this case, \( x \) is called a standard hypernode. Otherwise, \( x = [x_n] \) is called a nonstandard hypernode.

We turn now to the definition of a “hyperbranch.” Let \( x = [x_n] \) and \( y = [y_n] \) be two hypernodes. Also, let \( b = [(x_n, y_n)] \), where \( \{(x_n, y_n)\} \) is a sequence of pairs of nodes from \( G \) such that, for almost all \( n \), \( \{x_n, y_n\} \) is a branch in \( G \); that is, \( \{n: \{x_n, y_n\} \in B\} \in \mathcal{F} \). It can

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\(^1\) Also called a nonprincipal ultrafilter.

\(^2\) Our terminology should not be confused with that of a hypergraph—an entirely different concept [2].
be shown [6, page 155] that this definition is independent of the representative sequences 
\( (x_n) \) and \( (y_n) \) chosen of \( x \) and \( y \) respectively and that we truly have an equivalence relation 
for the set of all sequences of branches from \( G \). We let \( b = \{[x_n, y_n]\} \) denote such an 
equivalence class and will call it a hyperbranch; we write \( b = \{x, y\} \). Also, \(*B\) will denote the 
set of all hyperbranches. If \( x = [x_n] \) and \( y = [y_n] \) are standard hypernodes, then \( b = \{[x, y]\} \) 
is called a standard hyperbranch. Otherwise, \( b \) is called a nonstandard hyperbranch.

Finally, the pair \(*G = \{*X, *B\}\) denotes the enlargement of \( G \). It is a special case of a nonstandard graph, as defined in [6, page 155].

3 Distances and Galaxies in Enlarged Graphs

The length \(|P_{x,y}|\) of any path \( P_{x,y} \) connecting two nodes \( x \) and \( y \) in a graph \( G \) is the number of branches in \( P_{x,y} \). The distance \( d(x, y) \) between \( x \) and \( y \) is \( d(x, y) = \min\{|P_{x,y}|\} \), where the minimum is taken over all paths terminating at \( x \) and \( y \). In the trivial case, \( d(x, x) = 0 \). \( d \) satisfies the triangle inequality, namely, for any three nodes \( x, y, \) and \( z \) in \( G \), \( d(x, y) \leq d(x, z) + d(z, y) \). In fact, \( d \) satisfies the other metric axioms, too, and the set \( X \) of nodes in \( G \) along with \( d \) is a metric space.

The metric \( d \) can be extended into an internal function \( *d \) mapping the Cartesian product \(*X \times *X\) into the set of hypernaturals \(*N\) as follows: For any \( x = [x_n] \) and \( y = [y_n] \) in \(*X\), \( *d \) is defined by

\[
*d(x, y) = [d(x_n, y_n)] \in *N.
\]

By the transfer principle, we have, for any three hypernodes \( x, y, \) and \( z \),

\[
d(x, z) \leq d(x, y) + d((y, z)). \tag{1}
\]

From the point of view of an ultrapower construction, this means that

\[
\{u: d(x_n, x_n) \leq d(x_n, y_n) + d(y_n, z_n)\} \in \mathcal{F}.
\]

The other metric axioms, such as \( d(x, x) = 0 \), are obviously satisfied by \( *d \).

\(^3\)If \( G \) were a finite graph, then every hypernode (resp. hyperbranch) could be identified with a node (resp. branch) in \( G \), and \(*G\) would be identified with \( G \).
We define the “galaxies” of $\mathcal{G}$ as nonstandard subgraphs of $\mathcal{G}$ by first defining the “nodal galaxies.” Two hypernodes $x = [x_n]$ and $y = [y_n]$ are taken to be in the same nodal galaxy $\hat{G}$ of $\mathcal{G}$ if $d(x, y)$ is no greater than a standard hypernatural $k$, that is, if there exists a natural number $k \in \mathbb{N}$ such that $\{n : d(x_n, y_n) \leq k\} \in F$. In this case, we say that $x$ and $y$ are limitedly distant, and we write $d(x, y) \leq k$.

Let $N_{x,y}$ be the set of all standard hypernaturals that are no less than $d(x, y)$. $N_{x,y}$ is a well-ordered set, and therefore it has a minimum $k_{x,y}$. So, we can say that $x$ and $y$ are in the same nodal galaxy $\hat{G}$ if $d(x, y) = k_{x,y}$.

Lemma 3.1. The nodal galaxies partition the set $\mathcal{X}$ of all hypernodes in $\mathcal{G}$.

Proof. The property of two hypernodes being limitedly distant is a binary relation on $\mathcal{X}$ that is obviously reflexive and symmetric. Its transitivity follows directly from (1). Alternatively, we can use an ultrapower argument. Assume that $x = [x_n]$ and $y = [z_n]$ are in some nodal galaxy and that $y$ and $z = [z_n]$ are in some nodal galaxy; we want to show that those galaxies are the same. There exist two standard natural numbers $k_1$ and $k_2$ such that $N_{x,y} = \{n : d(x_n, y_n) \leq k_1\} \in F$ and $N_{y,z} = \{n : d(y_n, z_n) \leq k_2\} \in F$. Since $d(x_n, z_n) \leq d(x_n, y_n) + d(y_n, z_n)$,

$$\{n : d(x_n, z_n) \leq k_1 + k_2\} \geq N_{x,y} \cap N_{y,z} \in F.$$

So, the left-hand side is a set in $F$. Thus, $x$ and $z$ are limitedly distant, too, and $x, y$, and $z$ are all in the same nodal galaxy. □

We define a galaxy $\Gamma$ of $\mathcal{G}$ as a maximal nonstandard subgraph of $\mathcal{G}$ whose hypernodes are all in the same nodal galaxy $\hat{G}$; that is, the hyperbranches of $\Gamma$ corresponding to $\hat{G}$ are all those pairs $\{x, y\}$ such that $x, y \in \hat{G}$. We will say that a hypernode $x$ is in $\Gamma$ when $x \in \hat{G}$ and that a hyperbranch $\{x, y\}$ is in $\Gamma$ when $x, y \in \hat{G}$. It follows from Lemma 3.1 that the galaxies of $\mathcal{G}$ partition $\mathcal{G}$ in the sense of graphical partitioning (i.e., each hyperbranch is in one and only one galaxy).

The principal galaxy $\Gamma_0$ of $\mathcal{G}$ is that unique galaxy, each of whose hypernodes is limitedly distant from some standard hypernode (and therefore from all standard hypernodes). All the nodes in $G$ will be (i.e., can be identified with) standard hypernodes in $\Gamma_0$, but there may be nonstandard hypernodes in $\Gamma_0$ as well. The following examples illustrate this point.
Example 3.2. Consider the endless (i.e., two-way infinite) path:

\[ P = \langle \ldots, x_{-1}, b_{-1}, x_0, b_0, x_1, b_1 \ldots \rangle \]

with nodes \( x_k \) and branches \( b_k, k \in \mathbb{Z} \), \( \mathbb{Z} \) being the set of integers. The enlargement \( \ast P \) of \( P \) has hypernodes, each being represented by \([x_{k_n}]\) where \( \langle k_n \rangle \) is some sequence of integers. Each hyperbranch is represented by \([\{x_{k_n}, x_{k_n+1}\}]\). The nodal galaxies are infinitely many because they correspond bijectively with the galaxies of the enlargement \( \ast \mathbb{Z} \) of \( \mathbb{Z} \). Moreover, the principal galaxy \( \Gamma_0 \) of \( \ast P \) has only standard hypernodes and in fact is (i.e., can be identified with) \( P \) itself. Also, every galaxy is graphically isomorphic to \( \Gamma_0 \) and therefore to every other galaxy. \( \square \)

Example 3.3. Now, consider a one-ended path:

\[ T = \langle x_0, b_0, x_1, b_1, x_2, b_2, \ldots \rangle \]

