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Upset Paths and 2-Majority Tournaments

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UPSET PATHS AND 2-MAJORITY TOURNAMENTS

A Thesis

Presented to the

Faculty of

California State University,

San Bernardino

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

in

Mathematics

by

Rana Ali Alshaikh

June 2016
Upset Paths and 2-Majority Tournaments

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Abstract

In 2005, Alon, et al. proved that tournaments arising from majority voting scenarios have minimum dominating sets that are bounded by a constant that depends only on the notion of what is meant by a majority. Moreover, they proved that when a majority means that Candidate $A$ beats Candidate $B$ when Candidate $A$ is ranked above Candidate $B$ by at least two out of three voters, the tournament used to model this voting scenario has a minimum dominating set of size at most three. This result gives 2-majority tournaments some significance among all tournaments and motivates us to investigate when a given tournament can be considered a 2-majority tournament. In this thesis, we prove, among other things, that the presence of an upset path in a tournament allows us to conclude the tournament is realizable as a 2-majority tournament.
I am grateful for the help of many people. First and foremost, to my mother and my father: your love, prayers and encouragement, without which I wouldn’t have been able to follow my passion for mathematics. All success I’ve had is rooted in the effort they invested in my upbringing. Secondly, special thanks go to my husband Hatim for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. To my lovely daughters, Jana and Deem, your unconditional love gives me the power of making a balance in my life. I would also like to thank my brothers and my sisters for always being next to me when my life gets challenging.

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Chapter 1

Introduction

Imagine the following voting scenario: There is an election in which the candidates are ranked by each voter and Candidate A beats Candidate B precisely when Candidate A is ranked above Candidate B in a majority of the voter rankings. We will call this $k$-majority voting. In this thesis, we represent every candidate as a point. If Candidate A beats Candidate B, we draw an arrow from the point representing Candidate A to the point representing Candidate B. The resulting diagram, which we will call a tournament, can be used as a mathematical tool to decide the winner in a contest. We will refer to the points in the tournament as the vertices and the arrows between the vertices as arcs.

Figure 1.1: A case when we have difficulty picking a winner.
Continuing with our scenario, suppose there are \( n \) candidates in an election. You might have imagined that determining a winner is simple, fair, and consistent. This is certainly true when there are only two candidates. It might also be easy when, for example, there are \( n \) candidates and there is an arrow directed from Candidate A to every other candidate in the resulting tournament. That means Candidate A beats everyone in the election. However, the task of picking a winner, or winners, is often much more complicated. Consider the following circumstance: Candidate A beats Candidate B, Candidate B beats Candidate C, and Candidate C beats Candidate A as in Figure 1.1.

In this scenario, it seems picking a winner is impossible. In fact, it is complicated whenever this case happens in the resulting tournament. Often, there is not a single best way to determine the winner. In voting theory, one studies the advantages and disadvantages of different methods of selecting a winner in a contest. One method is to find a small collection of vertices, which we call a dominating set, such that for any vertex \( x \) in the election, not in the dominating set, there exists a vertex in the dominating set that beats \( x \).

In general, tournaments can have minimum dominating sets that are arbitrarily large [Erd63]. In some voting scenarios, the upper bound for the size of a minimum dominating set is small, no matter how many candidates there are, which makes the task of picking a winner or winners easier. However, in other voting scenarios, the upper bound for the size of a minimum dominating set might be big. The focus of our study is to find what structures in a tournament \( T \) that gives \( T \) the possibility of having a small upper bound on the size of a minimum dominating set. Specifically, we will search for a structure that, when present in a tournament, will imply that the tournament is a model for a voting scenario in which there is a minimum dominating set of size at most three.

We divide this thesis into six chapters. In this chapter, we introduced the voting problem that inspired us. Chapter two introduces all important definitions and notation that the reader will need to understand our study. Chapter three illustrates previous related work that inspired us to choose this topic. In Chapter four and Chapter five, we develop techniques, identify specific structures, and prove that when these structures are present, we can say that a tournament can have a minimum dominating set of size no greater than three. In Chapter six, we conclude by summarizing and reviewing our findings, and we suggest possible further investigations.
Chapter 2

Preliminaries, Notation and Terminology

In this chapter, we define some relevant terminology and develop some useful notation that we can use to formalize the mathematical model for voting we described in the introduction. We also state some basic results from graph theory. Most of the material that is introduced here can be found in a basic graph theory book such as Graphs and Digraphs, sixth edition, by Gary Chartrand, Linda Lesniak and Ping Zhang [CLZ10].

A graph $G$ is a finite nonempty set $V$ of objects called vertices together with a possibly empty set $E$ of two element subsets of $V$ called edges. A graph is called complete when $E$ consists of all two element subsets of $V$. A graph $H$ is a subgraph of a graph $G$ if $V(H) \subseteq V(G)$ and $E(H) \subseteq E(G)$. We notate this by $H \subseteq G$.

If $\{u, v\}$ is an edge in a graph $G$, we write this edge as $uv$ or $vu$. When the order of vertices in an edge is important, we say that the edge is a directed edge or an arc. We write $uv$ or $u \rightarrow v$ to designate that there is an arc directed from $u$ to $v$. If all the edges of a graph are directed, then it is called a digraph.

Let $D = (V, A)$ be a digraph with a set $V$ of vertices and a set $A$ of arcs, and let $x \in V$. The number of arcs that are directed from $x$ is called the out degree of $x$, written $od(x)$. The number of arcs that are directed to $x$ is called the in degree of $x$, written $id(x)$.

A digraph is called a tournament if between every pair of vertices $x$ and $y$ there exists a directed edge, either from $x$ to $y$ or from $y$ to $x$, but not both. In other words, a
tournament $T$ is an orientation of a complete graph. Figure 1.1 is a tournament with the set of vertices $V = \{A, B, C\}$ and the set of arcs $\{AB, BC, CA\}$. In a tournament on $n$ vertices, we say that a vertex $x$ is a source if $id(x) = 0$ and $od(x) = n - 1$. We say that a vertex $y$ is a sink if $od(y) = 0$ and $id(y) = n - 1$.

In a graph $G$, for any two vertices $x, y \in G$, we say that $x$ dominates $y$ or $y$ dominates $x$ if there is an edge between $x$ and $y$. Also, we say that a set $X$ of vertices dominates a set $Y$ of vertices, $X \rightarrow Y$, if for every $y \in Y$ there exists $x \in X$ such that $x \rightarrow y$. A dominating set $X$ in $G$ is a set of vertices such that $X \rightarrow V(G)$. A minimum dominating set $X$ in $G$ is a smallest set of vertices $X$ such that $X \rightarrow V(G)$. The domination number of $G$ is the size of a minimum dominating set in $G$. We denote this $\gamma(G)$. Domination number is a well-studied graph parameter. Let $D = (V, A)$ be a digraph with a set $V$ of vertices and a set $A$ of arcs. If $xy \in A$, we write $x \rightarrow y$ and say $x$ dominates $y$ or $x$ beats $y$. A dominating set $X$ in $D$ is a set of vertices such that $X \rightarrow V(D)$. A subset $X$ of the vertex set of a digraph is called a dominating set if for any vertex $v$ not in $X$ there exists a vertex $x \in X$ such that $x$ dominates $v$. There are far fewer papers concerning dominating sets in digraphs and tournaments than in graphs. According to Reid et al., 90% of the papers on domination consider domination in undirected graphs [RMHH04].

In voting theory, digraphs and tournaments can be used to model a voting scenario and possibly determine a winner. The winner is called the tournament solution. When a tournament has a source, a tournament solution is easily found; namely, it is the source. Otherwise, the structure of the dominating set can be used to narrow down a tournament solution.

A path $P$ in a digraph $D$ is a finite sequence of distinct vertices $v_1v_2...v_k$ such that $v_iv_{i+1}$ is an arc in $D$ for $i = 1, 2, ..., k - 1$. We called a path $v_1v_2...v_k$ in a digraph $D$ together with the arc $v_kv_1$ a cycle. In other words, a cycle in $D$ is a closed path. In the voting scenario we mentioned in Chapter one, we assumed that there are three candidates: $A, B,$ and $C$. The relationship between the three is depicted in the tournament shown in Figure 1.1. The path $ABC\!A$ forms a cycle. This cycle is one structure that makes choosing a tournament solution difficult.

