Multi-prover games and their parallel repetition

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June 2017

AN ESSAY PRESENTED TO AIMS RWANDA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE IN MATHEMATICAL SCIENCES

AIMS | African Institute for Mathematical Sciences RWANDA

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Contents

1. Introduction

Games are inherent to human nature and are present in all cultures. In a game there are: goals, rules, challenges, interactions, conflicts, skill, strategies and chance (McGonigal, 2011; Crawford, 1984). History shows that the scientific study of the chance to win a game or of making decisions under uncertainty and risks has given birth to what we call nowadays probability theory which has many applications (Freund, 2012). The mathematical study of rules of a game allows to compute the winning probability according to strategies used and to determine the optimal strategy and the existence of a solution.

The multi-prover games, introduced by Ben-Or, Goldwasser, Kilian, and Wigderson (1988) are the kind of games whose rules, strategies and outcomes have been mathematized. For this reason, a prover game is a mathematical game. A prover game is a game which is played between at least two players called provers against a referee called also a verifier. It is a concept originating from theoretical computer science.

Let us talk about what a prover game is by restricting it to only two players as an illustration. In effect, we consider that a two-prover game G is played between two provers 1 and 2 against the verifier ϕ. Let X and Y be respectively the set of questions addressed to players 1 and 2. We denote by S and T respectively sets of answers to question set X and Y. The verifier samples a couple of questions $(x, y) \in_\mu Q \subseteq X \times Y$ according to the probability distribution μ on Q and sends the question x to the prover 1 and y to the prover 2. Their answers can be accepted or rejected by the verifier ϕ, that is the verifier is a predicate defined from $X \times Y \times S \times T$ to $\{0, 1\}$. Both provers win the game if the verifier accepts both answers, that is if $\phi(x, y, f(x), g(y)) = 1$ where f and g are strategies used respectively by the prover 1 and the prover 2. Otherwise, they lose. Note that each prover does not know the question addressed to the other and communication during the games is not allowed. Nevertheless, before the game starts, they are allowed to agree on a strategy that can help them to increase the probability to win the game.

Thus, the probability to win this two-prover game is the probability of the verifier to accept both answers. Therefore, the value of the game G denoted by $\mathrm{val}(G)$ is the winning probability of provers 1 and 2 when they use the optimal couple (f, g) of strategies, namely: $\mathrm{val}(G) = \max_{f,g} \Pr[\phi(x, y, f(x), g(y)) = 1]$.

Ben-Or, Goldwasser, Kilian, and Wigderson (1990) presented a concrete application in real life of what can mean two provers and the verifier. He considered that the verifier is the Bank, which interacts with two untrusted provers, for instance two bank identification cards. The two provers can jointly agree on a strategy to convince the verifier of their identity. However, to believe the validity of their identity proving procedure, the verifier must make sure that the two provers can not communicate with each other during the course of the proof process.

Similarly, given such two-prover game G played between two provers 1 and 2 against a verifier. Let n be a natural number greater than 1. Based on the two-prover game G, we can construct another game G^n called *$n-$fold parallel repetition of G* or *product game G^n*. In this game, the verifier samples independently n questions for each of the prover 1 and 2. He sends them all at once and receives n answers. The two provers win if the verifier accepts on all n instances, that is when n copies of the game G are won simultaneously. Thus, the value of the $n-$*fold parallel repetition of* G denoted by $\mathrm{val}(G^n)$ is the maximum success probability over all possible couple of strategies. Given $\mathrm{val}(G)$ for some non-trivial game, the determination of $\mathrm{val}(G^n)$ seems not to be simple. Raz (1998) gave an upper bound of $\mathrm{val}(G^n)$. This upper bound continues to be improved (Holenstein, 2007; Raz and Rosen, 2012; Dinur and Steurer, 2014; Dinur, Harsha, Venkat, and Yuen, 2016). The definition of two-prover games can be expanded similarly to multi-prover games. However, a general result like Raz (1998) is not known for multi-prover games.

Parallel repetition of prover games finds its application in many areas: hardness of approximation, cryptography, quantum mechanics, interactive proof systems, probabilistically checkable proofs Tamaki (2015); Dinur, Harsha, Venkat, and Yuen (2016). That is, a main application of prover games is in proving that certain computational problems are difficult not only to solve exactly but also to approximate.

Furthermore, mathematical games, namely games for which rules, strategies and outcomes have been mathematized are related to the number theory, which in turn is related to arithmetic combinatorics. Verbitsky (1996) gave a general upper bound of the parallel repetition of two prover games by applying the density version of the Hales-Jewett theorem from the field called additive combinatorics. Tao and Vu (2006) describe additive combinatorics as " *a marriage of number theory, harmonic analysis, combinatorics, and ideas from ergodic theory, which aims to understand very simple systems: the operations of addition and multiplication and how they interact*". Additive combinatorics is also known for its famous theorems like: Van der Waerden's theorem, Szeméredi's theorem and Green-Tao theorem on the sequence of prime numbers.

The density version of the Hales-Jewett theorem states that given natural number k, r, there exists a natural number $DHJ(k, r)$ such that every $n \geq DHJ(k, r)$ and every subset A of the set $\{1, 2, \ldots, k\}^n$ with density at least δ contains a combinatorial line (Polymath, 2012).

Thus, the aim of this research is to analyse the relationship between the Hales-Jewett theorem and the parallel repetition of multi-prover games. Specifically, first this study explores what the Hales-Jewett theorem is and what parallel repetition of multi-prover games is. Then, the study generalizes some notions defined for two-prover games to multi-prover games. Finally, this study shows that Hales-Jewett theorem implies parallel repetition and also parallel repetition implies the Hales-Jewett theorem.

By establishing the connection between parallel repetition of multi-prover games and the density version of the Hales-Jewett theorem, we want to show that we can always find a result that connects disparate fields of mathematics.

This research is composed of four chapters where the introduction is the first chapter. In chapter 2, an exploration on the Hales-Jewett theorem is presented. These implications are shown: Hales-Jewett theorem implies Van der Waerden's theorem, Hales-Jewett theorem implies Szemerédi's theorem and Szemerédi's theorem implies Van der Waerden's theorem. Chapter 3 deals with the parallel repetition of multi-prover games. Also, a generalisation of known notions on two-prover games is presented. Chapter 4 analyses the relationship between parallel repetition of multi-prover games and the Hales-Jewett theorem. We prove these two implications between parallel repetition of multi-prover games and the density version of Hales-Jewett theorem.

2. On the Hales-Jewett theorem

In this part, some notions about the Hales-Jewett theorem are presented. Firstly, we start with some basic notions on arithmetic progression, which are important for understanding the next point. After, we introduce some elementary notions about Van der Waerden's theorem and Szemerédi's theorem. We highlight that Van der Waerden's theorem is a particular case of Szemerédi's theorem. Ultimately, we present the two forms of the Hales-Jewett theorem and link these one to the two first theorems.

2.1 Arithmetic progression

2.1.1 Definition. Let $a_1, a_2, \ldots, a_n, \ldots$ be a sequence of numbers.

This sequence of numbers forms an **arithmetic sequence** if every term of this sequence is obtained by adding a constant to the previous term.

The constant is simply the difference between two consecutive terms.

If a_1 and a_n represent the first and the $n-$th term of a sequence, and d the constant, then the general term a_n of this sequence is expressed as:

$$a_n = a_1 + (n-1)d.$$

Knowing a_m and the constant d, then a_n can be expressed as:

$$a_n = a_m + (n-m)d.$$

2.1.2 Arithmetic progression of length k. Let a and d be two fixed numbers.

An arithmetic progression of length k is an arithmetic sequence of k numbers of the form $a + nd$. a is the first term of the arithmetic progression, d is the difference between two consecutive terms and $n = 0, 1, \ldots, k-1$, that is, we have k consecutive values of n.

We denote by AP(k) or AP$-k$ or $k-$AP, the arithmetic progression of length k.

2.2 Van der Waerden's theorem

Before stating the Van der Waerden's theorem, let us introduce and define some concepts and notation.

A *partition* of a set A is a collection of nonempty and mutually disjoint subsets A_i of A, such that $A = \cup A_i$ and $A_i \cap A_j = \emptyset, \quad i \neq j$. Thus, a partition is also a sequence $A_1, A_2, \ldots, A_n$ of mutually nonempty and disjoint subsets of set A. A_i are known as *blocks*.

We denote by $\mathbb{Z}^+$, the set of positive integers. Let $m \in \mathbb{Z}^+$, we designate by $[m]$ the set $\{1, 2, \ldots, m\}$.