Each hypernode in the enlargement \( \ast T \) of \( T \) is represented by \([x_{k_n}]\), where \( \langle k_n \rangle \) is some sequence of natural numbers. Thus, \( \ast T \) has a hypernode set \( \ast X \) that can be identified with the set \( \ast \mathbb{N} \) of hypernaturals. Hence, \( \ast T \) has an infinitely of galaxies, too. The principal galaxy \( \Gamma_0 \) of \( \ast T \) is the one-ended path \( T \). However, any hypernode \( x = [x_{k_n}] \) in a galaxy \( \Gamma \) different from \( \Gamma_0 \) will be such that, for every \( m \in \mathbb{N} \), \( \{n: k_n > m\} \in \mathcal{F} \). Such a hypernode is adjacent both to \([x_{k_n+1}]\) and to \([x_{k_n-1}]\), where we are free to replace \( x_{k_n-1} \) by, say, \( x_0 \) whenever \( k_n = 0 \). (The set \( \{n: k_n = 0\} \) will not be a member of \( \mathcal{F} \) when \( x = [x_{k_n}] \) is in \( \Gamma \).) Thus, \( x = [x_{k_n}] \in \Gamma \) has both a predecessor and a successor, which implies that \( \Gamma \) is graphically isomorphic to an endless path. In fact, all the galaxies other than \( \Gamma_0 \) are isomorphic to each other, being identifiable with an endless path. \( \square \)

Example 3.4. Consider next the grounded, one-way infinite ladder \( L \) of Figure 1. Now, for every \( k \in \mathbb{N} \), \( d(x_k, x_g) = d(x_k, x_{k+1}) = 1 \), and, for every \( k, l \in \mathbb{N} \) with \( |k - l| > 1 \), \( d(x_k, x_l) = 2 \). In this case, for every two hypernodes \( x \) and \( y \), \( d(x, y) \leq [2] = 2 \). Thus, every two hypernodes are limitedly distant from each other, which means that \( \ast L \) has only one galaxy, its principal galaxy \( \Gamma_0 \). Now, \( \Gamma_0 \) has both standard and nonstandard hypernodes. \( \square \)
Example 3.5. Furthermore, consider the graph \( G \) obtained from \( L \) by appending a one-ended path \( P \) starting at \( x_g \), but otherwise isolated from \( L \), as shown in Figure 2. In this case, we again have an infinity of galaxies by virtue of the isolation of \( P \) from \( L \). The principal galaxy \( \Gamma_0 \) has both standard and nonstandard hypernodes, its nonstandard hypernodes being due to \( L \). All the other galaxies are graphically isomorphic to an endless path (as in Example 3.3) and thus to each other, but not to \( G \) and not to \( \Gamma_0 \). □

A subgraph \( G_s \) of \( G \) with the property that there exists a natural number \( k \) such that \( d(x, y) \leq k \) for all pairs of nodes \( x, y \) in \( G_s \) will be called a finitely dispersed subgraph of \( G \). Example 3.5 suggests that the structures of the galaxies other than \( \Gamma_0 \) do not depend upon any finitely dispersed subgraph of \( G \). This is true in general because the nodes \( x_n \) in any representative \( \langle x_n \rangle \) of any hypernode in a galaxy other than \( \Gamma_0 \) must lie outside any finitely dispersed subgraph of \( G \) for almost all \( n \) whatever be the choice of that finitely dispersed subgraph.

For instance, consider

Example 3.6. Let \( D_2 \) be the 2-dimensional grid; that is, we can represent \( D_2 \) by having its nodes at the lattice points \((k, l)\) of the 2-dimensional plane, where \( k, l \in \mathbb{Z} \) and with its branches being \( \{(k, l), (k+1, l)\} \) and \( \{(k, l), (k, l+1)\} \). So, the hypernodes of \( *D_2 \) occur at \( *\mathbb{Z} \times *\mathbb{Z} \). Under this representation, the principal nodal galaxy of \( *D_2 \) will have its nodes at the lattice points of \( \mathbb{Z} \times \mathbb{Z} \).

Next, let \( G \) be a connected graph obtained from \( D_2 \) by deleting or appending finitely many branches to \( D_2 \). So, outside a finitely dispersed subgraph of \( G \), \( G \) is identical to \( D_2 \). Then the principal galaxy \( \Gamma_0 \) of \( *G \) is the same as (i.e., is graphically isomorphic to) \( G \), but every other galaxy is the same as \( D_2 \). □

In view of Examples 3.3 and 3.4, the following theorem is pertinent. As always, we assume that \( G \) is connected and has an infinite node set \( X \).

Theorem 3.7. Let \( G \) be locally finite. Then, \( *G \) has at least one hypernode not in its principal galaxy \( \Gamma_0 \) and thus at least one galaxy \( \Gamma_1 \) different from \( \Gamma_0 \).

Proof. Choose any \( x_0 \in X \). By connectedness and local finiteness, for each \( n \in \mathbb{N} \), the set \( X_n \), of nodes that are at a distance of \( n \) from \( x_0 \) is nonempty and finite. Also, \( \bigcup X_n = X \)
by the connectedness of $G$. By König's Lemma [4, page 40], there is a one-ended path $P$
starting at $x_0$. $P$ must pass through every $X_n$. Thus, there is a subsequence $(x_0, x_1, x_2, \ldots)$
of the sequence of nodes of $P$ such that $x_n \in X_n$; that is, $d(x_n, x_0) = n$ for every $n$. Set $x = [x_n]$. Then, $x$ must be in a galaxy $\Gamma_1$ that is different from the principal galaxy $\Gamma_0$. \Box

4 When $\hat{G}$ Has a Hypernode Not in Its Principal Galaxy

In this section, $G$ is connected and infinite but not necessarily locally finite. Let $\Gamma_a$ and $\Gamma_b$ be two galaxies that are different from the principal galaxy $\Gamma_0$ of $\hat{G}$. We shall say that $\Gamma_a$ is closer to $\Gamma_0$ than is $\Gamma_b$ and that $\Gamma_b$ is further away from $\Gamma_0$ than is $\Gamma_a$ if there are a
$y = [y_n]$ in $\Gamma_a$ and a $z = [z_n]$ in $\Gamma_b$ such that, for some $x = [x_n]$ in $\Gamma_0$ and for every $m \in \mathbb{N}$, we have

$$N_0(m) = \{n: d(z_n, x_n) - d(y_n, x_n) \geq m\} \in \mathcal{F}.$$  

Any set of galaxies for which every two of them, say, $\Gamma_a$ and $\Gamma_b$ satisfy this condition will be said to be totally ordered according to their closeness to $\Gamma_0$. With Lemma 3.1 in hand, the conditions for a total ordering (reflexivity, antisymmetry, transitivity, and connectedness) are readily shown. For instance, the proof of Theorem 4.3 below establishes transitivity.

Lemma 4.1. These definitions are independent of the representative sequences $(x_n)$, $(y_n)$, and $(z_n)$ chosen for $x$, $y$, and $z$.

Proof. Let $(x'_n)$, $(y'_n)$, and $(z'_n)$ be any other such representative sequences. Then,

$$d(z_n, x_n) \leq d(z_n, x'_n) + d(x'_n, x_n).$$

So,

$$d(z'_n, x'_n) \geq d(z_n, x_n) - d(z_n, x'_n) - d(x'_n, x_n) = d(z_n, x_n)$$

for all $n$ in some $N_1 \in \mathcal{F}$. Also,

$$d(y'_n, x'_n) \leq d(y'_n, y_n) + d(y_n, x_n) + d(x_n, x'_n) = d(y_n, x_n)$$

for all $n$ in some $N_2 \in \mathcal{F}$. Therefore,

$$d(z'_n, x'_n) - d(y'_n, x'_n) \geq d(z_n, x_n) - d(y_n, x_n)$$
for all \( n \in N_1 \cap N_2 \in \mathcal{F} \). So, for \( N_0(m) \) as defined above and for each \( m \) no matter how large,

\[
\{ n : d(z_n', x_n') - d(y_n', x_n') \geq m \} \supseteq N_0(m) \cap N_1 \cap N_2 \in \mathcal{F},
\]

which implies that the left-hand side is also a set in \( \mathcal{F} \). This proves Lemma 4.1. \( \square \)

We will say that a set \( A \) is a \textit{totally ordered, two-way infinite sequence} if there is a bijection from the set \( \mathbb{Z} \) of integers to the set \( A \) that preserves the total ordering of \( \mathbb{Z} \).