When no cycle exists in a tournament, we call the tournament acyclic. A tournament $T$ is transitive if for any vertices $a, b$ and $c$ whenever $ab$ and $bc$ are arcs of $T$, it
must be that $ac \in A(T)$. In the next lemma, we will prove that transitive tournaments
are acyclic.

**Lemma 2.1.** A tournament $T$ is transitive if and only if $T$ is acyclic.

*Proof.* Let a tournament $T = (V, A)$ be transitive, we prove that $T$ is acyclic. Suppose
not. Then $T$ has at least one cycle. Let $v_1v_2...v_kv_1$, $k \geq 3$ be a cycle in $T$. Since $v_1v_2$
and $v_2v_3$ are arcs in $T$, and $T$ is transitive, it follows that $v_1v_3$ is an arc in $T$. Similarly,$v_1v_4, v_1v_5, ..., v_1v_k \in A(T)$; a contradiction since $v_k \rightarrow v_1$. Therefore, $T$ is acyclic.

Conversely, let $T$ be acyclic, we prove that $T$ is transitive. Suppose not. Then
there exist vertices $v_1, v_2$ and $v_3$ such that $v_1v_2, v_2v_3$ and $v_3v_1$ are arcs in $T$. This makes
a cycle and contradicts that $T$ is acyclic. Thus, $T$ is transitive. \qed

The next lemma gives a well-known and important property of acyclic turno-
maments.

**Lemma 2.2.** If a tournament $T$ is acyclic, then $T$ has exactly one source and one sink.

*Proof.* If a tournament $T$ is acyclic, we prove that $T$ has a source. Suppose not. Let a
tournament $T$ be acyclic, then there is no vertex $v$ such that $id(v) = 0$. Let $P : u_1u_2...u_k$
be a maximal length path in $T$. Since $id(u_1) > 0$, there exists a vertex $w$ such that
$w \rightarrow u_1$. If $w \notin P$, then $w \cup P$ is a longer path; a contradicition. If $w \in P$, then
$u_1u_2...wu_1$ is a cycle in $T$; a contradiction. Therefore, there exists a sink $v$ such that
$id(v) = 0$.

If a tournament $T$ is acyclic, we prove that $T$ has a sink. Suppose not. Let
a tournament $T$ be acyclic, then there is no vertex $u_k$ such that $od(u_k) = 0$. Let $P : u_1u_2...u_k$
be a maximal length path in $T$. Since $od(u_k) > 0$, there exist a vertex $w$ such that
$u_k \rightarrow w$. If $w \notin P$, then $w \cup P$ is a longer path; a contradicition. If $w \in P$, then
$u_kw...u_{k-2}u_{k-1}u_k$ is a cycle in $T$; a contradiction. Therefore, there exists a sink $u_k$ such
that $od(u_k) = 0$.

To prove uniqueness of the source, let $u_1$ and $u_2$ be two sources in $T$. Then
there is a directed edge between every pair of vertices. If $u_1 \rightarrow u_2$, then $u_1$ is the source
but not $u_2$. If $u_2 \rightarrow u_1$, then $u_2$ is the source, not $u_1$. Similarly, to prove uniqueness
of the sink, let $v_1$ and $v_2$ be two sinks in $T$. Then there is an arc between every pair of
vertices. If $v_1 \rightarrow v_2$, then $v_2$ is the sink but not $v_1$. If $v_2 \rightarrow v_1$, then $v_1$ is the sink, not
$v_2$. \qed
Note that for any acyclic tournament $T$, the source $x$ itself is a dominating set in the tournament. In fact, $x$ is the unique minimum dominating set of size one. In this case, the tournament solution can easily be found because $x$ uniquely beats all the vertices. Therefore, $x$ is the winner in the election.

A path in a digraph $D$ that contains all the vertices of $D$ is called a Hamiltonian path. A Hamiltonian cycle is a closed Hamiltonian path. A Hamiltonian digraph is a digraph $D$ that has a Hamiltonian cycle. We can clearly see that not all digraphs have a Hamiltonian path. However, all tournaments must have a Hamiltonian path as we prove in the following lemma.

**Lemma 2.3.** Every tournament $T$ has a Hamiltonian path.

*Proof.* Suppose not. Let $P : v_1v_2...v_k$ be a longest path in $T$. Since $P$ is not Hamiltonian, there exists a vertex $x \notin V(P)$. By the maximality of $P$, $x \rightarrow v_k$ and consequently, $x \rightarrow v_{k-1}$. If $x \rightarrow v_i$ for all $i \in \{1, 2, ..., k\}$, then $x \rightarrow v_1$ and the path $xP$ is longer than $P$. Let $r$ be the largest index in $\{1, 2, ..., k\}$ such that $v_r \rightarrow x$. Then $x \rightarrow v_{r+1}$ and so $v_1v_2...v_rxv_{r+1}...v_r$ is a path in $T$ longer than $P$. \qed

![Figure 2.1: Every tournament $T$ has a Hamiltonian path.](image)

A path $P : v_1v_2...v_k$ in a tournament $T$ is called a forward path if $v_i \rightarrow v_j$ for all $i$ and $j$ such that $1 \leq i < j \leq k$. The next lemma proves that a Hamiltonian forward path exists in any acyclic tournament.

**Lemma 2.4.** If a tournament $T$ is acyclic, then $T$ has a Hamiltonian forward path.
Proof. By Lemma 2.3, $P : v_1v_2...v_\ell$ is a Hamiltonian path in $T$. If $P$ is not a forward path, then $v_j \rightarrow v_i$ for some values of $i$ and $j$ such that $1 \leq i < j \leq k$. Since $T$ is acyclic, by definition, $T$ cannot have any cycles. But $v_jv_{j+1}...v_\ell v_j$ is a cycle, which contradicts our assumption that $T$ is acyclic. Therefore, $T$ has a Hamiltonian forward path. \qed
Chapter 3

Voting and k-Majority Tournaments

In this chapter, we will discuss some important results discovered by N. Alon, G. Brightwell, H. A. Kierstead, A. V. Kostochka and P. Winkler [ABK+05]. The topic of this thesis was inspired by these results.

3.1 $k$-Majority Voting

We will now formally develop the idea of $k$-majority voting. Each voter orders all the candidates by his preference. The resulting orderings are called linear orderings. We use $\Pi$ to denote the collection of the voters’ linear orderings of the candidates. A voter’s linear ordering define when one candidate is preferred over another for each individual voter. In other words, linear orderings form a binary relationship between the candidates. Suppose we have linear orderings $\Pi : P_1, P_2, ..., P_r$ on a finite set of candidates. When Candidate $x$ is ranked higher than Candidate $y$ in the linear ordering $P_i$, we write $x >_i y$. If $x >_i y$ for more than the half values of $i$ in the set $\{1, 2, ..., r\}$, then $x$ beats $y$ in the election. In this case, we say $x$ dominates $y$ and write $x \rightarrow y$. Notice that for $n$ candidates, $\{x_1, x_2, ..., x_n\}$, if we have $x_1 \rightarrow x_2 \rightarrow x_3 \rightarrow ... \rightarrow x_n \rightarrow x_1$, it is difficult to select a winner or a group of winners in such an election. One way to decide a winner or a group of winners is to find a minimum dominating set on $\{x_1, x_2, ..., x_n\}$. To do so, we need to find a minimum group of candidates, let us denote it $X$, so that for every
candidate \( x \) in the election, there is a candidate \( y \in X \) such that \( y \to x \).

### 3.2 \( k \)-Majority Tournaments

We model a \( k \)-majority voting scenario as described in the previous section using a digraph where the vertices represent the candidates. Let \( \Pi : P_1, P_2, ..., P_k \) be linear orderings on a finite set of vertices \( V \). When \( r \) is odd, the resulting digraph is a tournament since, between any two candidates, one will always be ranked above the other in a majority of the linear orderings [MSW11]. We say that a tournament \( T \) is a \( k \)-majority tournament if \( T \) can be realized by some set of \( 2k - 1 \) linear orderings on \( V(T) \) [ABK+05]. For instance, a 2-majority tournament that has a vertex set \( V \) is realized by three linear orderings on \( V \), while a 3-majority tournament is realized by five linear orderings on \( V \).