Let X be a set and r be a positive integer. We want to colour elements of set X with r colours. If C represents the set of colours, then $|C| = r$ is the number of colours.

2.2.1 Definition. An r-colouring of X is a mapping $c : X \longrightarrow [r]$.

If $|X| = n$, then the number of r-colorings of X is n^r.

Let Y be a subset of X. We say that Y is *monochromatic* when the restriction $c\restriction_Y$ is constant, that is if $c(y)$ is the same for every $y \in Y$.

According to Polymath (2012), the Van der Waerden's theorem is stated as follows:

2.2.2 Theorem (Van der Waerden). *For every pair $(k, r) \in \mathbb{Z}^+ \times \mathbb{Z}^+$, there exists $N_0 \in \mathbb{Z}^+$ such that for every $N \geq N_0$ and for every r-colouring of $[N]$ there is a monochromatic arithmetic progression of length k.*

We know that an r-colouring is a function called c in definition (2.2.1). So, in other words we can find at least one subset of $\{1, 2, \ldots, N\}$ with $k-$elements such that all elements have the same colour and form an arithmetic progression of length k. That is, there exist $a, d \ \in \mathbb{N}$ with $d \neq 0$ such that: $c(a) = c(a+d) = c(a+2d) = \ldots = c(a+(k-1)d)$ where $a, a+2d, \ldots, a+(k-1)d$ are elements of the subset.

The Van der Waerden's theorem can also be formulated using partition (Dransfield et al., 2004) as:

2.2.3 Theorem (Van der Waerden). *For every $k, r \in \mathbb{Z}^+$, there exists $N_0 \in \mathbb{Z}^+$ such that for every $N \geq N_0$ and for every partition $A_1, \ldots, A_r$ of $[N]$, there is i, $1 \leq i \leq r$, such that the block A_i contains an arithmetic progression of length k.*

Note that for this version a block in a partition can be empty.

The existence of the number N_0 for which any r-colouring of the integer $\{1, \ldots, N_0\}$ is certain to have a monochromatic subset of cardinality k of which elements form an arithmetic progression was demonstrated constructively in 1927 by Bartel Leendert Van der Waerden (Van der Waerden, 1927).

Graham and Rothschild (1974) gave *another* proof of this theorem. The book entitled "*Purely Combinatorial Proofs of Van der Waerden-Type Theorem*" written by Gasarch et al. (2010) condenses the proof of Van der Waerden theorem.

In this theorem, to find the number N even showing that N_0 is not trivial are difficult. The least such number N_0 is called *Van der Waerden number* denoted as $W(k, r)$. In the rest of this chapter, we will use $W(k, r)$ or simply W to denote the least Van der Waerden number instead of N_0.

The general expression of $W(k, r)$ is not known, but for some k and r there are exact values known or there are some approximations of the lower or upper bound of $W(k, r)$ (Dransfield et al., 2004).

$W(1,r)$, $W(k,1)$ and $W(2,r)$ are known as *trivial* Van der Waerden numbers. So,

- $W(1,r) = 1$: the set of all subsets of a nonempty set contains necessary a singleton. A singleton forms an arithmetic progression of length 1 where the difference between two consecutive numbers is 0. To form a monochromatic arithmetic progression of length 1 by r-colouring a set, we need a set of at least one element.
- $W(k,1) = k$: by colouring a set with one colour, we automatically get a monochromatic arithmetic progression of length equals to the cardinality of the set.
- $W(2,r) = r+1$: to obtain a monochromatic arithmetic progression of length 2 by r-colouring a set, we need a set of at least $r+1$ elements.

For instance, let us find the Van der Waerden number $W(3,2)$, that is an number $W(3,2)$ such that every $2-$colouring of the set $[W(3,2)]$ contains a monochromatic arithmetic progression of length 3.

The value of $W(3,2)$ is greater than 8 because for any $2-$colouring of $[n]$, $n \in \{3,4,5,6,7,8\}$, we can find a $2-$colouring which does not contain a monochromatic arithmetic progression of length 3. For instance, the set $\{1,2,\ldots,8\}$ does not contain a monochromatic arithmetic progression of length 3 by $2-$colouring the set like in the table (2.1).

So, when $W(3,2) = 9$ we always find a monochromatic arithmetic progression of length 3 for any $2-$colouring of $[9]$. The table (2.1) shows one of the possibilities of colouring $\{1,2,3,4,5,6,7,8,9\}$. If the ninth number is blue, then 3, 6, 9 form an arithmetic progression. If the ninth number is red, then 1, 5, 9 form an arithmetic progression. Therefore, by adding a ninth number and colouring it using any of the two colors, we always create a monochromatic arithmetic progression of length 3.

1	2	3	4	5	6	7	8	9
R	B	B	R	R	B	B	R	

Table 2.1: A $2-$colouring of $\{1,2,\ldots,9\}$

The table (2.2) presents the 7 exact non-trivial Van der Waerden numbers (when $k \geq 3$) (Dransfield et al., 2004).

$k \setminus r$	2	3	4
3	9	27	76
4	35	293	
5	178		
6	1132		

Table 2.2: The 7 exact non-trivial values of Van der Waerden numbers.

As related previously, searching for the exact value of $W(k,r)$ remains an open problem. The number $W(k,r)$ becomes hard to find when the values of k and r increase. However, for some k and r there is an approximation of the lower or upper bound of $W(k,r)$ (Stevens and Shantaram, 1978; Herwig et al., 2007; Beeler and O'neil, 1979; Dransfield et al., 2004; Brown et al., 2008; Rabung and Lotts, 2012; Kouril and Paul, 2008). The table (2.3) summarizes these known lower bounds and includes the seven non-trivial Van der Waerden numbers known exactly.

k \ r	**2**	**3**	**4**	**5**	**6**
3	9	27	76	>170	>223
4	35	293	>1,048	>2,254	>9,778
5	178	>2,173	>17,705	>98,740	>98,748
6	1,132	>11,191	>91,331	>540,025	>816,981
7	>3,703	>48,811	>420,217	>1,381,687	>7,465,909
8	>11,495	>238,400	>2,388,317	>10,743,258	>57,445,718
9	>41,265	>932,745	>10,898,729	>79,706,009	>458,062,329
10	>103,474	>4,173,724	>76,049,218	>542,694,970	>2,615,305,384
11	>193,941	>18,603,731	>305,513,57	>2,967,283,511	>3,004,668,671

Table 2.3: Some lower bounds and exact non-trivial values of Van der Waerden numbers $W(k,r)$.

The estimation of lower and upper bounds is also an open problem. There exist some expressions that bound Van der Waerden numbers. Researchers are still looking for closer bound or exact general expression of these numbers. Erdos and Rado (1952), cited by Dransfield et al. (2004) established an inequality for the lower bound for $W(k,r)$.

$$\left[2(k-1)r^{k-1}\right]^{\frac{1}{2}} < W(k,r). \tag{2.2.1}$$

Berlekamp (1968) found a better bound when $k-1$ is a prime number and for $r=2$. But these bounds still require improvement.

$$(k-1)2^{k-1} < W(k,2). \tag{2.2.2}$$

Hence, for $p=k-1$, the expression (2.2.2) becomes:

$$p2^p < W(p+1,2). \tag{2.2.3}$$

So, $W(6,2) > 5 \times 2^5 = 160$, $W(8,2) > 7 \times 2^7 = 896$ and $W(12,2) > 11 \times 2^1 1 = 22528$. (Dransfield et al., 2004) improve this lower bound by using propositional satisfiability solvers for some small Van der Waerden numbers, for instance $W(8,2) > 1322$. Rabung and Lotts (2012) performs more. Thus, as related in table (2.3), most of the lower bounds used, came from Rabung and Lotts (2012).

The best known upper bound of $W(k,r)$ is the expression (2.2.4) which came from the work of Gowers (2001) on a new proof of the Szemerédi's theorem. Section (2.3) will talk about this theorem. The Szemerédi's theorem is the extension of the Van der Waerden's theorem, that is the Van der Waerden's theorem is implied by the Szemerédi's theorem:

$$W(k,r) \leq 2^{2^{r^{2^{2^{k+9}}}}} \tag{2.2.4}$$

2.3 Szemerédi's theorem

The Szemerédi's theorem is merely another formulation of the Van der Waerden's theorem in terms of *density version*. Below, we show that the Szemerédi's theorem implies the Van der Waerden's theorem.