**Theorem 4.2.** If \( G \) has a hypernode \( \mathbf{v} = [v_n] \) that is not in its principal galaxy \( \Gamma_0 \), then there exists a two-way infinite sequence of galaxies totally ordered according to their closeness to \( \Gamma_0 \) and with \( \mathbf{v} \) being in one of those galaxies.

**Note.** There may be many such sequences, and a galaxy in one sequence and a galaxy in another sequence may not be comparable according to their closeness to \( \Gamma_0 \). Also, a somewhat different version of this theorem with a rather longer proof can be found in the archival website, www.arxiv.org, under Mathematics, Zemanian.

**Proof.** Let \( \mathbf{x} = [(x, x, x, \ldots)] \) be a standard hypernode in \( \Gamma_0 \). Also, let \( \mathbf{v} = [v_n] \) be the asserted hypernode not in \( \Gamma_0 \). Thus, for each \( m \in \mathbb{N} \),

\[
\{ n : d(x, v_n) > m \} \in \mathcal{F}.
\]

Between every two nodes of a connected, conventionally infinite graph there is a geodesic path whose length is equal to the distance between those nodes. For each \( n \in \mathbb{N} \), choose a geodesic path \( P \) in \( G \) terminating at \( x \) and \( v_n \). If the natural number \( d(x, v_n) \) is even (resp. odd), there is a unique node \( u_n \) in \( P \) such that \( d(x, u_n) = d(u_n, v_n) = d(x, v_n)/2 \) (resp. \( d(x, u_n) = d(u_n, v_n) - 1 = (d(x, v_n) - 1)/2 \)). It follows from this that, if there is a \( k \in \mathbb{N} \) such that \( \{ n : d(x, u_n) \leq k \} \in \mathcal{F} \), then there is a \( k' \in \mathbb{N} \) with \( \{ n : d(x, v_n) \leq k' \} \in \mathcal{F} \), in violation of (2). Consequently, for each \( m \in \mathbb{N} \), \( \{ n : d(x, u_n) > m \} \in \mathcal{F} \). This implies that \( \mathbf{u} = [u_n] \) is in a galaxy \( \Gamma_0 \) different from the principal galaxy \( \Gamma_0 \).

Furthermore, with \( d(x, v_n) \) being even (resp. odd) again and with \( u_n \) being chosen as before,

\[
d(x, v_n) - d(x, u_n) = d(x, v_n)/2
\]
\[
\frac{d(x, v_n) - d(x, u_n)}{(d(x, v_n) + 1)/2).
\]

Now, if there is a \( k \in \mathbb{N} \) such that

\[
\{n: d(x, v_n) - d(x, u_n) \leq k\} \in \mathcal{F},
\]

then there is a \( k' \in \mathbb{N} \) such that

\[
\{n: d(x, v_n) \leq k'\} \in \mathcal{F},
\]

again in violation of (2). Thus, for each \( m \in \mathbb{N} \),

\[
\{n: d(x, v_n) - d(x, u_n) > m\} \in \mathcal{F}.
\]

This implies that \( u = [u_n] \) and \( v = [v_n] \) are in different galaxies, \( \Gamma_a \) and \( \Gamma_b \) respectively, with \( \Gamma_a \) being closer to \( \Gamma_0 \) than is \( \Gamma_b \).

We can now repeat this argument with \( \Gamma_b \) replaced by \( \Gamma_a \) and with \( u = [u_n] \) playing the role that \( v = [v_n] \) played to find still another galaxy \( \Gamma'_a \) different from \( \Gamma_0 \) and closer to \( \Gamma_0 \) than is \( \Gamma_a \). Continual repetitions yield an infinite sequence of galaxies indexed by, say, the negative integers and totally ordered by their closeness to \( \Gamma_0 \).

The conclusion that there is an infinite sequence of galaxies progressively further away from \( \Gamma_0 \) than is \( \Gamma_b \) is easier to prove. With \( v \in \Gamma_b \) as before, we have that, for every \( m \in \mathbb{N} \),

\[
\{n: d(x, v_n) > m\} \in \mathcal{F}.
\]

Therefore, for each \( n \in \mathbb{N} \), we can choose \( w_n \) as an element of \( \langle v_n \rangle \) such that

\[
d(x, w_n) \geq d(x, v_n) + n. \tag{3}
\]

Hence, for each \( m \in \mathbb{N} \),

\[
\{n: d(x, w_n) > m\} \supseteq \{n: d(x, v_n) > m\}.
\]

Since the right-hand side is a member of \( \mathcal{F} \), so too is the left-hand side. Thus, \( w = [w_n] \) is in a galaxy different from \( \Gamma_0 \). Moreover, from (3) we have that, for each \( m \in \mathbb{N} \),

\[
\{n: d(x, w_n) - d(x, v_n) > m\}
\]

is a cofinite set and therefore is a member of \( \mathcal{F} \). Consequently, \( w \) is in a galaxy \( \Gamma_c \) that is further away from \( \Gamma_0 \) than is \( \Gamma_b \).
We can repeat the argument of the last paragraph with $\Gamma_c$ in place of $\Gamma_b$ to find still another galaxy $\Gamma'_c$ further away from $\Gamma_0$ than is $\Gamma_c$. Repetitions of this argument show that there is an infinite sequence of galaxies indexed by, say, the positive integers and totally ordered by their closeness to $\Gamma_0$.

The conjunction of the two infinite sequences along with $\Gamma_b$ yields the conclusion of the theorem. □

By virtue of Theorem 3.7, the conclusion of Theorem 4.2 holds whenever $G$ is locally finite.

In general, the hypothesis of Theorem 4.2 may or may not hold. Thus, $\mathcal{G}$ either has exactly one galaxy, its principal one $\Gamma_0$, or has infinitely many galaxies.

Instead of the idea of “totally ordered according to closeness to $\Gamma_0$,” we can define the idea of “partially ordered according to closeness to $\Gamma_0$” in much the same way. Just drop the connectedness axiom for a total ordering.

**Theorem 4.3.** Under the hypothesis of Theorem 4.2, the set of galaxies of $\mathcal{G}$ is partially ordered according to the closeness of the galaxies to the principal galaxy $\Gamma_0$.

**Proof.** Reflexivity and antisymmetry are obvious. Consider transitivity: Let $\Gamma_a$, $\Gamma_b$, and $\Gamma_c$ be galaxies different from $\Gamma_0$. (The case where $\Gamma_a = \Gamma_0$ can be argued similarly.) Assume that $\Gamma_a$ is closer to $\Gamma_0$ than is $\Gamma_b$ and that $\Gamma_b$ is closer to $\Gamma_0$ than is $\Gamma_c$. Thus, for any $x$ in $\Gamma_0$, $u$ in $\Gamma_a$, $v$ in $\Gamma_b$, and $w$ in $\Gamma_c$ and for every $m \in \mathbb{N}$, we have

$$N_{uw} = \{n : d(v_n, x_n) - d(u_n, x_n) \geq m\} \in \mathcal{F}$$

and

$$N_{vw} = \{n : d(w_n, x_n) - d(v_n, x_n) \geq m\} \in \mathcal{F}.$$ 

We also have

$$d(w_n, x_n) - d(u_n, x_n) = d(w_n, x_n) - d(v_n, x_n) + d(v_n, x_n) - d(u_n, x_n).$$

So,

$$N_{uw} = \{n : d(w_n, x_n) - d(u_n, x_n) \geq 2m\} \supseteq N_{uw} \cap N_{vw} \in \mathcal{F}.$$ 