Alon, et.al. studied upper bounds of the cardinality of a minimum dominating set in a \( k \)-majority tournament \( T \) [ABK+05]. Let \( F(k) \) be the maximum over all \( k \)-majority tournaments of the cardinality of a minimum dominating set. They proved that the cardinality of a minimum dominating set in a \( k \)-majority tournament is bounded by a value that does not depend on the number of vertices in the tournament, so that \( F(k) \) is finite and exists for all \( k > 0 \). Specifically, they proved that \( F(k) \leq \left( 80 + \mathcal{O}(1) \right) k \log k \), where the \( \mathcal{O}(1) \) term tends to zero as \( k \) tends to infinity [ABK+05]. This result is in contrast to the following result by Paul Erős [Erd63]. Our statement of this result follows the statement given by Reid, et al [RMHH04].

**Lemma 3.1.** For every \( \epsilon > 0 \), there is an integer \( K \) such that for every \( k \geq K \), there exists a tournament \( T_k \) with no more than \( k^2 2^{2(\log 2 + \epsilon)} \).

This result shows that the cardinality of a minimum dominating set in general tournaments can be arbitrarily large.

### 3.3 2-Majority Tournaments

We are especially interested in 2-majority tournaments. Our interest stems from the following result [ABK+05]. We give the proof, with illustration, that is found in [ABK+05].
Theorem 3.2. The size of a dominating set is at most three for all 2-majority tournaments \((F(2) = 3)\). Moreover, if \(T\) does not have a dominating set of size one, then \(T\) has a dominating set of size three that induces a directed cycle.

Proof. Consider a 2-majority tournament \(T = (V, A)\) with a set \(V\) of vertices and a set \(A\) of arcs defined by three linear orderings \(P_1, P_2\) and \(P_3\) of \(V\). Consider the linear order \(P_3\). We look for a vertex \(c\) such that every vertex strictly greater than \(c\) in \(P_3\) is dominated by some vertex \(d\) with \(c \geq_3 d\). If no such \(c\) exists, then the top vertex in \(P_3\) is a dominating set in \(T\). We may, therefore, assume such a \(c\) exists and we choose \(c\) to be the least such vertex in \(P_3\). If another vertex dominates \(c\) then this contradicts our choice of \(c\).

![Figure 3.1: The linear orderings on \(V(T)\) in a 2-majority tournament.](image)

Let \(U\) be the set of vertices above \(c\) in \(P_3\). Then \(U = \{x \in V : x \geq_3 c\}\). If \(U\) is empty, then the top element in \(P_3\) is \(c\). Therefore, \(c \rightarrow \{c\}\), and \(c \rightarrow V\). This implies \(T\) again contains a dominating set of size one. Thus, we may assume that \(U\) is nonempty. We let \(D\) be the nonempty set of vertices not in \(U\) that dominates \(U\) in \(T\). We can write \(D = \{x \in V \setminus U : x \rightarrow U\}\). Therefore, for all \(d \in D\), \(d \geq_1 U\) for \(i = 1, 2\) but not for \(i = 3\). Let \(R\) be the remaining collection of vertices. That is, \(R = V \setminus (U \cup D \cup \{c\})\).

Let \(u_1\) be the maximum element of \(U\) in \(P_3\) and \(u_2\) be the maximum element of \(U\) in \(P_2\). For all \(d \in D\), either \(c \geq_1 d\) or \(c \geq_2 d\). Therefore, \(c \rightarrow D\) since \(c \geq_3 D\).
Any element \( x \in V \setminus U \) satisfies \( x <_3 \{ u_1, u_2 \} \). So, if \( x \) dominates both \( u_1 \) and \( u_2 \), then it satisfies \( u_1, u_2 <_i x \) for \( i = 1, 2 \). Therefore, if \( d \in D \), then \( d \) dominates all of \( U \). It follows that for any vertex \( d \in D \), \( d >_1 u_1 \) and \( d >_2 u_2 \). Thus \( d \rightarrow \{ u_1, u_2 \} \). Since \( \{ u_1, u_2 \} \) is above \( R \) in \( P_3 \), \( u_1 >_1 R_1 \) and \( u_2 >_2 R_2 \), we see that \( \{ u_1, u_2 \} \) dominates all vertices in \( R \). This is illustrated in Figure 3.1. Thus, if we fix a \( d \in D \), the set \( \{ c, d, u_1, u_2 \} \) is a dominating set of \( V(T) \) of size four, as shown in Figure 3.2.

However, we can do better. Let \( R = R_1 \cup R_2 \) such that \( R_i = \{ x \in R : x <_i u_i \} \), and \( u_i \rightarrow R_i \) for all \( i \) in \( \{ 1, 2 \} \). Since \( u_1, u_2 <_i d \) for both \( i \) in \( \{ 1, 2 \} \) and \( c \rightarrow d \), there exists \( i \) in \( \{ 1, 2 \} \) such that \( u_i <_i c \). Let \( u_2 <_2 c \). Since \( c \) above \( R \) in \( P_3 \), then \( c \rightarrow R_2 \). It follows that \( \{ c, d, u_1 \} \rightarrow V \). If \( c \in D \) then \( c >_1 R_1 \). Then \( c \rightarrow V \) and we have a dominating set of size one. If this is not the case, then we will have a cycle \( cdu_1c \) and the set \( \{ c, d, u_1 \} \) of vertices dominates all of \( V \), as shown in Figure 3.2.

Figure 3.2: Improve a minimum dominating set on a 2-majority tournament.
We conclude from Alon, et.al.’s study that $F(2) = 3$, so that there is a small upper bound for all minimum dominating sets in 2-majority tournaments. However, the upper bound for a minimum dominating set in a $k$-majority tournament when $k \geq 3$ is not tight, and it is relatively large when $k$ is large. In the next section, we consider a method using what is known about 2-majority tournaments to attempt to improve the upper bound on $F(3)$.

We can easily draw a 2-majority tournament given three linear orderings $P_1$, $P_2$ and $P_3$. For example, Let $T$ be a 2-majority tournament on vertex set $V = \{a, b, c, d, e, f\}$ realized by the linear orderings $P_1 : b > a > c > d > e > f$, $P_2 : c > d > a > f > e > b$ and $P_3 : e > f > a > b > c > d$. The resulting tournament can be drawn as follows:

![Diagram of 2-majority tournament]

Figure 3.3: The resulting 2-majority tournament from the given linear orderings $P_1$, $P_2$ and $P_3$.

### 3.4 Inherited 2-Majority Tournaments

Alon, et.al. also investigated the maximum overall 3-majority tournaments of a minimum dominating set [ABK+05]. By way of an example, they proved that $F(3) \geq 4$. However, the upper bound they gave for $F(3)$ was less than or equal to 80(3 log 3), which is a relatively big bound.
One way to improve this upper bound might be to investigate the structural differences that arise between 3-majority tournaments and 2-majority tournaments. A 3-majority tournament is realized by five linear orderings. In a 3-majority tournament $T$, if we restrict our attention to any three of the linear orderings, these three linear orderings will realize a 2-majority tournament on $V(T)$. We call such a 2-majority tournament $T$ an inherited 2-majority tournament of a 3-majority tournament. Thus, a given 3-majority tournament has $\binom{5}{2} = 10$ different inherited 2-majority tournaments. Let $T_i$ be the inherited 2-majority tournaments on a 3-majority tournament $T$ for $i \in \{1, 2, \ldots, 10\}$. Let $D_i$ be a minimum dominating set for $T_i$. Then $|D_i| = 1$ or $|D_i| = 3$ for all $i$, by Theorem 3.2. If $|D_i| = 3$, then $D_i$ is a 3-cycle.

**Proposition 1.** If $T_1$ and $T_2$ are inherited 2-majority tournaments from a 3-majority tournament $T$ such that $T_1$ and $T_2$ share exactly one linear ordering and $x \rightarrow V$ in both $T_1$ and $T_2$, then $x \rightarrow V$ in $T$.