Let us consider A a nonempty subset of the set $[N]$. The density of A inside $[N]$ is a positive real number $\delta = \frac{|A|}{N}$. It is clear that $0 < \delta \leq 1$.

The theorem (2.3.1) is the famous Szemerédi's theorem. Famous because the various proofs of the Szemerédi's theorem connect disparate fields of mathematics (combinatorics, harmonic analysis, ergodic theory, number theory, ...). Arana (2015) analysed the depth of th Szemerédi's theorem by assembling the thoughts of some mathematicians (like Erdos and Terence Tao) about the major accomplishment of this theorem. According to Polymath (2012), the Szemerédi's theorem is formulated as:

2.3.1 Theorem (Szemerédi's theorem). *For every $k \in \mathbb{Z}^+$ and every $0 < \delta \leq 1$ there exists an integer $N_0(k, \delta) \geq 1$ such that for every $N \geq N_0$ and every subset $A \subseteq [N]$ of size $|A| \geq \delta N$ contains an arithmetic progression of length k.*

The Szemerédi's theorem has a formulation which uses the notion of positive upper density.

Let A be a subset of the integers $\mathbb{Z}$ with positive upper density, that is, satisfying

$\limsup\limits_{N\to\infty} \frac{|A\cap[-N,N]|}{|[-N,N]|} > 0$. Then, for any $k \geq 3$, A contains infinitely many arithmetic progressions of length k.

As conjecture, the Szemerédi's theorem was formulated by Erdös and Turán (1936). There are several proofs of this theorem. The cases $k = 1$ and $k = 2$ are trivial. Roth (1953, 1970) proved the case $k = 3$. The case $k = 4$ was proved by Szemerédi (1969) and he gave the general case (Szemerédi, 1975).

Some of proofs necessitated the use of other theories external to combinatorics. Thus, the ergodic theory (*theory related to dynamical system with invariant measures and chaos theory*) has been used to prove this theorem by Furstenberg (1977); Furstenberg, Katznelson, and Ornstein (1982). Gowers (1998, 2001) used Fourier analysis and the inverse theory of additive combinatorics to show this theorem. A few years later Gowers (2007) used a hypergraph regularity lemma to prove this theorem. A quantitative ergodic theory proof, version of Furstenberg et al. (1982) has been presented by Tao (2006) which does not involve some concepts used in the previous proofs: the axiom of choice, the use of infinite sets or measures, the use of the Fourier transform or inverse theorems from additive combinatorics.

2.3.2 The Szemerédi's theorem implies the Van der Waerden's theorem..

Proof. Let us assume that the Szemerédi's theorem (2.3.1) is true, that is $\forall k \in \mathbb{Z}^+$, $0 < \delta \leq 1$, $\exists N_0(k, \delta) \in \mathbb{Z}^+ / \forall N \geq N_0$ and $\forall A \subseteq [N]$, $|A| \geq \delta N$ contains an arithmetic progression of length k. So, the aim is to show the Van der Waerden's theorem from the Szemerédi's theorem. This means to show that by r-colouring the set $\{1, 2, \ldots, N\}$, we obtain at least one monochromatic arithmetic progression of length k.

Let us notice that we have shown (2.2.2) and (2.2.3) that r-colouring a set is to partition it to r blocks.

Let $A_1, A_2, \ldots, A_r$ be a partition of the set $\{1, \ldots, N\}$ in r blocks, that is $\{1, \ldots, N\} = A_1 \cup A_2 \cup \ldots \cup A_r$. Sometimes a block can be empty for this r-colouring. For instance, it occurs when $r > N$, that is the number of colors is bigger than the number of elements of the set to colour. When $r < N$, it is obvious that there exist two blocks with the same colour. Note that the color of the block A_i is indicated by the number i for $1 \leq i \leq r$.

Let A_{max} be the set having the largest number of elements. For example, by partitioning $\{1, \ldots, N\}$ into r equal parts, the cardinality of the largest set is: $A_{max} = A_i = \frac{N}{r}$.

Let us show that the cardinality of every A_i cannot be less than $\frac{N}{r}$. Let us assume that $|A_i| < \frac{N}{r}$, then $|A_1| + |A_2| + \ldots + |A_r| < \frac{N}{r} + \ldots + \frac{N}{r} = \frac{rN}{r} = N$, that is $\displaystyle\sum_{i=1}^{r} |A_i| < N$. Therefore, for $1 \leq i \leq r$, in this case A_i does not form a partition which is a contradiction.

Hence, the cardinality of some of A_i is greater or equal to $\frac{N}{r}$. Obviously, the cardinality of A_{max} is greater or equal to the cardinality of A_i, that is $|A_{max}| \geq |A_i|$, for $1 \leq i \leq r$. So,

$$\begin{aligned} |A_1| + |A_2| + \ldots + |A_r| = N &\Longrightarrow |A_{max}| + |A_{max}| + \ldots + |A_{max}| \geq N \\ &\Longleftrightarrow r|A_{max}| \geq N \\ &\Longleftrightarrow |A_{max}| \geq \frac{1}{r}N \\ &\Longleftrightarrow |A_{max}| \geq \delta N \end{aligned}$$

where $\delta = \frac{1}{r}$. As $|A_{max}| \geq \delta N$ for $N \geq N_0(k, 1/r)$ and according to the Szemerédi's theorem (2.3.1) the subset A_{max} contains an arithmetic progression of length k. Note that A_{max} is monochromatic because it has been obtained by r-colouring the set $\{1, 2, \ldots, N\}$. Therefore, A_{max} is a monochromatic arithmetic progression of length k. □

This proof show that we can obtain Van der Waerden's theorem from Szemerédi's theorem when $\delta = \frac{1}{r}$.

2.3.3 Quantitative bounds of the Szemerédi's theorem. In the previous section (2.3.2) we have shown that the Van der Waerden's theorem is a particular case of the Szemerédi's theorem. This implies that the Szemerédi's number $N(k, \delta)$ is greater or equal to the Van der Waerden's number $W(k, r)$ when $\delta = \frac{1}{r}$. There is still no general exact expression of $W(k, r)$, but we have shown previously that only the exact value of 7 non-trivial Van der Waerden numbers are known for some smaller k and r. For the remaining cases there are only some approximations of the lower and upper bounds.

As for Van der Waerden's numbers, the general expression of Szemerédi's numbers $N(k, \delta)$ is not known. The search for this number is an open problem. However, there are some quantitative approximations of the lower and upper bounds of Szemerédi's numbers. The following definition will be helpful for the approximation of the lower and upper bounds of Szemerédi's numbers $N(k, \delta)$.

2.3.4 Definition. Let $N = N(k, \delta)$ be the Szemerédi's number. Let V be the largest subset of $\{1, 2, \ldots, N\}$ without an arithmetic progression of length k. We denote by $r_{k,N}$ the size of the set V, that is $r_{k,N} = |V|$.

The *density of* V denoted by $\delta_{k,N}$ is defined as: $\delta_{k,N} = \frac{|V|}{N}$. We call $\delta_{k,N}$ the *density Szemerédi's number*. Sometimes, the number $r_{k,N} = |V|$ is also called *density Szemerédi's number*.

In the following expressions for the estimation of lower and upper bounds of $\delta_{k,N}$, the logarithms used are binary.

Lower bound Behrend (1946) constructed the lower bound of the density of the largest subset of $\{1, 2, \ldots, N\}$ that contains no arithmetic progression of length $k = 3$. He proved that for any $\epsilon > 0$ and for an unspecified positive constant :

$$\delta_{3,N} \geq \frac{C}{2^{2\sqrt{2}(1+\epsilon)\sqrt{\log N}}} \tag{2.3.1}$$

Elkin (2010) improved the result of Behrend (2.3.1) by a factor $\Theta(\sqrt{\log N})$[1] and showed that:

$$\delta_{3,N} \geq \frac{C(\log N)^{1/4}}{2^{2\sqrt{2}\sqrt{\log N}}} \tag{2.3.2}$$

For $k \geq 1 + 2^{n-1}$, $n = \lceil \log k \rceil$, Robert Alexander Rankin in 1961, cited by O'Bryant (2011) proved that for $\epsilon > 0$, if N is sufficiently large then:

$$\delta_{k,N} \geq \frac{C}{2^{n 2^{(n-1)/2}(1+\epsilon)\sqrt[n]{\log N}}} \tag{2.3.3}$$

Basing on (2.3.1), (2.3.2) and (2.3.3), O'Bryant (2011) constructed a general lower bound (2.3.4) for the density of the largest subset of $\{1, 2, \ldots, N\}$ that contains no arithmetic progression of length k.

$$\delta_{k,N} \geq C_k 2^{-n 2^{(n-1)/2}\sqrt[n]{\log N} + \frac{1}{2n}\log\log N} \tag{2.3.4}$$

where $C_k > 0$ is an unspecified constant. The expression (2.3.4) is presently the best known lower bounds for all k.