Thus, $N_{uw} \in \mathcal{F}$. Since $m$ can be chosen arbitrarily, we can conclude that $\Gamma_a$ is closer to $\Gamma_0$ than is $\Gamma_c$. □
5 The Hyperordinals

In the following sections, we shall extend the results obtained so far to enlargements of transfinite graphs of rank 1, that is, to enlargements of I-graphs. For this purpose, we need to replace the set \( \mathbb{N} \) of hypernaturals by a set of "hyperordinals"; these are defined as follows. A hyperordinal \( \alpha \) is an equivalence class of sequences of ordinals where two such sequences \( (\alpha_n) \) and \( (\beta_n) \) are taken to be equivalent if \( \{ n : \alpha_n = \beta_n \} \in \mathcal{F} \). We denote \( \alpha \) also by \([\alpha_n]\) where again the \( \alpha_n \) are the elements of one (any one) of the sequences in the equivalent class. Any set of hyperordinals is totally ordered by the inequality relation. That is, given any hyperordinals \( \alpha = [\alpha_n] \) and \( \beta = [\beta_n] \), exactly one of the sets:

\[
\{ n : \alpha_n < \beta_n \}, \quad \{ n : \alpha_n = \beta_n \}, \quad \{ n : \alpha_n > \beta_n \}
\]

will be in \( \mathcal{F} \). So, exactly one of the expressions:

\[
\alpha < \beta, \quad \alpha = \beta, \quad \alpha > \beta
\]

holds.

6 Walks in 1-Graphs

1-graphs arise when conventionally infinite graphs are connected at their infinite extremities through 1-nodes, the latter being a generalization of the idea of a node. Such 1-nodes and the resulting 1-graphs are defined in [5, Section 2.1] and also in [6, Section 2.3]. Let us restate the needed definitions concisely.

We will be dealing with two kinds of nodes and two kinds of graphs. A conventionally infinite graph \( G^0 \) will now be called a 0-graph and the nodes in \( G^0 \) will be called 0-nodes in order to distinguish these ideas from those pertaining to transfinite graphs of rank 1. Similarly, what we called a "hypernode" previously will henceforth be called a 0-hypernode, and what we called a "galaxy" in the enlargement of a 0-graph will now be called a 0-galaxy.

An infinite extremity of a 0-graph \( G^0 \) is defined as an equivalence class of one-ended paths in \( G^0 \), where two such paths are considered to be equivalent if they are eventually identical. Such an equivalence class is called a 0-tip of \( G^0 \). \( G^0 \) may have one or more 0-tips.
(or possibly none at all). To obtain the "1-nodes," the set of 0-tips is partitioned in some fashion into subsets, and to each subset a single 0-node may (or may not) be added under the proviso that, if a 0-node is added to one subset, it is not added to any other subset. Then, each subset (possibly augmented with a 0-node) is called a 1-node. With $X^1$ denoting the set of 1-nodes and $X^0$ the set of 0-nodes of $G^0$, the 1-graph $G^1$ is defined as the triplet:

$$G^1 = \{X^0, B, X^1\},$$

and $G^0 = \{X^0, B\}$ is now called the 0-graph of $G^1$. Furthermore, a path in $G^0$ is now called a 0-path, and connectedness in $G^0$ is now called 0-connectedness. We will consistently append the superscript 0 to the symbols and the prefix 0- to the terminology for concepts from Sections 2 through 4 regarding 0-graphs.

In order to define the "1-galaxies," we need the idea of distances in a 1-graph $G^1$. But now, we must make a significant choice. The distances between two nodes (0-nodes or 1-nodes) can be defined as the minimum length of all paths—or, alternatively, of all walks—connecting the two nodes. It turns out that a path need not exist between two nodes in a 1-graph $G^1$, but a walk always will exist between them. To ensure the existence of at least one path between every two nodes, additional conditions must be imposed on $G^1$ (see [5, Conditions 3.2-1 and 3.5-1] or [6, Condition 3.1-2]), and this leads to a more restrictive and yet more complicated theory involving distances. Such can be done, but it is more general and simpler to use walk-based distance ideas. This we now do.

A nontrivial 0-walk $W^0$ in a 0-graph is the conventional concept. It is a (finite or one-way infinite or two-way infinite) alternating sequence:

$$W^0 = \{\ldots, z^0_{-1}, b_{-1}, z^0_0, b_0, z^0_1, b_1, \ldots\}$$

of 0-nodes $z^0_m$ and branches $b_m$, where each branch $b_m$ is incident to the two 0-nodes $z^0_m$ and $z^0_{m+1}$ adjacent to it in the sequence. If the sequence terminates at either side, it is required to terminate at a 0-node. The 0-walk is called two-ended or finite if it terminates on both sides, one-ended if it terminates on just one side, and endless if it terminates on neither side.

A trivial 0-walk is a singleton set whose sole element is a 0-node.
A one-ended 0-walk $W^0$ will be called *extended* if its 0-nodes are eventually distinct, that is, if it is eventually identical to a one-ended path. We say that $W^0$ *traverses* a 0-tip if it is extended and eventually identical to a representative of that 0-tip. Finally, $W^0$ is said to *reach* a 1-node $x^1$ if $W^0$ traverses a 0-tip contained in $x^1$. In the same way, an endless 0-walk can reach two 1-nodes (or possibly reach the same 1-node) by traversing two 0-tips, one toward the left and the other toward the right. When this is so, we say that the endless 0-walk is *extended*. On the other hand, if a 0-walk terminates at a 0-node contained in a 1-node, we again say that the 0-walk reaches both of those nodes and does so through a branch incident to that 0-node.

Every two-ended 0-walk contains a 0-path that terminates at the two 0-nodes at which the 0-walk terminates, so there is no need to employ 0-walks when defining distances in a 0-graph. On the other hand, such a need arises for 1-graphs. To meet this need, we first define a 0-secrion $S^0$ in a 1-graph $G^1$ as a subgraph $S^0$ of the 0-graph $G^0$ of $G^1$ induced by a maximal set of branches that are pairwise 0-connected in $G^0$. A 1-node $x^1$ is said to be *incident to* $S^0$ if either it contains a 0-node incident to a branch of $S^0$ or it contains a 0-tip having a representative one-ended path lying entirely within $S^0$. In this case, we also say that that 0-tip belongs to $S^0$. Given two 1-nodes $x^1$ and $y^1$ incident to $S^0$, there will be a 0-walk $W^0$ in $S^0$ that reaches each of $x^1$ and $y^1$ through a 0-tip belonging to $S^0$ or through a branch in $S^0$. Moreover, there may also be a 0-walk $W^0$ in $S^0$ that reaches the same 1-node at both extremities of $W^0$. To be more specific, let us state

**Lemma 6.1.** Let $S^0$ be a 0-section in $G^1$, and let $x^1$ and $y^1$ be two 1-nodes incident to $S^0$. Then, there exists a 0-walk in $S^0$ that reaches $x^1$ and $y^1$.

**Proof.** That $x^1$ is incident to $S^0$ means that there is a 0-path $P^0_x$ in $S^0$ that either reaches $x^1$ through a 0-tip of $x^1$ or reaches $x^1$ through a branch. Similarly, there is such a 0-path $P^0_y$ reaching $y^1$. Let $u^0$ be a node of $P^0_x$, and let $v^0$ be a node of $P^0_y$. Since $S^0$ is 0-connected, there is a 0-path $P^0_{uv}$ in $S^0$ terminating at $u^0$ and $v^0$ (possibly a trivial 0-path if $u^0 = v^0$). Then, $P^0_x \cup P^0_{uv} \cup P^0_y$ as a 0-walk in $S^0$ as asserted. $\square$

---

4 For examples of when a 0-walk is needed because a 0-path won’t do, see Figures 3.1 and 3.2 of [5] and Figures 4.1, 5.1, 5.2, and 5.3 of [6].
A nontrivial, two-ended 1-walk \( W^1 \) is a finite sequence:

\[
W^1 = (x_0, W^0_0, x_1, W^0_1, \ldots, x_{m-1}, W^0_{m-1}, x_m)
\]  

(5)

with \( m \geq 1 \) that satisfies the following conditions.