**Proof.** We may assume that $T_1$ has linear orderings $P_1, P_2, P_3$, and $T_2$ has linear orderings $P_3, P_4, P_5$. Let $y \in V$ and suppose $y \rightarrow x$ in $T_1$ and in $T_2$. Then $x >_i y$ for at least two values of $i \in \{1, 2, 3\}$ and for at least two values of $i \in \{3, 4, 5\}$. This implies $x >_i y$ for at least three values of $i \in \{1, 2, 3, 4, 5\}$. Therefore, $x \rightarrow y$ in $T$. Since $y$ was arbitrarily chosen, $x \rightarrow V$ in $T$. \qed

**Proposition 2.** If $x$ is a dominating set shared by at least four of the inherited 2-majority tournaments from a 3-majority tournament $T$, then $x \rightarrow V$ in $T$.

**Proof.** Let $T_1$ have linear orderings $P_1, P_2, P_3$. If $T_2$ shares exactly one linear ordering with $T_1$, then, by Proposition 1, $x \rightarrow V$ in $T$. Assume that $T_2$ shares two linear orderings with $T_1$. Let $T_2$ have linear orderings $P_1, P_2, P_4$. If $T_3$ shares exactly one linear ordering with $T_1$ or $T_2$, then, by Proposition 1, $x \rightarrow V$ in $T$. Assume that $T_3$ has linear orderings $P_1, P_2, P_5$. Notice that no two of $T_1$, $T_2$ and $T_3$ share exactly one linear ordering. It follows that $T_4$ must have linear orderings that share exactly one linear ordering with $T_i$ for some values of $i \in \{1, 2, 3\}$. Thus, by Proposition 1, $x \rightarrow V$ in $T$. \qed
Chapter 4

Upset Paths and 2-Majority Tournaments

Let $P : v_1v_2...v_k$ be a path in a tournament $T$. We call $P$ an upset path if when the arcs of the path are reversed, the resulting tournament is acyclic with source $v_k$ and sink $v_1$. The notion of an upset path was first defined by Melcher et al. [MR10]. Let $T'$ be the tournament obtained from $T$ by reversing the arcs in the upset path $P$. Tournament $T'$ is acyclic with exactly one source $v_k$ and one sink $v_1$. Obviously, all cycles in the tournament $T$ must contain at least one arc of the upset path.

Figure 4.1: Upset path in the tournament $T$ and the tournament $T'$.

In Figure 4.1, the tournament $T$ has an upset path $P : abc$. We obtain $T'$ by
reversing the arcs in $P$. Note that $T'$ is acyclic with source $c$ and sink $a$. In this example, it is easy to check that all cycles in $T$ contain at least one arc of the upset path. It is not too difficult to verify that the last two vertices in an upset path in a tournament $T$ also form a dominating set in $T$. Vertex $c$ dominates all of $V - \{b\}$ and $b \rightarrow c$. Thus, $\{b, c\}$ forms a minimum dominating set in $T$.

In this chapter, we will derive the relationship between upset paths and 2-majority tournaments. Our method is to investigate tournaments that have an upset path. We will see that the presence of an upset path will imply that other structural properties exist in the tournament. For any tournament $T$, we say that $T$ is realizable as a 2-majority tournament if $T$ can be constructed as a 2-majority tournament using exactly three linear orderings of $V(T)$. Our conjecture is that if we have a tournament $T$ with an upset path, then $T$ is realizable as a 2-majority tournament. To prove this conjecture, the challenge will be to construct three linear orderings of the vertices that will realize $T$ as a 2-majority tournament. Thus, it seems reasonable to investigate structures that exist in tournaments that, when present, will make this process easier.

The structure of a Hamiltonian forward path allows us to construct linear orderings to realize a tournament as a 2-majority tournament.

**Lemma 4.1.** If a tournament $T$ is acyclic, then $T$ is realizable as a 2-majority tournament.

**Proof.** Since $T$ is acyclic, by Lemma 2.4, there is exists a Hamiltonian forward path. Let $v_1v_2v_3...v_k$ be a Hamiltonian forward path in $T$. Therefore, we can write the vertices in $T$ in three linear orderings $P_1$, $P_2$ and $P_3$ as the following: $P_1 : v_1 > v_2 > v_3 > ... > v_k$, $P_2 : v_1 > v_2 > v_3 > ... > v_k$ and $P_3$ can be anything. Thus, $T$ is realizable as a 2-majority tournament.

**Lemma 4.2.** Let $|V(T)| \geq 3$. If $xy$ is an upset path in tournament $T$ of length one, then $T$ is not acyclic.

**Proof.** Suppose not. Then $T$ is acyclic. Let $T'$ be the tournament obtained from $T$ after reversing the arc $xy$. In $T'$, $y$ is a source and $x$ is a sink. Therefore, since $|V(T)| \geq 3$, there exists a vertex $t$ such that $t \rightarrow x$ and $y \rightarrow t$ in $T$. Then $xytx$ is a cycle in $T$; a contradiction.
Lemma 4.3. If a tournament $T$ has an upset path, then $T$ is not acyclic.

Proof. Suppose not. Then $T$ is acyclic and contains an upset path $P : v_1 v_2 \ldots v_k$. Let $T'$ be the tournament obtained from $T$ by reversing all the arcs in $P$. By definition of the upset path, $v_k$ is a source in $T'$ and $v_1$ is a sink in $T'$. Since $T$ is acyclic, it contains a source $s$ and a sink $t$. It must be that $s$ and $t$ are distinct from $v_k$ and $v_1$. Thus, $s \rightarrow v_k$ in $T'$ and $v_1 \rightarrow t$ in $T'$; a contradiction.

Lemma 4.4. If $P : av_1 v_2 \ldots v_k b$ is a shortest upset path in a tournament $T$, then there must exist a cycle in $T$ containing the arc $av_1$ and no other arc in $P$, and there must
exist a cycle in $T$ containing the arc $v_kb$ and no other arc in $P$.

**Proof.** If no such a cycle containing $v_kb$ exists, then $P : av_1v_2...v_{k-1}$ is a shorter upset path in $T$; a contradiction. A similar argument applies when no such cycle containing $av_1$ exists. \(\square\)

**Remark (Number of cycles in $T$).** Let $T$ be a tournament. If $T$ has an upset path $P : v_1v_2$ of length one, then the number of cycles in $T$ must be greater than or equal one. For all $T$ that has an upset path $P$ of length $\geq 2$, then the number of cycles in $T$ must be greater than or equal two.

**Lemma 4.5.** Let $P : v_1v_2...v_k$ be a shortest upset path in a tournament $T$, then the tournament on $V(T) - V(P)$ must be acyclic.

**Proof.** Suppose not, then there exists at least one cycle in $V(T) - V(P)$. By reversing all arcs in $P$, the resulting tournament is not acyclic. Therefore, $P$ is not an upset path in $T$. \(\square\)

**Lemma 4.6.** Let $T$ be a tournament on $n \geq 3$ vertices that has an upset path of length one, then $T$ is realizable as a 2-majority tournament.

**Proof.** Let $T$ be a tournament that has an upset path $xy$ of length one. Let $T'$ be the tournament obtained from $T$ by reversing the arc $xy$. Then $T'$ is acyclic with source $y$ and sink $x$, and it has a dominating set of size one; $D = \{y\}$. By Lemma 4.1, we can realize $T'$ using three linear orderings $P_1, P_2$ and $P_3$. Since $y$ is the source, then $y$ is greater than all vertices in $V$ in at least two linear orders. Moreover, since $x$ is the sink, $x$ is less than all other vertices in at least two linear orderings. Also, because there is no cycle that does not contain the arc $xy$, we can order the vertices so that $y = v_1, v_2, ..., v_n = x$ forms a Hamiltonian forward path by Lemma 2.4. We use this Hamiltonian path to define the linear orderings on $V$ as following. Let $P_1 : y > v_2 > v_3 > ... > v_{n-1} > x$, $P_2 = P_1$ and $P_3$: can be anything.

Now we can write $T$ as a 2-majority tournament as shown in Figure 4.4. To do so, we note that:

(i) $y \rightarrow (V(T) - x)$.

(ii) $(V(T) - y) \rightarrow x$. 
(iii) By Lemma 2.4 there is a Hamiltonian forward path \( v_1, v_2, \ldots, v_n \) on \( V(T) - \{x, y\} \).