Upper bound Gowers (2001) worked on a new proof of Szemerédi's theorem and presented that the upper bound of the density of the largest subset of $\{1, 2, \ldots, N\}$ that contains no arithmetic progression of length k is:

$$\delta_{k,N} \leq (\log\log N)^{-2^{-2^{k+9}}} \tag{2.3.5}$$

[1] The big Theta (Θ) expresses the tight asymptotic bounds, that is the intersection of the upper asymptotic bounds (big-O) and the lower asymptotic bounds (big-Ω)

Bloom (2016) improved the upper bound for $k = 3$:

$$\delta_{3,N} \leq C\frac{(\log \log N)^4}{\log N}. \tag{2.3.6}$$

For $k = 4$, Green and Tao (2006) improved the result (2.3.5) of Gowers (2001) as follows:

$$\delta_{4,N} \leq CNe^{-c\sqrt{\log \log N}} \tag{2.3.7}$$

for some absolute constant $c > 0$.

2.4 Hales-Jewett theorem and its density version.

Before announcing the Hales-Jewett theorem and its density version, let us introduce and define notions about combinatorial lines. Combinatorial line is for Hales-Jewett theorem what arithmetic progression is for Van der Waerden's theorem, that is Hales-Jewett theorem is based on structures called combinatorial lines.

Let k and n be two positive integers.

We know that $[k]^n = \underbrace{[k] \times [k] \times \ldots \times [k]}_{n \text{ set-factors of } [k]} = \{(x_1, x_2, \ldots, x_n) : \ x_i \in [k]\}$. The set $[k]^n$ contains k^n elements.

For instance, for $k = 3$ and $n = 2$, $[3]^2 = \{11, 12, 13, 21, 22, 23, 31, 32, 33\}$. For $k = 3$ and $n = 6$, an element of the set $[3]^6$ is : 121132. In total, in the set $[3]^6$ there are 729 different elements.

Let us consider the set $([k] \times \{x\})^n$. Similarly, the set $([k] \times \{x\})^n$ contains $(k+1)^n$ elements. x is called *wildcard*.

Given $k, n \in \mathbb{N}$, we call x*-string* (or n-dimensional *variable word* with k letters or alphabets), a finite word $a_1a_2 \ldots a_n$ of the symbols $a_i \in [k] \cup \{x\}$, where at least one symbol a_i is x. We denote an x-string by $w(x)$. Let D denote the set of all strings: $D = \{w(x)\}$. The cardinality of D is: $D = (k+1)^n - k^n$.

For any integer $i \in [k]$ and x-string $w(x)$, we denote by $w(x; i)$ the string obtained from $w(x)$ by replacing each x by i.

2.4.1 Definition. A *combinatorial line* is a set of k strings $\{w(x; i) : \ i \in [k]\}$ where $w(x)$ is an x-string .

That is a combinatorial line is a set of k finite words obtained by replacing x in the word $w(x; i)$ by $i \in \{1, 2, \ldots k\}$. A combinatorial line can also be written as a $k \times n$ matrix in this case, where columns are composed either by $(a_ia_i \ldots a_i)^T$ or by $(12\ldots)^T$ (T denotes transpose).

For instance, the number of combinatorial lines in $[3]^2 = \{11, 12, 13, 21, 22, 23, 31, 32, 33\}$ is $(3+1)^2 - 3^2 = 16 - 9 = 7$. These 7 combinatorial lines are given in figure (2.1) which correspond

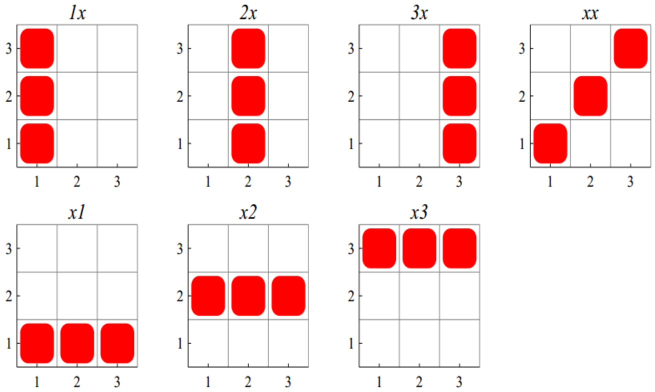

Figure 2.1: Combinatorial lines in $[3]^2$ (Source: Polymath (2010))

each to the winning position of a tic-tac-toe game. Note that the diagonal winning position $\{13, 22, 31\}$ in a tic-tac-toe is not a combinatorial line.

For $k = 3$ and $n = 8$, a combinatorial line over alphabets $\{1, 2, 3\}$ for the word $w(x) = 1xx2x23x$ is the set : $\{w(x; i) = 1ii2i23i\ :\ i \in [3]\} = \{11121231, 12222232, 13323233\}$. As matrix representation, this combinatorial line can be expressed as:

$$\begin{pmatrix} 1 & 1 & 1 & 2 & 1 & 2 & 3 & 1 \\ 1 & 2 & 2 & 2 & 2 & 2 & 3 & 2 \\ 1 & 3 & 3 & 2 & 3 & 2 & 3 & 3 \end{pmatrix}$$

Sets which do not contain any combinatorial lines are called *line-free*. So, according to Polymath (2012), the Hales-Jewett is stated as:

2.4.2 Theorem (Hales-Jewett theorem). *For every pair of positive integers k and r there exists a positive number $HJ(k, r)$ such that for every $n \geq HJ(k, r)$ and every r-colouring of the set $[k]^n$ there is a monochromatic combinatorial line.*

There are several proofs of the Hales-Jewett theorem. The original proof has been given by Hales and Jewett (1987). Shelah (1988) proved a primitive recursive[2] bound for the Hales-Jewett number using simple induction. Nilli (1990) presented a compact form of Shelah's Proof of the Hales-Jewett Theorem. This condensed form states that for every $k, r \geq 1$, $HJ(k, r) \leq \frac{1}{kr} h_4(k + m + 2)$ with h_i is a function defined as: $h_1(n) = 2n$; for $i > 1$, $h_i = h_{i-1}(h_{i-1}(\dots h_{i-1}(1)))$ where h_{i-1} is taken n times.

Matet (2007) gave a variant of Shelah's proof of the Hales–Jewett theorem by replacing Shelah's pigeonhole lemma by an appeal to the Ramsey's theorem.

The Hales-Jewett theorem has also a density version. By considering a nonempty subset A of the set $[k]^n$, the density of A inside $[k]^n$ is a positive real number $\delta = \frac{|A|}{k^n}$. Values of δ are bounded by 0 and 1, specifically $0 < \delta \leq 1$.

[2] Primitive recursion is a procedure that defines the value of a function at an argument n by using its value at the previous argument $n - 1$. In a computer, a primitive recursive bound can be implemented only using do-loops (see https://plato.stanford.edu/entries/recursive-functions/#1.3).

Let denote by $DHJ(k,\delta)$ the density Hales-Jewett number. The density version of the Hales-Jewett theorem is announced according to Polymath (2012) as follows:

2.4.3 Theorem (Density version of Hales-Jewett theorem). *For any $k \in \mathbb{Z}^+$ and any real number $0 < \delta \leq 1$, there exists a positive integer $DHJ(k,\delta)$ such that if $n \geq DHJ(k,\delta)$ and A is any subset of $[k]^n$ with $|A| \geq \delta k^n$, then A contains a combinatorial line.*

The proof of the density version of the Hales-Jewett theorem has been demonstrated by Furstenberg and Katznelson (1991) using ergodic methods[3]. Polymath (2012) gave an elementary non-ergodic proof of the density version of the Hales-Jewett theorem by giving a quantitative bound on how large n needs to be and qualified this theorem as one of the fundamental results of Ramsey theory. A simplified version of Polymath (2012) has been given by Dodos et al. (2013) using a purely combinatorial proof of the density Hales–Jewett Theorem.