1. \( x_1, \ldots, x_{m-1} \) are 1-nodes, while \( x_0 \) and \( x_m \) may be either 0-nodes or 1-nodes.

2. For each \( k = 0, \ldots, m - 1 \), \( W^0_k \) is a nontrivial 0-walk that reaches the two nodes adjacent to it in the sequence.

3. For each \( k = 1, \ldots, m - 1 \), at least one of \( W^0_{k-1} \) and \( W^0_k \) reaches \( x_k \) through a 0-tip, not through a branch. Also, if \( m = 1 \), \( W^0_0 \) reaches at least one of \( x_0 \) and \( x_1 \) through a 0-tip.

A one-ended 1-walk is a sequence like (5) except that it extends infinitely to the right. An endless 1-walk extends infinitely on both sides. A trivial 1-walk is a singleton set whose sole element is either a 0-node or a 1-node.

We now define a more general kind of connectedness (called "1-wconnectedness") to distinguish it from path-based 1-connectedness). Two branches (resp. two nodes—either 0-nodes or 1-nodes) will be said to be 1-wconnected if there exists a 0-walk or 1-walk that terminates at a 0-node of each branch (resp. that terminates at those two nodes). If a terminal node of a walk is the same as, or contains, or is contained in the terminal node of another walk, the two walks taken together form another walk. We call this the conjunction of the two walks. It follows that 1-wconnectedness is a transitive binary relation for the branch set \( B \) of the 1-graph \( G^1 \) and is in fact an equivalence relation. If every two branches of \( G^1 \) are 1-wconnected, we will say that \( G^1 \) is 1-wconnected.

7 Walk-Based Distances in a 1-Graph

The length \( |W^0| \) of a 0-walk \( W^0 \) is defined as follows: If \( W^0 \) is two-ended, \( |W^0| \) is the number \( n_0 \) of branch traversals in it; that is, each branch is counted as many times as it appears in \( W^0 \). If \( W^0 \) is one-ended and extended, we set \( |W^0| = \omega \), the first transfinite ordinal. If \( W^0 \) is endless and extended in both directions, we set \( |W^0| = \omega \cdot 2 \).
As for a nontrivial two-ended 1-walk $W^1$, its length $|W^1|$ is taken to be

$$|W^1| = \sum_{k=0}^{m} |W^0_k|$$

where the sum is over the finitely many 0-walks $W^0_k$ in (5). Thus,

$$|W^1| = \omega \cdot \tau_1 + \tau_0$$

(6)

where $\tau_1$ is the number of traversals of 0-tips performed by $W^1$ and $\tau_0$ is the number of traversals of branches in all the two-ended (i.e., finite) 0-walks appearing as terms in (5). We take $\sum_{k=0}^{m} |W^0_k|$ to be the natural sum of ordinals; this yields a normal expansion of an ordinal [1, pages 354-355]. $\tau_1$ is not 0 because $W^1$ is a nontrivial, two-sided 1-walk. However, $\tau_0$ may be 0, this occurring when every $W^0_k$ in (5) is one-ended or endless.

A 0-node is called \textit{maximal} if it is not contained in a 1-node, and \textit{non maximal} otherwise. A distance measured from a nonmaximal 0-node is the same as that measured from the 1-node containing it. Given two nodes $x$ and $y$ (of ranks 0 or 1), we define the \textit{wdistance}$^5$

$$d(x, y) = \min |W_{x,y}|$$

(7)

where the minimum is taken over all two-ended walks (0-walks or 1-walks) terminating at $x$ and $y$. That minimum exists because any set of ordinals is a well-ordered set. In view of (6), $d(x, y) < \omega^2$. If $x = y$, we set $d(x, x) = 0$.

Clearly, if $x \neq y$, $d(x, y) > 0$ and $d(x, y) = d(y, x)$. Furthermore, the conjunction of two two-ended walks is again a two-ended walk, whose length is the natural sum of the ordinal lengths of the two walks. So, by taking minimums appropriately, we obtain the triangle inequality:

$$d(x, z) \leq d(x, y) + d(y, z)$$

(8)

where again the natural sum of ordinals is understood. Altogether then, we have

\textbf{Lemma 7.1.} The ordinal-valued \textit{wdistances} between the \textit{maximal} nodes of a 1-graph satisfy the metric axioms.

\footnote{We write “\textit{wdistance}” to distinguish this walk-based idea from a distance based on paths.}
Enlargements of I-Graphs and Hyperdistances in Them

In [6, pages 163-164], a nonstandard I-node was defined as an equivalence class of sequences of sets of tips shorted together, with the tips taken from sequences of possibly differing I-graphs. But, since each set of tips shorted together is a 1-node, that definition of a nonstandard I-node can also be stated as an equivalence class of sequences of 1-nodes. Specializing to the case where all the I-graphs are the same, we have the following definition of a nonstandard I-node, which we now call a "1-hypernode."

Consider a given I-graph along with a chosen free ultrafilter \( F \). Two sequences \( (x^n) \) and \( (y^n) \) of I-nodes in \( G^I \) are taken to be equivalent if \( \{ n : x^n = y^n \} \in F \). It is easy to show that this is truly an equivalence relation. Then, \( x^I = [x^n] \) denotes one such equivalence class, where the \( x^n \) are the elements of any one of the sequences in that class. \( x^I \) will be called a 1-hypernode.

The enlargement of the I-graph \( G^I = \{ X^0, B, X^1 \} \) is the nonstandard I-graph

\[ \ast G^I = \{ \ast X^0, \ast B, \ast X^1 \} \]

where \( \ast X^0 \) and \( \ast B \) are respectively the set of 0-hypernodes and branches in the enlargement of the 0-graph \( G^0 = \{ X^0, B \} \) of \( G^I \) and \( \ast X^1 \) is the set of 1-hypernodes defined above, that is, the set of all equivalence classes of sequences of 1-nodes taken from \( X^1 \).

We define the hyperdistance \( d \) between any two hypernodes \( x \) and \( y \) of \( \ast G^I \) (of ranks 0 and/or 1) to be the internal function

\[ d(x, y) = [d(x_n, y_n)]. \] (9)

Since distances in \( G^I \) are less than \( \omega^2 \), \( d(x, y) \) is a hyperordinal less than \( \omega^2 \). We say that a 0-hypernode \( x^0 = [x^n] \) is maximal if the set of \( n \) for which \( x_n \) is not contained in a 1-node is a member of \( F \). All the 1-nodes in this work are perforce maximal because there are no nodes of higher rank. \( d \), when restricted to the maximal hypernodes, also satisfies the metric axioms, in particular, the triangle inequality:

\[ d(x, z) \leq d(x, y) + d(y, z) \] (10)

But, now \( d \) is hyperordinal-valued.
9 The Galaxies of $\mathcal{G}^1$

The $0$-galaxies of $\mathcal{G}^1$ are defined just as they are for the enlargement $\mathcal{G}^0$ of a 0-graph; see Section 3. However, we henceforth write "0-galaxy" in place of "galaxy" and "0-limitedly distant" in place of "limitedly distant."

As was mentioned above, each 0-section of $\mathcal{G}^1$ is the subgraph of the 0-graph $G^0\{X^0, B\}$ of $\mathcal{G}^1$ induced by a maximal set of branches that are 0-connected. A 0-section is a 0-graph by itself. So, within the enlargement $\mathcal{G}^1$, each 0-section $S^0$ enlarges into $\mathcal{S}^0$ as defined in Section 2. Within each enlarged 0-section there may be one or more 0-galaxies. As a special case, a particular 0-section may have only finitely many 0-nodes, and so its enlargement is itself—all its 0-hypernodes are standard. On the other hand, there may be infinitely many 0-galaxies in some enlarged 0-section. Moreover, the enlarged 0-sections do not, in general, comprise all of the enlarged 0-graph $\mathcal{G}^0 = \{ \mathcal{X}^0, \mathcal{B} \}$ of $\mathcal{G}^1$. Indeed, there can be a 0-hypernode $x^0 = [x_n]$ where each $x_n$ resides in a different 0-section; in this case $x^0$ will reside in a 0-galaxy that is not in any enlargement of a 0-section.