![Diagram of tournament T and its linear orderings.](image)

Figure 4.4: The tournament \( T \) and its linear orderings.

Therefore, \( T \) is realizable as a 2-majority tournament as shown in Figure 4.4. 

**Lemma 4.7.** If \( P : v_1v_2\ldots v_k \) is a shortest upset path on a tournament \( T \) of length at least two, then \( |V(T) - V(P)| \geq 2 \).

*Proof.* If \( |V(T) - V(P)| = 0 \), then \( V(T) = V(P) \) and \( T' \), a tournament obtained from \( T \) by reversing the arcs in \( P \), is transitive. By Lemma 2.4, \( v_1v_2\ldots v_k \) is a Hamiltonian forward path in \( T' \). This implies that every consecutive collection of vertices in \( P \) is a cycle in \( T \). By reversing the arcs in the subpath \( P' : v_1v_2\ldots v_{k-2}v_{k-1} \), we obtain an acyclic tournament. This contradicts the minimality of \( P \).

If \( |V(T) - V(P)| = 1 \), then let \( V(T) - V(P) = \{u\} \). Then \( v_k \to u \) and \( u \to v_1 \). If \( u \to v_2 \), then there is no cycle in \( T \) containing the arc \( v_1v_2 \) and no other arc in \( P \).
Hence, the path $v_2v_3...v_k$ is a shorter upset path in $T$. Thus, we may assume $v_2 \to u$. If $v_i \to u$, for some $i \in \{2,3,\ldots,k\}$, then there is no cycle in $T$ containing the arc $v_{k-1}v_k$ and no other arc in $P$. Thus, the path $v_1v_2...v_{k-1}$ is a shorter upset path in $T$. Therefore, it must be that for some $i \in \{2,3,\ldots,k\}$, $u \to v_i$. Let $j$ be the smallest such $i$. Then $v_{j-1} \to u$ and $u \to v_j$. Thus, $v_{j-1}uv_jv_{j-1}$ is a 3-cycle in $T'$; a contradiction. It follows that $|V(T) - V(P)| \geq 2$.

**Lemma 4.8.** If $P : v_1v_2...v_k$ is an upset path of length at least two, then there exist vertices $u$ and $w$ in $V(T) - V(P)$ such that $u \to v_2$ and $v_2 \to w$.

**Proof.** By Lemma 4.7, $|V(T) - V(P)| \geq 2$. Let $V(T) - V(P) = \{u_1, u_2, \ldots, u_\ell\}$. If $u_i \to v_2$ for all $i \in \{1,\ldots,\ell\}$, then there is no cycle in $T$ that contains the arc $v_1v_2$ and no other arc in $P$. Therefore, $v_2v_3...v_k$ is a shorter upset path; a contradiction. Thus, there exists a vertex $u \in V(T) - V(P)$ such that $v_2 \to u$. Symmetrically, there exists a vertex $w \in V(T) - V(P)$ such that $w \to v_{k-1}$. If $v_2 \to w$, then $v_2wv_{k-1}v_{k-2}...v_2$ is a cycle in $T'$; a contradiction. Therefore, $w \to v_2$.

**Theorem 4.9.** If a tournament $T$ has an upset path of length two or less, then $T$ is realizable as a 2-majority tournament.

**Proof.** By Lemma 4.6, we may assume that a shortest upset path has length two. Let $xyz$ be a shortest upset path in $T$. If $V - \{x,y,z\} = \emptyset$, then $x \to y$, $y \to z$ and $z \to x$. Therefore, $xyz$ is not a shortest upset path.

First, suppose $|V - \{x,y,z\}| = 1$. Let $V - \{x,y,z\} = \{v\}$. We have two cases: If $v \to y$, then $xyz$ is not a minimal upset path in $T$ since $yz$ is an upset path in $T$; a contradiction. If $y \to v$, then $xyz$ is not a minimal upset path in $T$ since $xy$ is an upset path in $T$; a contradiction too. Thus, there must be at least two vertices in $V - \{x,y,z\}$

Now let $v,u \in V - \{x,y,z\}$. Suppose $|V - \{x,y,z\}| = 2$, and let $T'$ be the acyclic tournament obtained from $T$ after reversing the arcs in $xyz$. Then $T'$ has source $z$ and sink $x$. Note that since $z$ is a source and $x$ is a sink in $T'$, we have $z \to \{x,u,v\}$ and $x$ is dominated by $u$ and $v$. We divided our argument for the remaining three arcs into cases depending on the direction of the arc between $u$ and $v$.

If $u \to v$, then, by Lemma 4.4, it must be that either $v \to y$ and $y \to u$ or $y \to v$ and $u \to y$. If $v \to y$ and $y \to u$, then $uvyu$ is a cycle avoiding $P$; a contradiction.
y → v and u → y, then T can be realized as a 2-majority tournament as shown in Figure 4.5.

Figure 4.5: The tournament T when u → v along with linear orderings that make T realizable as a 2-majority tournament.

If v → u, then, by Lemma 4.4, it must be that either y → v and u → y or v → y and y → u. If y → v and u → y, then vuyv is a cycle avoiding P; a contradiction. If v → y and y → u, then T realizable as a 2-majority tournament as shown in Figure 4.6.

We need to prove that if |V − {x, y, z}| ≥ 3, then T is realizable as a 2-majority tournament. Let A and B be two sets of vertices such that $A = \{v \in V − \{x, y, z\} : v → y\}$ and $B = \{v \in V − \{x, y, z\} : y → v\}$. By Lemma 4.8, there exists at least one vertex in A and at least one vertex in B. It follows that A and B are nonempty sets.

Then for all $a \in A$, $a → x$ and $z → a$ and for all $b \in B$, $b → x$ and $z → b$. Moreover, if $a \in A$ and $b \in B$ such that $b → a$, then there exists a cycle $ayba$ that avoids P; a contradiction. Therefore, $a → b$ for all $a \in A$ and $b \in B$. Since $T'$ is transitive, each of the subtournaments $I_A$ and $I_B$ induced on A and B, respectively, must be transitive. Therefore, by Lemma 2.4, A contains a Hamiltonian forward path $H_A : a_1, a_2, ..., a_s$ and B contains a Hamiltonian forward path $H_B : b_1, b_2, ..., b_t$. Thus, T can be realized as a 2-majority tournament determined by the three linear orderings $P_1, P_2$ and $P_3$ as shown.
Figure 4.6: The tournament $T$ when $v \rightarrow u$ along with linear orderings that make $T$ realizable as a 2-majority tournament.

in Figure 4.7.

Figure 4.7: The tournament $T$ when $a \rightarrow b$ along with linear orderings that make $T$ realizable as a 2-majority tournament.
Theorem 4.10. If a tournament $T$ has an upset path, then $T$ is realizable as a 2-majority tournament.

Proof. Let $T$ be a tournament that has an upset path $P : v_1v_2v_3...v_k$ of length $k - 1$. By the definition of an upset path, if we reverse the arcs in $P$, we will get an acyclic tournament $T'$ which, by Lemma 4.1, can be realized as a 2-majority tournament with a dominating set of size one. For $j = 1, 2, ..., k - 1$, let $U_j = \{v \in V(T) - V(P) : v_{j+1} \rightarrow v$ and $v \rightarrow v_i, \forall i \leq j\}$. Note that no vertex in $V(T) - V(P)$ is dominated by $v_1$, and no vertex in $V(T) - V(P)$ dominates $v_k$. For example, $U_1 = \{v \in V(T) - V(P) : v_2 \rightarrow v\}$ and $U_2 = \{v \in V(T) - V(P) : v_3 \rightarrow v$ and $v \rightarrow v_i, \forall i \leq 2\}$.

If the only cycle in $T$ that contain $v_1v_2$ but not $v_{k-1}v_k$ also avoid $U_1, U_2, ..., U_{k-1}$, then $P - v_1v_2$ is a shorter upset path; a contradiction. Therefore, there must be at least one cycle in $T$ containing $v_1v_2$ and vertices in $\bigcup_{i=1}^{k-1} U_i$. Similarly, there must be at least one cycle in $T$ containing $v_{k-1}v_k$ and vertices in $\bigcup_{i=1}^{k-1} U_i$. By Lemma 4.6 there exists at least one vertex in each of $U_1$ and $U_{k-1}$.