There are four important theorems we have talked about: the Van der Waerden's theorem (2.2.2), the Szemerédi's theorem (2.3.1), the Hales-Jewett theorem (2.4.2) and the density Hales-Jewett theorem (2.4.3). In (2.3.2) we have shown that the Szemeredi's theorem implies the Van der Waerden's theorem. It is reasonable to show these three implications: the density version of the Hales-Jewett theorem implies the Hales-Jewett theorem, the Hales-Jewett theorem implies the Van der Waerden's theorem, and the density version of the Hales-Jewett theorem implies the Szemerédi's theorem.

2.4.4 Density version of the Hales-Jewett theorem implies the Hales-Jewett theorem. To show that this density version of Hales-Jewett theorem implies the Hales-Jewett theorem, we need only to set as in (2.3.2), $\delta = \frac{1}{r}$. By r-colouring the set $[k]^n$, that is by partitioning to r classes, if A_{max} is the set containing the maximum number then $|A_{max}| \geq \frac{k^n}{r} = \delta k^n$. Hence, according to (2.4.3), A_{max} contains a combinatorial line.

2.4.5 Hales-Jewett theorem implies Van der Waerden's theorem. To show that the Hales-Jewett theorem implies Van der Waerden's theorem, we need only to show that combinatorial line corresponds to the arithmetic progression.

Let us assume that the Hales-Jewett theorem is true and show that the combinatorial line of k elements contained to the subset A corresponds to the arithmetic progression of length k.

We have defined $[k]$ as the set $\{1, 2, \ldots, k\}$. Instead to start by 1, let us start by 0. In this part, $[k]$ expresses the set $\{0, 1, \ldots, k-1\}$. It is obvious that $[k] = \mathbb{Z}/k\mathbb{Z}$.

Let n be the positive number of the Hales-Jewett theorem, that is $n \geq HJ(k,r)$, then the set $[k]^n = (\mathbb{Z}/k\mathbb{Z})^n = \{(y_0, y_1, \ldots, y_{n-1}) : \ y_i \in [k]\}$ has k^n elements. Similarly, $[k^n] = \{0, 1, \ldots, k^n - 1\}$ has also k^n elements. Note that the set $[k^n]$ contains natural number. While, elements of the set $[k]^n$ can be interpreted as the digits in base$-k$ number system of the numbers $\{0, 1, \ldots, k^n - 1\}$.

Let us consider the bijection $f : [k]^n \longrightarrow [k^n]$ defines as follows:

[3] Ergodic theory studies dynamical systems with an invariant measure and related problems. Ergodic theory can be described as the statistical and qualitative behavior of measurable group and semigroup actions on measure spaces.

$$f(y_0, y_1, \ldots, y_{n-1}) = y_0 + y_1 k + y_2 k^2 + \ldots + y_{n-1} k^{n-1}.$$

Let $w(x) \in ([k] \cup \{x\})^n \setminus [k]^n$ be an x-string. The combinatorial line generates by $w(x)$ is a set of k elements defined by $\{w(x; i) : i \in [k]\}$.

Let $w(x; i)$ and $w(x; i + 1)$ be two consecutive elements of the combinatorial line generates by $w(x)$. We denote $w(x; i) = (y_{0,i}, y_{1,i}, \ldots, y_{n-1,i})$ and $w(x; i + 1) = (y_{0,i+1}, y_{1,i+1}, \ldots, y_{n-1,i+1})$ where the elements $y_{j,i} \in [k]$ for $0 \leq j \leq n - 1$ and $0 \leq i \leq k - 1$.

So, it is obvious that $w(x; i)$ is a vector. By definition of addition in a vector space, the difference between two consecutive elements $w(x; i)$ and $w(x; i+1)$ of this combinatorial line is a constant (vector). Let us call this constant $l = (l_0, l_1, \ldots, l_{n-1}) = w(x; i + 1) - w(x; i)$.

For $j \in \{0, 1, \ldots, n - 1\}$, l_j has two values: $l_j = \begin{cases} 1 & \text{if } y_{j,i} \neq y_{j,i+1} \\ 0 & \text{if } y_{j,i} = y_{j,i+1} \end{cases}$.

Let $w(x; 0) = (y_{0,0}, y_{1,0}, \ldots, y_{n-1,0})$ be the first element of the combinatorial line generated by $w(x)$. Then, for $0 \leq i \leq k - 1$ an element $w(x; i)$ of the combinatorial line can be expressed as:

$$w(x; i) = w(x; 0) + il.$$

Let us call a the image of $w(x; 0)$ by f, that is $a = f(w(x; 0))$ and d the image of l by f, that is $d = f(l)$. a and d are both integers. We denote by J the set $\{j : \ y_{j,i} \neq y_{j,i+1}\}$. The integer d can be expressed as:

$$d = f(l) = l_0 + l_1 k + \ldots + l_{n-1} k^{n-1} = \sum_{j=0}^{n-1} l_j k^j = \sum_{j \in J} k^j.$$

Thus, $f(w(x; i)) = a + id$, a and d fixed, $0 \leq i \leq k - 1$. Hence, the set $\{a + id : \ i \in [k]\}$ forms an arithmetic progression of length k. So, for any combinatorial line of k elements corresponds an arithmetic progression of length k.

Therefore, the Hales-Jewett theorem implies the Van der Waerden's theorem where k and r are the same and $HJ(k, r) \geq W(k, r)$.

2.4.6 Density version of the Hales-Jewett theorem implies the Szemerédi's theorem. We have shown that any combinatorial line of k elements corresponds an arithmetic progression of length k. Also, we have established that there exists a bijection between $[k]^n \longrightarrow [k^n]$. So, we just need to set $N(k, \delta) = k^n$ to show that the Hales-Jewett theorem implies the Szemerédi's theorem where $n \geq DHJ(k, \delta)$.

As we have shown in (2.3.2) that the Szemerédi's theorem implies the Van der Waerden's theorem, we can establish by transitivity that the density version of the Hales-Jewett implies the Van der Waerden's theorem.

2.4.7 Density Hales-Jewett number. Let $n \geq 0$ and $k \geq 1$. The *density Hales-Jewett number* denoted by $d_{k,n}$ is defined as the size of the largest subset of the set $[k]^n = \{1, 2, \ldots, k\}^n$ which contains no combinatorial line. Let W be this largest subset, then $d_{k,n} = |W|$. Note that W is also called a *line-free*. Furthermore, the density of W can also be defined by the quotient $\frac{|W|}{n^k}$. In this case, the density is denoted by $\Delta_{k,n}$, that is $\Delta_{k,n} = \frac{|W|}{n^k}$.

The combinatorial line is to $d_{k,n}$ what the arithmetic progression is to $\delta_{k,N}$ (for the Szemerédi's theorem). That is, the major difference between $d_{k,n}$ and $\delta_{k,N}$ is located on the definition of the largest subset: combinatorial line for the first and arithmetic progression for the second.

Furstenberg and Katznelson (1991) showed that $d_{k,n} = o(k^n)$ (respectively $r_{k,N} = o(k^n)$) as $n \longrightarrow \infty$. It means that $d_{k,n}$ (respectively $r_{k,N}$) grows slower than any constant fraction of k^n. In another words, the growth rate of $d_{k,n}$ (respectively $r_{k,N}$) is strictly less than the growth rate of k^n.

For $k = 1$ and $k = 2$, the density Hales-Jewett numbers $d_{1,n}$ and $d_{2,n}$ are easier than other cases. Thus, $d_{1,n} = 1$ and $d_{2,n} = \binom{n}{\lfloor \frac{n}{2} \rfloor}$ where $\lfloor x \rfloor$ is the floor function.

Polymath (2010) used both human and computer-assisted arguments to compute some non-trivial density Hales-Jewett numbers for $k = 3$ when $n = 0, \ldots, 6$.

$\mathbf{n}$	0	1	2	3	4	5	6
$\mathbf{d_{3,n}}$	1	2	6	18	52	150	450

Table 2.4: Some known values of $d_{3,n}$ for $n = 0, \ldots, 6$.

Let us give examples of the line-free derived from Polymath (2010) for $k = 3$ and $n = 2$ and $n = 3$.