Something more can happen with regard to the 0-galaxies in $\mathcal{G}^1$. 0-galaxies can now contain 1-hypernodes. For example, this occurs when a 1-node $z^1$ is incident to a 0-section $S^0$ through a branch. Then, the standard 1-hypernode $x^1$ corresponding to $z^1$ is 0-limitedly distant from the standard 0-hypernodes in $\mathcal{S}^0$. So, there is a 0-galaxy containing not only $\mathcal{S}^0$ but $x^1$ as well. See Example 9.3 below in this regard. In general, the nodal 0-galaxies partition the set $\mathcal{X}^0 \cup \mathcal{X}^1$ of all the hypernodes in $\mathcal{G}^1$. As we shall see in Examples 9.1 and 9.2 below, there may be a singleton 0-galaxy containing a 1-hypernode only.

Let us now turn to the "1-galaxies" of $\mathcal{G}^1$. Two hypernodes $x = [x_n]$ and $y = [y_n]$ (of ranks 0 and/or 1) in $\mathcal{G}^1$ will be said to be in the same nodal 1-galaxy $l^1$ if there exists a natural number $k \in \mathbb{N}$ depending on the choices of $x$ and $y$ such that \{n : d(x_n, y_n) \leq \omega \cdot k\} \in \mathcal{F}$. In this case, we say that $x$ and $y$ are $1$-limitedly distant, and we write \(d(x, y) \leq [\omega \cdot k]\) where \([\omega \cdot k]\) denotes the standard hyperordinal corresponding to \(\omega \cdot k\). This defines an equivalence relation on the set $\mathcal{X}^0 \cup \mathcal{X}^1$ of all the hypernodes in $\mathcal{G}^1$. Indeed, reflexivity and symmetry are obvious. For transitivity, assume that $x$ and $y$ are 1-limitedly distant and that $y$ and $z$ are 1-limitedly distant, too. Then, there are natural numbers $k_1$ and $k_2$
such that

\[ N_{xy} = \{ n : d(x_n, y_n) \leq \omega \cdot k_1 \} \in \mathcal{F} \]

and

\[ N_{yz} = \{ n : d(y_n, z_n) \leq \omega \cdot k_2 \} \in \mathcal{F} \]

By the triangle inequality (8),

\[ N_{xz} = \{ n : d(x_n, z_n) \leq \omega \cdot (k_1 + k_2) \} \supseteq N_{xy} \cap N_{yz} \in \mathcal{F} \]

So, \( N_{xz} \in \mathcal{F} \) and therefore \( x \) and \( z \) are 1-limitedly distant. We can conclude that the set \( *X^0 \cup *X^1 \) of all hypernodes in \( *G^1 \) is partitioned into nodal 1-galaxies by this equivalence relation.

Corresponding to each nodal 1-galaxy \( \Gamma^1 \), we define a 1-galaxy \( \Gamma^1 \) as a nonstandard subgraph of \( *G^1 \) consisting of all the hypernodes in \( \Gamma^1 \) along with all the hyperbranches both of whose 0-hypernodes are in \( \Gamma^1 \).

No hyperbranch can have its two incident 0-hypernodes in two different 0-galaxies or two different 1-galaxies because the distance between their 0-hypernodes is 1. Thus, the hyperbranch set \( *B \) is also partitioned by the 0-galaxies and more coarsely by the 1-galaxies.

The principal 1-galaxy \( \Gamma^1_0 \) of \( *G^1 \) is the 1-galaxy whose hypernodes are 1-limitedly distant from a standard hypernode in \( *G^1 \) (i.e., from a node of \( G^1 \)).

Note that the enlargement \( *S^0 \) of each 0-section \( S^0 \) of \( G^1 \) has its own principal 0-galaxy \( \Gamma^0_0(S^0) \). Moreover, every \( *S^0 \) lies within the principal 1-galaxy \( \Gamma^1_0 \). Indeed, any standard hypernode \( x \) by which \( \Gamma^1_0 \) may be defined and any standard 0-hypernode \( y^0 \) by which \( \Gamma^0_0(S^0) \) may be defined are 1-limitedly distant. Also, the hyperdistance \( d(y^0, z^0) \) between any two 0-hypernodes \( y^0 \) and \( z^0 \) of \( *S^0 \) is no larger than a hypernatural \( k \). So, by the triangle inequality (10), every 0-hypernode of \( *S^0 \) is 1-limitedly distant from \( x \). Whence our assertion.

Example 9.1. Consider an endless 1-path \( P^1 \) having an endless 0-path between every consecutive pair of 1-nodes in \( P^1 \). The 0-sections of \( P^1 \) are those endless 0-paths, and each of their enlargements have an infinity of 0-galaxies in \( *P^1 \). However, there are other 0-galaxies in \( *P^1 \), infinitely many of them. Indeed, consider a 0-hypernode \( x^0 = [x_n^0] \), where
each 0-node $x_n^0$ lies in a different 0-section of $P^1$; $x^0$ will lie in a 0-galaxy $\Gamma^0$ different from all the 0-galaxies in any enlargement of a 0-section of $P^1$. The 0-hypernodes of $\Gamma^0$ will be the 0-hypernodes that are 0-limitedly distant from $x^0$. Furthermore, there are still other 0-galaxies now. Each 1-hypernode $x^1 = [x_n^1]$ is the sole member of a 0-galaxy. In fact, the nodal 0-galaxies partition the set of all the 0-hypernodes and 1-hypernodes.

On the other hand, the principal 1-galaxy of $*P^1$ consists of all the standard 1-hypernodes corresponding to the 1-nodes of $P^1$ along with the enlargements of the 0-sections of $P^1$. Also, there will be infinitely many 1-galaxies, each of which contains infinitely many 0-galaxies along with 1-hypernodes. In this particular case, each of the 1-galaxies is graphically isomorphic to the principal 1-galaxy, but this is not true in general.

**Example 9.2.** An example of a nonstandard 1-graph $*G^1$ having exactly one 1-galaxy (its principal one) and infinitely many 0-galaxies is provided by the enlargement of the 1-graph $G^1$ obtained from the 0-graph of Figure 1 by replacing each branch by an endless 0-path, thereby converting each 0-node into a 1-node. Again each endless path of that 1-graph $G^1$ is a 0-section, and its enlargement is like that of Example 3.2. There are infinitely many such 0-galaxies in each enlargement of a 0-section. Also, there are infinitely many 0-galaxies, each consisting of a single 1-hypernode. With regard to the 1-galaxies, the enlargement $*G^1$ of $G^1$ mimics that of Example 3.4, except that now the rank 0 is replaced by the rank 1. The hyperdistance between every two 1-hypernodes (resp. 0-hypernodes) is no larger than $\omega \cdot 4$ (resp. $\omega \cdot 6$). Hence, $*G^1$ has only one 1-galaxy, its principal one.

**Example 9.3.** Here is an example where each of the 1-hypernodes is not isolated as the sole member within a 0-galaxy. Replace each of the horizontal branches in Figure 1 by an endless 0-path, but do not alter the branches incident to $x_g$. Now, the nodes $x_k$ ($k = 0, 1, 2, \ldots$) become 1-nodes $x_k^1$, each containing a 0-node of the branch incident to $x_k^1$ and $x_g$. Each 1-hypernode is 0-limitedly distant from the standard 0-hypernode $x_g$ and thus is not so isolated. The 1-hypernodes (whether standard or nonstandard) along with the standard 0-hypernode for $x_g$ and the (standard or nonstandard) hyperbranches incident to $x_g$ all comprise a single 0-galaxy. Moreover, there will be other 0-galaxies obtained through equivalence classes of sequences of these nodes and branches. In fact, each of the endless
paths that replace the horizontal branches yield infinitely many 0-galaxies. Again, the nodal 0-galaxies partition the set of all the hypernodes in \( G^1 \).