For $1 \leq a < b \leq k - 1$, it must be that $x \rightarrow y$ for all $x \in U_b$ and $y \in U_a$. By Lemma 4.5, given a set of vertices of the form $X = \{x_1, x_2, ..., x_{k-1}\}$ where $x_i \in U_i$, the tournament on $X$ is acyclic with source $x_{k-1}$ and sink $x_1$. For each $j$, by definition, every vertex $x \in U_j$ has the properties: $v_{j+1} \rightarrow x$ and $x \rightarrow v_i$, for $i = 1, 2, ..., j$. Moreover, we have $v_\ell \rightarrow x$, for $\ell = j + 2, j + 3, ..., k$. If this were not the case, then for some $\ell \in \{j + 2, ..., k\}$ we would have $x \rightarrow v_\ell$. Upon reversing the arcs in $P$, the cycle $xv_\ell v_{\ell-1}...v_j x$ will be created, contradicting the assumption that $P$ is an upset path.

Each subtournament on the vertices in $U_j$ is acyclic, which gives us a natural ordering of the vertices in $U_j$: $\pi_j : x_{j,1} > x_{j,2} > x_{j,3} > ... > x_{j,s_j}$, where $x_{j,1}, x_{j,2}, x_{j,3}, ..., x_{j,s_j}$ is a Hamiltonian forward path in the subtournament on $U_j$, the vertex $x_{j,1}$ is the source in $U_j$ and the vertex $x_{j,s_j}$ is the sink in $U_j$. We draw the tournament $T$ in Figure 4.9.

The table in Figure 4.8 describes the subtournament on $V(P)$.

In order for three linear orderings $P_1, P_2, P_3$ on $V(T)$ to realize $T$ as a 2-majority tournament, the subtournament on the vertices in the upset path $P$ must also be realized by the linear orderings $P_1, P_2, P_3$. Based on the table in Figure 4.8, it is clear that meeting the following four conditions will suffice:

(i) For $v_i, (2 \leq i \leq k)$ we have $v_{i-1} >_1 v_i$ and either $v_{i-1} >_2 v_i$ or $v_{i-1} >_3 v_i$. 


<table>
<thead>
<tr>
<th>vertex in $P$</th>
<th>what dominates the vertex</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_k$</td>
<td>$v_{k-1}$</td>
</tr>
<tr>
<td>$v_{k-1}$</td>
<td>$v_{k-2}$</td>
</tr>
<tr>
<td>$v_{k-2}$</td>
<td>$v_{k-3}, v_k$</td>
</tr>
<tr>
<td>$v_{k-3}$</td>
<td>$v_{k}, v_{k-1}$</td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$v_i$</td>
<td>$v_{i-1}$ and ${v_k, v_{k-1}, \ldots, v_{i+2}}$</td>
</tr>
</tbody>
</table>

Figure 4.8: This table describes the relationships between the vertices in $T$.

(ii) Every vertex in $\{v_k, v_{k-1}, \ldots, v_{i+2}\}$ is above $v_i$ in $P_2$ and $P_3$, when $(1 \leq i \leq k - 2)$.  

Figure 4.9: The tournament $T$ with an upset path of length $k$.  

(iii) For $v_i, (1 \leq i \leq k - 1)$ we have $v_i >_1 v_{i+1}$ and either $v_i >_2 v_{i+1}$ or $v_i >_3 v_{i+1}$.

(iv) For all $l \in \{1, ..., i - 2\}$, $v_i >_2 v_l$ and $v_i >_3 v_l$.

Based on the following three facts, we can determine where each subordering $\pi_j$ on $V(U_j)$ can be placed:

(i) $\{v_{j+1}, ..., v_k\} \rightarrow \pi_j$.

(ii) $\pi_j \rightarrow \{v_j, v_{j-1}, ..., v_1\}$.

(iii) $\pi_j \rightarrow \{\pi_1, \pi_2, ..., \pi_{j-1}\}$.

There are two cases to represent $V(T)$ whether $|V(P)|$ is odd or even. Please see Figure 4.10 when $|V(P)|$ is even, and Figure 4.11 when $|V(P)|$ is odd.

$P_1: v_1 > v_2 > \pi_1 > v_3 > \pi_2 > v_4 > \pi_3 > ... > v_{k-2} > \pi_{k-3} > v_{k-1} > \pi_{k-2} > v_k > \pi_{k-1}$

$P_2: \pi_{k-1} > v_{k-1} > v_k > \pi_{k-2} > \pi_{k-3} > ... > \pi_4 > \pi_3 > v_3 > v_4 > \pi_2 > \pi_1 > v_1 > v_2$

$P_3: v_k > \pi_{k-1} > \pi_{k-2} > v_{k-2} > v_{k-1} > ... > \pi_4 > v_4 > v_5 > \pi_3 > \pi_2 > v_3 > v_4 > \pi_1 > v_1$

Figure 4.10: Linear orderings when $|V(P)| \equiv 0 \pmod{2}$.

$P_1: v_1 > v_2 > \pi_1 > v_3 > \pi_2 > v_4 > \pi_3 > ... > v_{k-2} > \pi_{k-3} > v_{k-1} > \pi_{k-2} > v_k > \pi_{k-1}$

$P_2: \pi_{k-1} > v_{k-1} > v_k > \pi_{k-2} > \pi_{k-3} > ... > \pi_4 > \pi_3 > v_3 > v_4 > \pi_2 > \pi_1 > v_1 > v_2$

$P_3: \pi_{k-1} > v_{k-1} > v_k > \pi_{k-2} > \pi_{k-3} > ... > \pi_4 > v_4 > v_5 > \pi_3 > \pi_2 > v_3 > v_4 > \pi_1 > v_1$

Figure 4.11: Linear orderings when $|V(P)| \equiv 1 \pmod{2}$.

Therefore, $T$ is realizable as 2-majority tournament.

Remark (Minimum dominating sets in $T$). Now we can locate all minimum dominating sets in $T$. $D = \{v_{k-1}, v_k\}$ is not the only minimum dominating set in $T$, but $\{v_k, x\}$ is also a minimum dominating set in $T$, for all $x \in U_{k-1}$.
Chapter 5

UP-Sets and 2-Majority Tournaments

In this chapter, we assume $T$ is a tournament that contains at least one cycle. Let $\{P_1, P_2, ..., P_h\}$ be a collection of vertex-disjoint paths in a tournament $T$. We call this collection a *UP-set of size* $h$ if upon reversing the arcs in each set of the paths in this collection, we obtain a new tournament $T'$ that is acyclic and for some not necessarily distinct $i$ and $j$ in $\{1, 2, ..., h\}$, the source in $T'$ is the terminal vertex in $P_i$ and the sink in $T'$ is the initial vertex in $P_j$. Note that a UP-set of size one is an upset path. Thus, UP-sets generalize the notion of upset paths. Given a UP-set $S = \{P_1, P_2, ..., P_h\}$, let $A = \bigcup_{i=1}^{h} A(P_i)$ be the union of all arcs in the paths in $S$. We call $A$ the *arc set* of the UP-set.

A *minimal UP-set* is a UP-set whose arc set does not properly contain the arc set of another UP-set. Intuitively, any UP-set should contain a minimal UP-set. We call a tournament $T$ an *$h$-critical* tournament if it has a minimal UP-set of size $h$, but no minimal UP-set of size less than $h$.

**Lemma 5.1.** Let $S = \{P_1, P_2, ..., P_h\}$ be a UP-set in a tournament $T$, then $S$ contains a minimal UP-set.

**Proof.** Suppose not. Then $S$, itself, is not a minimal UP-set. Therefore, the arc set $A$ of $S$ properly contains the arc set $A_1$ of another UP-set $S_1$. Similarly, $S_1$ is not a minimal UP-set, so $A_1$ properly contains in $A_2$, the arc set of another UP-set $S_2$. Continuing in this fashion, we obtain the following properly nested sequence of arc sets of UP-sets:
\[ \mathcal{A} \supset \mathcal{A}_1 \supset \mathcal{A}_2 \supset \ldots \]

Since \( \mathcal{A} \) is a finite set, this nested sequence must terminate, implying that the final set is the arc set of a minimal UP-set contained in \( \mathcal{S} \); a contradiction.