- For $n = 2$, there are 4 largest line-free of $[3]^2$ each with cardinality $d_{3,2} = 6:$
  $\{12, 13, 21, 22, 31, 33\}, \{11, 12, 21, 23, 32, 33\}, \{11, 13, 22, 23, 31, 32\}, \{12, 13, 21, 23, 31, 32\}.$
- For $n = 3$, the largest line-free of $[3]^3$ with cardinality $d_{3,3} = 18$ is:
  $\{112, 113, 121, 122, 131, 133, 211, 212, 221, 223, 232, 233, 311, 313, 322, 323, 331, 332\}.$

Knowing that $d_{3,0} = 1$, $d_{3,1} = 2$, Polymath (2010) gave an upper bound of $d_{3,n}$ for $n = 0, \ldots, 6$:

$$d_{3,n+1} \leq 3d_{3,n}$$

and for large n and for $k \geq 3$, $d_{k,n} \geq k^n \exp\left(-O(\log n)^{1/l}\right)$ where ℓ is the largest integer such that $2k > 2^\ell$. This lower bound can simply be written as: $d_{k,n} \geq k^n \exp\left(-O(\log n)^{1/\lceil \log_2 k \rceil}\right)$ where $\lceil x \rceil$=ceilling(x) is the least integer greater than or equal to x.

3. Parallel repetition of multi-prover games.

In this chapter we discuss about the parallel repetition of multi-prover games. Firstly, some notions about two-prover games are presented. Then, a generalisation to multiple provers is given. In the end, these notions are followed by notions about parallel repetition in which is presented the theorem that expresses the upper bound of the value of the success probability of the parallel repetition of multi-prover games.

3.1 Two-prover games.

3.1.1 Definitions. Consider a game G of incomplete information played between two persons cooperative (Player 1 and Player 2) (Verbitsky, 1996; Raz, 2010). [Jan: Change to: Consider a cooperative game...] A *two-prover one round game* or simply *two-prover game* (often called *game* in this work for short) is a game played between two players called *prover* and an additional player called *verifier* or *referee*. We denote it by $MIP(2, 1)$. [Jan: No, MIP is something else (it is a class of languages). Please delete this sentence.] Notice that a two-prover game is a concept originating from theoretical computer science. Let us introduce some basic idea of this game.

Let X, Y, S, T be finite sets. Let Q be a subset of $X \times Y$ ($Q \subseteq X \times Y$ can represent a set of pair of questions: X represent the set of possible questions for the first prover and Y a set of possible questions for the second prover). S and T can be interpreted respectively as set of possible answers associated respectively to X and Y.

A pair $(x, y) \in_{\mu} Q \subseteq X \times Y$ of questions is chosen randomly by the verifier, that is with a probability distribution measure $\mu : Q \longmapsto \mathbb{R}^{+}$. The verifier sends x to the first prover and y to the second prover. Each prover does not know the question addressed to the other and the communication during the game is not allowed. Nevertheless, before the game starts, they are allowed to agree on a strategy that will help them to increase the probability of winning the game. Let us introduce some main idea of this strategy.

The *strategy* used to answer the pair of questions (x, y) is a pair of functions (f, h) defined as: $f : X \longrightarrow S : x \longmapsto f(x)$ and $h : Y \longrightarrow T : y \longmapsto h(y)$. That is, $f(x) \in S$ is the answer to the question x using the strategy f by prover 1. Whereas $h(y) \in T$ is the answer to the question y using the strategy h by prover 2.

The role of the verifier is to accept or reject the answers given from both provers. Thus, the verifier is also a function. We denote the function "*verifier*" by ϕ and defined as: $\phi : (X, Y, S, T) \longrightarrow \{0, 1\} : (x, y, f(x), h(y)) \longmapsto \phi(x, y, f(x), h(y))$. ϕ is a predicate on (X, Y, S, T).

If $\phi(x, y, f(x), h(y)) = 1$, then the two players win. They lose if $\phi(x, y, f(x), h(y)) = 0$.

In sum, in this case $G = (\phi, Q \subseteq X \times Y, S, T, \mu)$ represents a game if X, Y, S, T are finite subset, [Jan: s/subset/sets] the function $\phi : Q \times S \times T \longmapsto \{0, 1\}$ is a predicate, and μ is a probability distribution measure. That is, a prover game is a tuple. [Jan: Delete last sentence. Formally it is a tuple, but it is not important.]

Prover games become interesting when we want to estimate the probability of winning the game according to the strategies used, and mainly when several questions are addressed simultaneously to each prover.

Let $\Pr[\phi(x, y, f(x), h(y)) = 1]$ be the winning probability associated to the one of the couples (f, h) of the strategies. In this case, the winning probability " $\Pr$" which can be the expectation is taken over the distribution μ.

As in all games, the aim of the two players is to maximize the winning probability according to their strategies. Let denote by $\mathrm{val}(G)$ the *value* of the winning probability associated to the optimal couple of strategies of the two provers for the game G where the probability is taken over the couple $(x, y) \in_\mu Q$. Then, $\mathrm{val}(G)$ is expressed as:

$$\mathrm{val}(G) = \max_{f,h} \Pr_{(x,y)\sim Q}[\phi(x, y, f(x), h(y)) = 1]$$

where $\Pr\limits_{(x,y)\sim Q}$ means that the probability is taken over the couple $(x, y) \in_\mu Q$ and $\max\limits_{f,h}$ means that the maximum winning probability is taken over all possible couples of strategies (f, g).

When $\mathrm{val}(G) = 1$, the game G is called *trivial*. In mostly of cases, we will consider a *non-trivial* game , [Jan: Space before comma.] that is a prover game with $\mathrm{val}(G) \neq 1$. The two-prover game G is called a *free game* if $Q = X \times Y$, that is, questions to players are independent. Another definition of a free game according to Barak, Rao, Raz, Rosen, and Shaltiel (2009) [Jan: Don't cite here, this is a common definition.] is when the probability distribution of the questions is a product probability distribution, that is $\mu_{XY} = \mu_X \mu_Y$. The probability distribution μ_{XY} is the joint distribution according to which the verifier chooses a pair of questions to the provers. μ_X (respectively μ_Y) the probability distribution for the verifier to choose a question in the set X (respectively Y).

Raz (2010) gave three nice definitions of kinds of prover games: projection game, unique game and XOR game. [Jan: Change this: There are more special kinds of games considered in the literature (cite Raz).]

A two-prover game G is called *projection game* if for every pair of questions $(x, y) \in X \times Y$ there is a function $f_{x,y} : T \longmapsto S$, such that, for every $a \in S,\ b \in T$, we have: $\phi(x, y, a, b) = 1$ if and only if $f_{x,y}(b) = a$.

The game G is *unique* if for every $(x, y) \in X \times Y$ the function $f_{x,y}$ is a bijection. Hence, a unique game is a particular case of a projection game.

When sets $T, S = \{0, 1\}$, then the unique game is called a *XOR* game. That is, when sets of question are composed only by 0 and 1. [Jan: s/only by/only of]

3.1.2 Relationship between graphs and two-prover games. The relationship between graphs and two-prover games is broad. Thus, in this part we present an elementary relationship by introducing a two-prover game through basic notions of graphs. Some advanced connections are been studied by [Jan: s/are/have] Laekhanukit (2014); Tamaki (2015); Dinur, Harsha, Venkat, and Yuen (2016).

Let X, Y be two vertex sets of a bipartite graph. $E \subseteq X \times Y$ an edge set, L a label set which can for instance contain some colours. By c_e we denote a set of constraints associated to edge $e \in E$, for example this constraint can be colouring vertices of edge e with different colours chosen in L. [Jan: Say that $c_e \subseteq L \times L$]

In this case for graphs, a two-prover game G is the game $G = (X, Y, E, L, C)$ where $C = \{c_e\}_{e \in E}$ is the set of (sets of) constraints associated to edges $e \in E$. In others words, a two-prover game G consists of a bipartite graph with vertex sets X, Y, an edge set $E \subseteq X \times Y$, a label set L and a set of constraints associated to edges.

[Jan: You are giving a definition that is not equivalent to your previous definition. You should not call two different things with the same name. At the very least you should make clear that this definition is not equivalent to the first one.]

Let us define two functions f and g which assign colours to each vertices $x \in X$ and $y \in Y$ by $f : X \longmapsto L$ and $g : Y \longmapsto L$. We say that f and g satisfy the constraint $c_{(x,y)}$ if $(f(x), g(y)) \in c_{(x,y)}$, that is if $f(x)$ and $g(y)$ satisfy the constraints in $c_{(x,y)}$. So, the value of the game is the success probability to find a couple of functions (f, g) that assigns the maximum of colours. [Jan: Maximum of colors?] Tamaki (2015) expresses this value as follows:

$$\mathrm{val}(G) = \max_{f,g} \Pr_{(x,y)\sim E} \{(f(x), g(y)) \in c_{(x,y)}\}$$

where the probability is taken over the edge $(x, y) \in E$ and the maximum of probability is taken over all optimal couple of strategies (f, g).