On the other hand, there is again only one 1-galaxy for \( G^1 \).

**Example 9.4.** The distances in the three preceding examples can be fully defined by paths. So, let us now present an example where walks are needed. The 1-graph \( G^1 \) of Figure 3 illustrates one such case. It consists of an infinite sequence of 0-subgraphs, each of which is an infinite series connections of four-branch subgraphs, each in a diamond configuration, as shown. To save words, we shall refer to such an infinite series connection as a "chain." The chain starting at the 0-node \( x_k^0 \) will be denoted by \( C_k \) \( (k = 0, 1, 2, \ldots) \). Each \( C_k \) is a 0-graph; it does not contain any 1-node. Each \( C_k \) has uncountably many 0-tips. One 0-tip has a representative 0-path starting at \( x_k^0 \), proceeding along the left-hand sides of the diamond configurations, and reaching the 1-node \( x_k^1 \). Another 0-tip has a representative 0-path that proceeds along the right-hand sides and reaches the 1-node \( x_{k+1}^1 \). Still other 0-tips of \( C_k \) (uncountably many of them) have representatives that pass back and forth between the two sides infinitely often to reach singleton 1-nodes; these are not shown in that figure. The chain \( C_k \) is connected to \( C_{k+1} \) through the 1-node \( x_{k+1}^1 \), as shown. Note that there is no path connecting, say, \( x_k^0 \) to \( x_{k+1}^0 \) when \( m - k \geq 2 \), but there is such a walk.

Each \( C_k \) is a 0-section, and its enlargement \( *C_k \) has infinitely many 0-galaxies. Also, the 1-nodes \( x_k^1 \) together produce infinitely many 0-galaxies, each being a single 1-hypernode. As before, the nodal 0-galaxies comprise a partition of \( *X^0 \cup *X^1 \).

On the other hand, the enlargement \( *G^1 \) of the 1-graph \( G^1 \) of Figure 3 has infinitely many 1-galaxies. Its principal one is a copy of \( G^1 \). Each of the other 1-galaxies is also a copy of \( G^1 \) except that it extends infinitely in both directions—infinitely to the left and infinitely to the right. Here, too, the nodal 1-galaxies comprise a partitioning of \( *X^0 \cup *X^1 \), but a coarser one.

These examples indicate that the enlargements of 1-graphs can have rather complicated structures.
10 Locally 1-Finite 1-Graphs and a Property of Their Enlargements

In general, \( G^1 \) has 1-galaxies other than its principal 1-galaxy. One circumstance where this occurs is when \( G^1 \) is locally finite in certain way, which we will explicate below.

We need some more definitions. Two 1-nodes of \( G^1 \) are said to be 1-wadjacent if they are incident to the same 0-section. A 1-node will be called a boundary 1-node if it is incident to two or more 0-sections. \( G^1 \) will be called locally 1-finite if each of its 0-sections has only finitely many incident boundary 1-nodes.\(^6\)

**Lemma 10.1.** Let \( x^1 \) be a boundary 1-node. Then, any 1-walk that passes through \( x^1 \) from any 0-section \( S^0_1 \) incident to \( x^1 \) to any other 0-section \( S^0_2 \) incident to \( x^1 \) must have a length no less than \( \omega \).

**Proof.** The only way such a walk can have a length less than \( \omega \) (i.e., a length equal to a natural number) is if it avoids traversing a 0-tip in \( x^1 \). But, this means that it passes through two branches incident to a 0-node in \( x^1 \). But, that in turn means that \( S^0_1 \) and \( S^0_2 \) cannot be different 0-sections. \( \Box \)

Remember that \( G^1 \) is called 1-wconnected if, for every two nodes of \( G^1 \), there is a 0-walk or 1-walk that reaches those two nodes.

**Lemma 10.2.** Any two 1-nodes \( x^1 \) and \( y^1 \) that are 1-wconnected but are not 1-wadjacent must satisfy \( d(x^1, y^1) \geq \omega \).

**Proof.** Any walk 1-wconnecting \( x^1 \) and \( y^1 \) must pass through at least one boundary 1-node different from \( x^1 \) and \( y^1 \) while passing from one 0-section to another 0-section. Therefore, that walk must be a 1-walk. By Lemma 10.1, its length is no less than \( \omega \). Since this is true for every such walk, our conclusion follows. \( \Box \)

The next theorem mimics Theorem 3.7 but at the rank 1.

**Theorem 10.3.** Let \( G^1 \) be locally 1-finite and 1-wconnected and have infinitely many boundary 1-nodes. Then, given any 1-node \( x^1_0 \) of \( G^1 \), there is a one-ended 1-walk \( W^1 \) starting

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\( ^6 \) Note that a 0-section in a locally 1-finite 1-graph may have infinitely many incident 1-nodes that are not boundary 1-nodes. Also, this definition of locally 1-finiteness does not prohibit 0-nodes of infinite degree.
at $x_0^1$:

$$W^1 = \langle x_0^1, W_0^0, x_1^1, W_1^0, \ldots, x_m^1, W_m^0, \ldots \rangle$$

such that there is a subsequence of $1$-nodes $x_{m_k}^1$, $k = 1, 2, 3, \ldots$, satisfying $d(x_0^1, x_{m_k}^1) \geq \omega \cdot k$.

**Proof.** $x_0^1$ need not be a boundary $1$-node, but it will be $1$-wadjacent to only finitely many boundary $1$-nodes because of local $1$-finiteness and $1$-wconnectedness. Let $X_0$ be the nonempty finite set of those boundary $1$-nodes. For the same reasons, there is a nonempty finite set $X_1$ of boundary $1$-nodes, each being $1$-wadjacent to some $1$-node in $X_0$ but not $1$-wadjacent to $x_0^1$. By Lemma 10.2, for each $x^1 \in X_1$, we have $d(x_0^1, x^1) \geq \omega$. In general, for each $k \in \mathbb{N}$, $k \geq 2$, there is a nonempty finite set $X_k$ of boundary $1$-nodes, each being $1$-wadjacent to some $1$-node in $X_{k-1}$ but not $1$-wadjacent to any of the $1$-nodes in $\bigcup_{l=0}^{k-2} X_l$.

By Lemma 10.2 again, for any such $x^1 \in X_k$, we have $d(x_0^1, x^1) \geq \omega \cdot k$.

We now adapt the proof of König's lemma: From each of the infinitely any boundary $1$-nodes in $G^1$, there is a $1$-walk reaching that boundary $1$-node and also reaching $x_0^1$. Thus, there are infinitely many $1$-walks starting at $x_0^1$ and passing through one of the $1$-nodes in $X_0$, say, $x_{m_0}^1$. Among those $1$-walks, there are again infinitely many $1$-walks passing through one of the $1$-nodes in $X_1$, say, $x_{m_1}^1$. Continuing in this way, we find an infinite sequence $(x_{m_1}^1, x_{m_2}^1, x_{m_3}^1, \ldots)$ of $1$-nodes occurring in a one-ended $1$-walk starting at $x_0^1$ and such that $d(x_0^1, x_{m_k}^1) \geq \omega \cdot k$. $\Box$

**Corollary 10.4.** Under the hypothesis of Theorem 10.3, the enlargement $*G^1$ of $G^1$ has at least one $1$-hypernode not in its principal galaxy $\Gamma_0^1$ and thus at least one $1$-galaxy $\Gamma^1$ different from its principal $1$-galaxy $\Gamma_0^1$.