**Lemma 5.2.** Let \( \mathcal{S} = \{P_1, P_2, \ldots, P_h\} \) be a minimal UP-set in a tournament \( T \). Let \( \mathcal{A} = \bigcup_{i=1}^{h} A(P_i) \) be the union of all arcs in the paths in \( \mathcal{S} \). Then, for all \( a \in \mathcal{A} \), there exists a cycle \( C \) such that \( C \cap (\mathcal{A} - \{a\}) = \emptyset \).

**Proof.** Suppose not. Then there exists \( a \in \mathcal{A} \) such that for any cycle \( C \) in \( T \), either \( C \cap \{a\} = \emptyset \) or \( C \) contains \( a \) and \( |C \cap \mathcal{A} - \{a\}| \geq 1 \). If every cycle in \( T \) avoids \( a \), then \( \mathcal{A} - \{a\} \) is the arc set of a UP-set properly contained in \( \mathcal{S} \), which contradicts the minimality of \( \mathcal{S} \).

Thus, every cycle \( C \) containing \( a \) must meet \( \mathcal{A} - \{a\} \) in at least one element. All such cycles will be eliminated upon reversing the arcs in \( \mathcal{A} - \{a\} \). If arc \( a \) does not contain the source nor the sink in \( T' \), the tournament obtained after reversing all arcs in \( \mathcal{A} \), then \( \mathcal{A} - \{a\} \) is the arc set of a UP-set properly contained in \( \mathcal{S} \); a contradiction.

Let \( a = uv \). If arc \( a \) contains both the source \( v \) and the sink \( u \) in \( T' \), then if \( x \) is any vertex other than \( u \) or \( v \), there is a cycle \( uwxu \) in \( T \) intersecting \( \mathcal{A} \) only in the arc \( a \); a contradiction.

Suppose arc \( a = uv \) contains exactly one of the source or the sink in \( T' \). Using symmetry, it suffices to assume that \( u \) is the sink in \( T' \). If there is no vertex \( y \) in \( T \) such that \( vy \) is an arc in \( T \) that is not in \( \mathcal{A} \). Then in \( T' \), \( v \) is a sink; a contradiction. Therefore, such an arc \( y \) exists. Since \( u \) is a sink in \( T' \), \( y \rightarrow u \) in \( T \) and \( wyu \) is a cycle in \( T \) disjoint from \( \mathcal{A} - \{a\} \); a contradiction.

The result now follows.

**Theorem 5.3.** Let \( T \) be a 2-critical tournament with at least one cycle and let \( \mathcal{S} = \{P_1, P_2\} \) be a minimal UP-set where \( P_1 \) and \( P_2 \) are both paths of length one. Then \( T \) is realizable as a 2-majority tournament.

**Proof.** Let \( P_1 : ab \) and \( P_2 : cd \). Let \( T' \) be the tournament obtained from the tournament \( T \) by reversing \( P_1 \) and \( P_2 \). We divide our argument into cases based on the cardinality of \( V - \{a, b, c, d\} \).
First, suppose $|V - \{a, b, c, d\}| = 0$. If, in $T'$, $d$ is the source and $c$ is the sink, then we have $b \rightarrow c$, $a \rightarrow c$, $d \rightarrow b$ and $d \rightarrow a$. Thus, in $T$, there is no cycle that contains $ab$ and not $cd$. This implies $cd$ is a UP-set of size one; contradicting the minimality of $S$. Similarly, it cannot be that $b$ is the source in $T'$ and $a$ is the sink in $T'$.

We deduce that, in $T'$, either $d$ is the source and $a$ is the sink, or $b$ is the source and $c$ is the sink. By symmetry, we may assume that $d$ is the source and $a$ is the sink in $T'$. If $b \rightarrow c$, then $\{abcd\}$ is a UP-set of size one; a contradiction. Therefore, $c \rightarrow b$. Then $T$ is acyclic, which is also a contradiction. From this, we conclude that $|V - \{a, b, c, d\}| \geq 1$.

Suppose $|V - \{a, b, c, d\}| = 1$ and let $V - \{a, b, c, d\} = \{u\}$. Up to symmetry, we must consider two scenarios: In $T'$, $d$ is the source and $c$ is the sink, and in $T'$, $d$ is the source and $a$ is the sink. If $d$ is the source and $c$ is the sink, then $d \rightarrow u$, $d \rightarrow a$, $d \rightarrow b$, $u \rightarrow c$, $a \rightarrow c$ and $b \rightarrow c$. By Lemma 5.2, there must be a cycle in $T$ containing the arc $ab$. It follows that $u \rightarrow a$ and $b \rightarrow u$. Then $T$ is realizable as a 2-majority tournament with the linear orderings $P_1$, $P_2$ and $P_3$ as shown in Figure 5.1.

\[\begin{align*}
P_1 &: d > u > a > b > c \\
P_2 &: b > u > a > c > d \\
P_3 &: c > d > a > b > u
\end{align*}\]

Figure 5.1: The tournament $T$ when, in $T'$, $d$ is the source and $c$ is the sink along with linear orderings that make $T$ realizable as a 2-majority tournament.

We may now assume that, in $T'$, $d$ is the source and $a$ is the sink, then $d \rightarrow u$, $d \rightarrow a$, $d \rightarrow b$, $u \rightarrow a$ and $c \rightarrow a$. By Lemma 5.2, there must be a cycle in $T$ containing
the arc $ab$ and not $cd$, and there must be a cycle in $T$ containing the arc $cd$ and not $ab$. It follows that $b \rightarrow u$ and $u \rightarrow c$. Therefore, it must be that $b \rightarrow c$. Otherwise, $bcub$ is a cycle which contradicts that $S$ is a minimal UP-set in $T$. Then $T$ is realizable as a 2-majority tournament with the linear orderings $P_1$, $P_2$ and $P_3$ as shown in Figure 5.2.

![Figure 5.2](image_url)

$P_1 : a > b > u > c > d$
$P_2 : c > d > u > a > b$
$P_3 : d > b > u > c > a$

Figure 5.2: The tournament $T$ when, in $T'$, $d$ is the source and $a$ is the sink along with linear orderings that make $T$ realizable as a 2-majority tournament.

Now suppose $|V - \{a, b, c, d\}| = k$. Up to symmetry, we must consider two scenarios: In $T'$, $d$ is the source and $c$ is the sink, and in $T'$, $d$ is the source and $a$ is the sink.

If $d$ is the source and $c$ is the sink, then $d \rightarrow a$, $d \rightarrow b$, $a \rightarrow c$ and $b \rightarrow c$. We partition $V - \{a, b, c, d\}$ into four sets of vertices. Let $U_1 = \{u \in V - \{a, b, c, d\} : a \rightarrow u \text{ and } b \rightarrow u\}$. Let $U_2 = \{u \in V - \{a, b, c, d\} : u \rightarrow a \text{ and } b \rightarrow u\}$. Let $U_3 = \{u \in V - \{a, b, c, d\} : u \rightarrow a \text{ and } u \rightarrow b\}$. Since, in $T'$, $d$ is the source and $c$ is the sink, $d \rightarrow U_1$, $d \rightarrow U_2$, $d \rightarrow U_3$, $U_1 \rightarrow c$, $U_2 \rightarrow c$ and $U_3 \rightarrow c$.

Each subtournament on the vertices in $U_j$ is acyclic, which gives us a natural ordering of the vertices in $U_j$: $\pi_j : x_{j,1} > x_{j,2} > x_{j,3} > \ldots > x_{j,s_j}$, where, by Lemma 2.4, $x_{j,1}, x_{j,2}, x_{j,3}, \ldots, x_{j,s_j}$ is a Hamiltonian forward path in the subtournament on $U_j$. The vertex $x_{j,1}$ is the source in $U_j$ and the vertex $x_{j,s_j}$ is the sink in $U_j$. We draw the
tournament $T$ in Figure 5.3.