3.1.3 Expander graphs. Let us discuss about some elementary notions of *expander graph* which will be useful in the following. These notions are derived mainly from the work of Raz and Rosen (2012). Before giving a definition of what is an expander graph, let us give a short definition of what are a bipartite graph, an unbalanced bipartite graph and a regular graph.

- The graph $G = (U; E) = (X, Y; E)$ is *bipartite*, where the vertex set $U = X \cup Y$ is partionned [Jan: s/partionned/partitioned] into two parts X and Y with $E \subseteq X \times Y$.
- The bipartite graph $G = (U; E) = (X, Y; E)$ is *unbalanced* when $|X| \neq |Y|$. Otherwise it is *balanced*.
- A graph is regular when each vertex has the same degree, that is each has the same number of neighbours.

Let $U = X \cup Y$ and $E \subseteq X \times Y$ be respectively the set of vertices and the set of edges of a graph G. Let d_X and d_Y be respectively the degree of each vertex $x \in X$ and the degree of each vertex $y \in Y$.

We denote by $(d_X, d_Y)-$bipartite graph an *unbalanced bipartite regular graph* on vertices $X \cup Y$.

Let $G_{XY} = (X, Y, E)$ a bipartite graph. The expander graph G_{XY} is based on the notions of singular values (absolute values of the eigenvalues) of the normalized adjacency matrix $M =$

$M(G_{XY})$ of G_{XY}, that is where each entry of M is divided by $\sqrt{d_X.d_Y}$. The singular-value decomposition theorem states that for an $|X|$-by-$|Y|$ matrix M , there exists a factorisation of the matrix M to the form $M = UDV^*$ where U is an $|X|$-by-$|X|$ unitary matrix ($U^* = U^{-1}$), D is an $|X|$-by-$|Y|$ diagonal matrix with non-negative real numbers on the diagonal and V^* is the conjugate transpose of a $|Y|$-by-$|Y|$ unitary matrix V. The columns of U are eigenvectors of MM^*. The columns of V are eigenvectors of M^*M. The diagonal value in the matrix D are square roots of the eigenvalues of MM^* and M^*M that correspond with the same columns in U and V.

So, a non-negative real number σ is a singular value for the matrix M if and only if there exists two unit-length vectors u and v such that $Mv = \sigma u$ and $M^*u = \sigma v$. The vector u is called left-singular and v right-singular for σ.

In $M = UDV^*$, the diagonal entries of D are equal to the singular values of M. Let us denote by σ_0 the singular value whose absolute value is the largest. The columns of U and V are, respectively, left- and right-singular vectors for the corresponding singular values.

As the matrix M is a normalized matrix, then all singular values are between 0 and 1 , therefore the singular value $\sigma_0 = 1$, that is $u = v$. We denote by $1 - \lambda$ the singular value whose value is the closest to 1 and that is not σ_0. λ is called the *spectral gap* of the graph G_{XY} and $1 - \lambda$ is called the *second singular value*.

Thus, a $(X, Y, d_X, d_Y, 1 - \lambda)-$expander graph is a $(d_X, d_Y)-$bipartite graph with the second singular value $1 - \lambda$ (Raz and Rosen, 2012). That is the expander graph is based on the notions of an unbalanced bipartite regular graph, the set of degrees of his vertices, and on singular value associated to the normalized adjacency matrix of the graph.

[Jan: This is a good exposition of algebraic expander graphs. Since you already wrote about them, it would be useful to explain their graph-theoretic properties (look up Cheeger inequality or expander mixing lemma). Also consider some examples: Is cycle an expander? Is complete graph? Random graph?]

[Jan: Consider separate subsection for expander graphs.]

3.1.4 Multi-prover games.. The rules of the multi-prover games are similar to two-prover games. But, as indicated by the term "multi", this game is playing [Jan: s/playing/played] with several provers (more than two players). That is, we are dealing with the general case.

Let us consider that there are $k-$provers, with $k \geq 2$. A $k-$ prover game is the game $G(\phi, Q \subseteq X^1 \times \cdots \times X^k, A^1, \cdots, A^k, \mu)$. So, $k-$tuple of questions $(x^1, \cdots, x^k) \in_\mu Q \subseteq X^1 \times \cdots \times X^k$ (with X^t set of questions) is chosen with probability distribution measure μ from a set of question, and the answer is a $k-$tuple vector $(a^1, \cdots, a^k) \in A^1 \times \cdots \times A^k$ (with A^t set of answers) according to question $(x^1, \cdots, x^k)$. The distribution measure μ associates an element of $Q \subseteq X^1 \times \cdots \times X^k$ to an element of $\mathbb{R}^+ \cap [0, 1] = (0, 1]$. A verifier chooses $k-$tuple of questions $(x^1, \cdots, x^k)$ and sends a question x^t to the prover t. The answer a^t of the prover t depends only on the question x^t. As for two-prover games, the players cannot communicate during the game, but they are allowed to agree on a strategy.

In this case, the strategy used to answer is a $k-$tuple of functions $(f^1, \cdots, f^k)$ defined as: $f^t : X^t \longrightarrow A^t : x^t \longmapsto f^t(x^t) = a^t$, for $1 \leq t \leq k$.

The predicate (verifier) on $(X^1 \times \cdots \times X^k, A^1 \times \cdots \times A^k)$ is defined as a function ϕ:

$$\begin{aligned}\phi : &X^1 \times \ldots \times X^k \times A^1 \times \ldots \times A^k \longmapsto \{0,1\}\\ &(x^1, \cdots, x^k, f^1(x^1), \cdots, f^k(x^k)) \longmapsto \phi(x^1, \cdots, x^k, f^1(x^1), \cdots, f^k(x^k)).\end{aligned}$$

All players win if $\phi(x^1, \cdots, x^k, f^1(x^1), \cdots, f^k(x^k)) = 1$.

Thus, the value of the multi-prover game G denoted by $\mathrm{val}(G)$ is the optimal winning probability of provers over all possible strategies. This value is expressed as follows:

$$\mathrm{val}(G) = \max_{f^1,\cdots,f^k} \Pr[\phi(x^1, \cdots, x^k, f^1(x^1), \cdots, f^k(x^k)) = 1].$$

Some notions on multi-prover games presented above mainly treat on one round. We can extend this concept from one round to several rounds. Thus, the $k-$provers $r-$round game is similar to the multi-prover with k players, but in this case the verifier executes a computation at most r rounds following a game. [Jan: NO, this is wrong! For r rounds provers and verifier exchange r messages. Please delete this.]

3.1.5 Some types of prover games.. In the table (3.1), we present some kinds of the prover game known. We give some references for further reading.

Prover game	References
Free	Verbitsky (1996)
Projection	Rao (2011)
Unique	Tamaki (2015)
Expander	Dinur et al. (2016)
Anchored	Bavarian et al. (2015)
GHZ	Dinur et al. (2016)
Fortified	Moshkovitz (2014)
XOR	Cleve et al. (2007)
Question set	Hązła et al. (2016)

Table 3.1: Some kinds of prover games.

[Jan: Remove et al. from citations.]

3.2 Parallel repetition.

3.2.1 Parallel repetition for two-prover games. Let G be a two-prover game and n a positive integer. Knowing the value of the game G, we are interesting [Jan: s/interesting/interested] to establish the relationship between $\mathrm{val}(G)$ and $\mathrm{val}(G^n)$. By executing n independent copies of G in parallel, we obtain what we call an $n-$*product game* G or a *product game* G^n or an *n-fold parallel repetition* G^n. Hence, a parallel repetition of a two-prover game G is a product game

G^n, that is approximatively [Jan: s/approximatively/approximately] speaking when n copies of the game G is tried to be won simultaneously by the two players. The game G is called the *base game* of the parallel repeated game G^n.

According to the definition of a prover G, let $G(\phi, Q \subseteq X \times Y, S, T, \mu)$ be a game. The product game G^n is the game $G^n(\phi^n, Q^n \subseteq X^n \times Y^n, S^n, T^n, \mu^n)$, where ϕ^n represents a predicate (referee or verifier), Q^n a product set of questions, S^n and T^n represent sets of answers, and μ^n represents the probability distribution measure. Let us express explicitly the sets Q^n and the functions μ^n and ϕ^n.