**Proof.** Set $x^1 = [(x_0^1, x_{m_0}^1, x_{m_1}^1, \ldots)] = [x_{m_n}^1]$, where the $x_{m_n}^1$ are the $1$-nodes specified in the preceding proof (replace $k$ by $n$). With $x_0^1$ being the standard $1$-hypernode corresponding to $x_0^1$, we have by Theorem 10.3 that $d(x_0^1, x^1) \geq [\omega \cdot n]$. Hence, $x^1$ is not $1$-limitedly distant from $x_0^1$ and thus must reside in a $1$-galaxy $\Gamma^1$ different from $\Gamma_0^1$. $\Box$

11 When $*G^1$ Has a 1-Hypernode Not in Its Principal Galaxy

We are at last ready to extend the results of Section 4 to the rank 1 of transfiniteness. The ideas are the much same as those of Section 4 except for the fact that the proof of Theorem
4.2 cannot be extended to the present case. This is because transfinite ordinals cannot be identified as being even or odd. We need another proof.

In this section $G^1$ is 1-wconnected and has an infinity of boundary 1-nodes, but $G^1$ need not be locally finite. Let $\Gamma^1_a$ and $\Gamma^1_b$ be two 1-galaxies of $*G^1$ that are different from the principal 1-galaxy $\Gamma^1_0$. We say that $\Gamma^1_a$ is closer to $\Gamma^1_0$ than is $\Gamma^1_b$ and that $\Gamma^1_b$ is further away from $\Gamma^1_0$ than is $\Gamma^1_a$ if there are a $y = [y_n]$ in $\Gamma^1_a$ and a $z = [z_n]$ in $\Gamma^1_b$ such that, for some $x = [x_n]$ in $\Gamma^1_0$ and for every $m \in N$,

$$\{n: d(z_n, x_n) - d(y_n, x_n) \geq \omega \cdot m\} \in \mathcal{F}.$$  
(The ranks of $x$, $y$, and $z$ may now be either 0 or 1.)

Any set of 1-galaxies for which every two of them, say, $\Gamma^1_a$ and $\Gamma^1_b$ satisfy these conditions will be said to be totally ordered according to their closeness to $\Gamma^1_0$. Here, too, the conditions for a total ordering are readily shown.

**Lemma 11.1.** These definitions are independent of the representative sequences $(x_n)$, $(y_n)$, and $(z_n)$ chosen for $x$, $y$, and $z$.

The proof of this lemma is the same as that of Lemma 4.1 except that the rank 0 is replaced by the transfinite rank 1. For instance, the natural number $m$ is now replaced by the ordinal $\omega \cdot m$.

**Theorem 11.2.** If $*G^1$ has a hypernode $v = [v_n]$ (of either rank 0 or rank 1) that is not in its principal 1-galaxy $\Gamma^1_0$, then there exists a two-way infinite sequence of 1-galaxies totally ordered according to their closeness to $\Gamma^1_0$ and with $v$ being in one of those galaxies.

**Proof.** In this proof, we use the fact that between any two nodes in a 1-graph there exists a geodesic walk terminating at those nodes; that is, the length of the walk is equal to the $\omega$distance between those nodes. This is a consequence of the facts that the walks terminating at those nodes have ordinal lengths and that any set of ordinals is well-ordered and thus has a least ordinal. That least ordinal must be the length of at least one walk terminating at those nodes, for otherwise the minimum of the walk-lengths would be larger.

As before, let $x = [(x, x, x, \ldots)]$ be a standard hypernode in $\Gamma^1_0$. $x$ can be of either rank 0 or 1. Since $v$ is not in $\Gamma^1_0$, we have that for each $m \in N$

$$\{n: d(x, v_n) > \omega \cdot m\} \in \mathcal{F}$$  
(11)
For each $n \in N$, if $d(x, v_n) < \omega \cdot 6$, set $u_n = x$, but, if $d(x, v_n) \geq \omega \cdot 6$, choose $u_n$ such that

$$d(x, v_n) \leq d(x, u_n) \cdot 3 \leq d(x, v_n) \cdot 2$$  \hspace{1cm} (12)$$

That the latter can be done can be seen as follows.

Choose a geodesic 1-walk $W^1$ terminating at $x$ and $v_n$. Remember that $W^1$, as given by (5), is incident to each of its nonterminal 1-nodes through at least one 0-tip, as was asserted by Condition 3 of the definition of $W^1$. Moreover, the transition through each 0-tip contributes $\omega$ to the length of $W^1$. Upon tracing $W^1$ from $x$ toward $v_n$, we must encounter at least two 1-nodes, both of which are neither closer to $x$ by one-third of the number of 0-tips traversed by $W^1$ nor further away from $x$ by two-thirds of the number of 0-tips traversed by $W^1$. A node on $W^1$ between those two 1-nodes can be chosen as $u_n$.

Suppose there is a $k \in N$ such that $\{n: d(x, u_n) \leq \omega \cdot k\} \in F$. By the left-hand inequality of (12),

$$\{n: d(x, v_n) \leq (\omega \cdot k) \cdot 3\} \supseteq \{n: d(x, u_n) \leq \omega \cdot k\} \in F.$$  

Hence, the left-hand set is a member of $F$, in contradiction to (11). (These sets cannot both be in the ultrafilter $F$.) Therefore, $u = [u_n]$ satisfies (11) for every $m \in N$ when $v_n$ is replaced by $u_n$; that is, $u$ is in a galaxy different from the principal 1-galaxy $\Gamma_b^1$.

Furthermore, by the right-hand inequality of (12),

$$d(x, u_n) \leq (d(x, v_n) - d(x, u_n)) \cdot 2.$$  

Suppose there exists a $j \in N$ such that

$$\{n: d(x, v_n) - d(x, u_n) \leq \omega \cdot j\} \in F.$$  

Then,

$$\{n: d(x, u_n) \leq (\omega \cdot j) \cdot 2\} \supseteq \{n: d(x, v_n) - d(x, u_n) \leq \omega \cdot j\} \in F$$

So, the left-hand set is in $F$, in contradiction to our previous conclusion that $u$ satisfies (11) with $v_n$ replaced by $u_n$. We can conclude that $u$ and $v$ are in different 1-galaxies $\Gamma_a^1$ and $\Gamma_b^1$, respectively, with $\Gamma_a^1$ closer to $\Gamma_b^1$ than is $\Gamma_b^1$.  

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We can now repeat this argument with $\Gamma_1^1$ replaced by $\Gamma_0^1$ and with $u = [u_n]$ playing the role that $v = [v_n]$ played to find still another galaxy $\Gamma_0^1/\Gamma_0^1$ different from $\Gamma_0^1$ and closer to $\Gamma_0^1$ than is $\Gamma_0^1$. Continual repetitions yield an infinite sequence of galaxies indexed by, say, the negative integers and totally ordered by their closeness to $\Gamma_0^1$.

The rest of the proof continues just like the argument for Theorem 4.2 that establishes a sequence of 1-galaxies progressively further away from $\Gamma_0^1$ than is $\Gamma_0^1$. In this case, the natural number $m$ is replaced by the ordinal $\omega \cdot m$; also, the last $n$ in (3) is replaced by $\omega \cdot n$. $\Box$

Finally, by mimicking the proof of Theorem 4.3, we can prove

**Theorem 11.3.** Under the hypothesis of Theorem 11.2, the set of 1-galaxies of $\mathcal{G}_1^1$ is partially ordered according to the closeness of the 1-galaxies to $\Gamma_0^1$.

### 12 Extensions to Higher Ranks of Transfiniteness

The extension of these results to the enlargements of transfinite graphs of any natural-number rank is quite similar to what we have presented. The ideas are the same, but the notations and the details of the arguments are somewhat more complicated. Moreover, further complications arise with the extension to the arrow rank $\omega$ of transfiniteness. Extensions to still higher ranks then proceed in much the same way. All this is explicated in the technical report [7], which can also be found in the archival web site, www.arxiv.org, under Mathematics, Zemanian.

### References


Figure Captions

Figure 1. A grounded, one-way infinite ladder. $x_g$ is its ground node.

Figure 2. A graph $G$ consisting of a grounded, one-way infinite ladder $L$ and a one-ended path connected to $L$ only at its ground node, as shown.

Figure 3. A 1-graph $G^1$ in which walks are needed to define distances between all the nodes.