By Lemma 5.2, there must be a cycle in $T$ containing the arc $ab$. It follows that there must be at least one vertex in $U_2$. Then $T$ is realizable as a 2-majority tournament with the linear orderings $P_1$, $P_2$ and $P_3$ as shown in Figure 5.3.

$$P_1 : d > \pi_3 > \pi_2 > a > b > \pi_1 > c$$
$$P_2 : \pi_3 > b > \pi_2 > a > \pi_1 > c > d$$
$$P_3 : c > d > \pi_3 > a > b > \pi_2 > \pi_1$$

Figure 5.3: The tournament $T$ when, in $T'$, $d$ is the source and $c$ is the sink along with linear orderings that make $T$ realizable as a 2-majority tournament.

We may now assume that, in $T'$, $d$ is the source and $a$ is the sink, then $d \to a$, $d \to b$ and $c \to a$. There will be two cases: $b \to c$ and $c \to b$.

If $b \to c$, then we partition $V - \{a, b, c, d\}$ into three sets of vertices. Let $V_1 = \{v \in V - \{a, b, c, d\} : b \to v \text{ and } c \to v\}$. Let $V_2 = \{v \in V - \{a, b, c, d\} : b \to v \text{ and } v \to c\}$. Let $V_3 = \{v \in V - \{a, b, c, d\} : v \to b \text{ and } v \to c\}$. Since, in $T'$, $d$ is the source and $a$ is the sink, $d \to V_1$, $d \to V_2$, $d \to V_3$, $V_1 \to a$, $V_2 \to a$ and $V_3 \to a$.

Each subtournament on the vertices in $V_j$ is acyclic, which gives us a natural ordering of the vertices in $V_j$: $\pi_j : x_{j,1} > x_{j,2} > x_{j,3} > ... > x_{j,s_j}$, where, by Lemma 2.4, $x_{j,1}, x_{j,2}, x_{j,3}, ..., x_{j,s_j}$ is a Hamiltonian forward path in the subtournament on $V_j$. 
The vertex $x_{j,1}$ is the source in $V_j$ and the vertex $x_{j,s_j}$ is the sink in $V_j$. We draw the tournament $T$ in Figure 5.4.

By Lemma 5.2, there must be a cycle in $T$ containing the arc $ab$ and not $cd$, and there must be a cycle in $T$ containing the arc $cd$ and not $ab$. It follows that either $V_2 \neq \phi$ or $V_1 \neq \phi$ and $V_3 \neq \phi$. Then $T$ is realizable as a 2-majority tournament with the linear orderings $P_1$, $P_2$ and $P_3$ as shown in Figure 5.4.

If $c \rightarrow b$, then we partition $V - \{a,b,c,d\}$ into three sets of vertices. Let $W_1 = \{w \in V - \{a,b,c,d\} : b \rightarrow w \text{ and } c \rightarrow w\}$. Let $W_2 = \{w \in V - \{a,b,c,d\} : w \rightarrow b \text{ and } c \rightarrow w\}$. Let $W_3 = \{w \in V - \{a,b,c,d\} : w \rightarrow b \text{ and } w \rightarrow c\}$. Since, in $T'$, $d$ is the source and $a$ is the sink, $d \rightarrow W_1$, $d \rightarrow W_2$, $d \rightarrow W_3$, $W_1 \rightarrow a$, $W_2 \rightarrow a$ and $W_3 \rightarrow a$.

Each subtournament on the vertices in $W_j$ is acyclic, which gives us a natural ordering of the vertices in $W_j$: $\pi_j : x_{j,1} > x_{j,2} > x_{j,3} > ... > x_{j,s_j}$, where, by Lemma
2.4. \( x_{j,1}, x_{j,2}, x_{j,3}, \ldots, x_{j,s_j} \) is a Hamiltonian forward path in the subtournament on \( W_j \). The vertex \( x_{j,1} \) is the source in \( W_j \) and the vertex \( x_{j,s_j} \) is the sink in \( W_j \). We draw the tournament \( T \) in Figure 5.5.

By Lemma 5.2, there must be a cycle in \( T \) containing the arc \( ab \) and not \( cd \), and there must be a cycle in \( T \) containing the arc \( cd \) and not \( ab \). It follows that \( W_1 \neq \phi \) and either \( W_2 \neq \phi \) or \( W_3 \neq \phi \). Then \( T \) is realizable as a 2-majority tournament with the linear orderings \( P_1 \), \( P_2 \) and \( P_3 \) as shown in Figure 5.5.

\[
\begin{align*}
P_1 &: a > \pi_3 > b > c > \pi_2 > d > \pi_1 \\
P_2 &: c > d > \pi_3 > \pi_2 > \pi_1 > a > b \\
P_3 &: d > \pi_3 > c > \pi_2 > b > \pi_1 > a
\end{align*}
\]

Figure 5.5: The tournament \( T \) when, in \( T' \), \( d \) is the source and \( a \) is the sink along with linear orderings that make \( T \) realizable as a 2-majority tournament.
Chapter 6

Conclusion

The property that 2-majority tournaments have a dominating set of size at most three motivates us to investigate what structures exist in a tournament $T$ that makes $T$ realizable as a 2-majority tournament. Let $T = (V, A)$ be a tournament with a set of vertices $V$ and a set of arcs $A$. Let $P : v_1v_2...v_k$ be a shortest upset path in $T$ of length $k - 1$. Let $T'$ be the tournament obtained from the tournament $T$ after reversing all arcs of $P$ in $T$.

Acyclic tournaments have one source and one sink. This property leads to some important results. First, if a tournament $T$ is acyclic, then $T$ has a Hamiltonian forward path. If a tournament $T$ is acyclic, then $T$ is realizable as a 2-majority tournament, and we have derived structures to build the three linear orderings $P_1, P_2$ and $P_3$ on $V(T)$. Let $|V(T)| \geq 3$. If $T$ has an upset path of length one, then $T$ is not acyclic. Let $P : v_1v_2...v_k$ be a shortest upset path in a tournament $T$, then the tournament on $V(T) - V(P)$ must be acyclic.

Moreover, our investigation of tournaments with upset paths has given us some structures that we can find in such tournaments. First, the arc $v_1v_2$ must be contained in a cycle that contains no other arcs in $P$. Also, the last arc in $P$, which is $v_{k-1}v_k$, must be contained in a cycle that contains no other arcs in $P$. Moreover, if $P$ is an upset path of length at least two in a tournament $T$, then there must exist at least two vertices in $V(T) - V(P)$. Moreover, there must exist distinct vertices $u$ and $w$ in $V(T) - V(P)$ such that $u \rightarrow v_2$ and $v_2 \rightarrow w$.

Our observation leads us to the following statements: First, for any tournament
such that $T$ has an upset path of length two or less, then $T$ is realizable as a 2-majority tournament, and we have derived structures to build the three linear orderings $P_1$, $P_2$ and $P_3$ on $V(T)$. Second, for any tournament $T$, such that $T$ has an upset path, then $T$ is realizable as a 2-majority tournament, and we have derived structures to build the three linear orderings $P_1$, $P_2$ and $P_3$ on $V(T)$. The linear orderings $P_1$, $P_2$ and $P_3$ depend on the parity of the number of vertices in $P$.

We also generalize the idea of the upset path in a tournament $T$. Let $S = \{P_1, P_2, ..., P_h\}$ be a UP-set in a tournament $T$, and let $\mathcal{A} = \bigcup_{i=1}^{h} A(P_i)$ be the union of all arcs in the paths in $S$. We have shown that every UP-set in $T$ contains a minimal UP-set. Moreover, if $S$ is a minimal UP-set in a tournament $T$, then for all $a \in \mathcal{A}$, there exists a cycle $C$ such that $C \cap (\mathcal{A} - \{a\}) = \phi$.

Let $T$ be a 2-critical tournament with at least one cycle and $S = \{P_1, P_2\}$ be a UP-set where $P_1$ and $P_2$ are both paths of length one. Then $T$ is realizable as a 2-majority tournament, and we have derived structures enabling us to build the three linear orderings $P_1$, $P_2$ and $P_3$ on $V(T)$.

Further studies must be done to find other structures in a tournament $T$ that, when present, imply $T$ can be realized as a 2-majority tournament. Something we would like to prove is that if a tournament $T$ is a 2-critical tournament with at least one cycle and $S = \{P_1, P_2\}$ is a UP-set, where $P_1$ is a path of length $m_1$, and $P_2$ is a path of length $m_2$, then $T$ is realizable as a 2-majority tournament.
Bibliography