Elements of Q^n take the form $((x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n))$ where $x_1, x_2, \ldots, x_n \in X$ and $y_1, y_2, \ldots, y_n \in Y$, that is a collection of $n-$tuple of couples $((x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n))$ is chosen randomly and uniformly from the set Q^n in accordance with the probability distribution measure μ^n. The element $((x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)) \in Q^n$ is identifying to the pair $((x_1, \ldots, x_n), (y_1, \ldots, y_n)) \in Q^n \subseteq X^n \times Y^n$.

Thus, the probability measure μ^n can be expressed as a function using μ:

$$\begin{aligned} \mu^n :& Q^n \subseteq X^n \times Y^n \longrightarrow \mathbb{R}^+ \\ & ((x_1, \ldots, x_n), (y_1, \ldots, y_n)) \longmapsto \mu^n((x_1, \ldots, x_n), (y_1, \ldots, y_n)) = \prod_{i=1}^{n} \mu(x_i, y_i). \end{aligned}$$

We denote by $\bar{x}$ the $n-$tuple $(x_1, \ldots, x_n)$, that is $\bar{x} = (x_1, \ldots, x_n)$.

The function ϕ^n is defined similarly to the function ϕ as:

$$\begin{aligned} \phi^n :& X^n \times Y^n \times S^n \times T^n \longrightarrow \{0, 1\} \\ & (\bar{x}, \bar{y}, \bar{s}, \bar{t}) \longmapsto \phi^n(\bar{x}, \bar{y}, \bar{s}, \bar{t}) = \bigwedge_{i=1}^{n} \phi[x_i, y_i, f_i(\bar{x}), h_i(\bar{y})] \end{aligned}$$

Where $\bigwedge$ represents the logical connective "AND" (conjunction). Note that f_i is a function of $\bar{x}$ and not just x_i in the expression of the predicate ϕ^n.

We know that in the truth table for the logical operator "AND", the only case so that the value of two propositions be true is when the two propositions are true. Then, the logical connective $\bigwedge$ from ϕ^n can be replaced by $\prod$. That is, $\bigwedge\limits_{i=1}^{n} \phi[x_i, y_i, f_i(\bar{x}), h_i(\bar{y})] = \prod\limits_{i=1}^{n} \phi[x_i, y_i, f_i(\bar{x}), h_i(\bar{y})]$.

As there are two provers, n-vectors (questions) are revealed to each prover: $(x_1, \ldots, x_n)$ to prover 1 and $(y_1, \ldots, y_n)$ to prover 2 who both respond with couple of strategies (F, H) with $F = (f_1, f_2, \ldots, f_n)$ and $H = (h_1, h_2, \ldots, h_n)$ where f_i and h_i represent respectively strategies associated to the questions $\bar{x}$ and $\bar{y}$.

Strategies F and H are functions defined as:

$$\begin{aligned} F :& X^n \longrightarrow S^n \\ & \bar{x} \longmapsto F(\bar{x}) = (f_1(\bar{x}), \ldots, f_n(\bar{x})) \end{aligned}$$

and

$$\begin{aligned} H :& Y^n \longrightarrow T^n \\ & \bar{y} \longmapsto H(\bar{y}) = (h_1(\bar{y}), \ldots, h_n(\bar{y})) \end{aligned}$$

Now, the winning case occurs when $\bigwedge\limits_{i=1}^{n} \phi[x_i, y_i, f_i(\bar{x}), h_i(\bar{y})] = 1$, that is both provers win if they win concomitantly in all n coordinates. Each of the n copies are treated independently by the referee.

Then, the value of the game G^n, that is the success probability is:

$$\mathrm{val}(G^n) = \max_{F,H} \Pr\left[\bigwedge_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right].$$

The winning probability of G^n and the one of G are linked by these relations:

$$\mathrm{val}(G)^n \leq \mathrm{val}(G^n) \leq \mathrm{val}(G). \tag{3.2.1}$$

Let us show the inequalities in (3.2.1) by splitting them into two parts:

$$\begin{cases} \mathrm{val}(G)^n \leq \mathrm{val}(G^n) \\ \mathrm{val}(G^n) \leq \mathrm{val}(G). \end{cases} \tag{3.2.2}$$

- The first inequality $\mathrm{val}(G)^n \leq \mathrm{val}(G^n)$.

  Proof. We know that the value of the game G is the optimal winning probability of provers over all possible strategies, that is the winning probability using the best couple of strategies. Le us denote by (f, h) this optimal couple of strategies used for the game G. Strategies f and h are defined as $f : X \longrightarrow S$ and $h : Y \longrightarrow T$. Then, $\mathrm{val}(G) = \max\limits_{f,g} \Pr[\phi(x, y, f(x), h(y)) = 1]$.

  As far as, let us denote by (F, H) a couple of strategies used to win the game G^n. F and G are $n-$tuple defined as: $F = (f_1, \ldots, f_n)$ and $H = (h_1, \ldots, h_n)$. Strategies F and H are defined as $F : X^n \longrightarrow S^n$ and $H : Y^n \longrightarrow T^n$. Here, notice that the couple (F, H) of strategies are not necessary the optimal. Then, the winning probability according to this couple of strategies is: $\Pr\left[\bigwedge\limits_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right]$.

  Since, each couple (x_i, y_i), for $1 \leq i \leq n$ is chosen randomly according to the probability distribution measure μ. Without loss of generality, for instance, let us assume that the couple (x_i, y_i) is chosen independently. Then, the winning probability becomes:

$$\Pr\left[\bigwedge_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right] = \prod_{i=1}^{n} \Pr\left[\phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right].$$

[Jan: No, this is wrong. x_i, y_i is always chosen independently, you don't have to "assume" this. But this does not imply your equation. The equation is wrong.]

Let us chose the optimal strategies f and h of G to play each parallel copy of G, that is $f_i(\bar{x}) = f(x_i)$ and $h_i(\bar{y}) = h(y_i)$ for $1 \leq i \leq n$. Then, the success probability becomes:

$$\begin{aligned}
\Pr\left[\bigwedge_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right] &= \prod_{i=1}^{n} \Pr\left[\phi(x_i, y_i, f(\bar{x}), h(\bar{y})) = 1\right] \\
&= \prod_{i=1}^{n} \mathrm{val}(G) \\
&= \mathrm{val}(G)^n.
\end{aligned}$$

[Jan: Here the equation becomes true, but the reason for that is that f_i, h_i depend only on x_i, y_i. Otherwise it is false.]

(f, h) is the optimal couple of strategies for the game G, this does not means that the couple (F, H) is the optimal couple of the strategies for the parallel repetition G^n. Then, the winning probability for G^n over the optimal couple of strategies is:

$$\begin{aligned}
\mathrm{val}(G^n) &= \max_{F,H} \Pr\left[\bigwedge_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right] \\
&\geq \Pr\left[\bigwedge_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right] \\
&= \prod_{i=1}^{n} \Pr\left[\phi(x_i, y_i, f(\bar{x}), h(\bar{y})) = 1\right] \\
&= \prod_{i=1}^{n} \mathrm{val}(G) \\
&= \mathrm{val}(G)^n.
\end{aligned}$$

Hence, $\mathrm{val}(G^n) \geq \mathrm{val}(G)^n$. □

- The second inequality: $\mathrm{val}(G^n) \leq \mathrm{val}(G)$.

Proof.

$$\begin{aligned}
\mathrm{val}(G^n) &= \max_{F,H} \Pr\left[\bigwedge_{i=1}^{n} \phi(x_i, y_i, f_i(\bar{x}), h_i(\bar{y})) = 1\right] \\
&\leq Pr\left[\phi(x_1, y_1, f_1(\bar{x}), h_1(\bar{y})) = 1\right] \\
&\leq \max_{f,g} \Pr[\phi(x_1, y_1, f(x), h(y)) = 1] \\
&= \mathrm{val}(G).
\end{aligned}$$

Hence, $\mathrm{val}(G^n) \leq \mathrm{val}(G)$. □

To support the relation $\mathrm{val}(G)^n \leq \mathrm{val}(G^n) \leq \mathrm{val}(G)$, let us give an example for which we define a strategy. [Jan: Make a section for this example.]

Let G be a two-prover game and $X = Y = \{0, 1\}$ be sets of questions addressed respectively to prover A and B. The rule of the game G is announced as this. The verifier ϕ chooses randomly and uniformly a couple of questions $(x, y) \in Q = X \times Y = \{(0, 0); (0, 1); (1, 0); (1, 1)\}$ and sends x to the prover A and y to the prover B. The sets of answers of the two provers are respectively $S = \{(a, K_A)\}$ and $T = \{(b, K_B)\}$ where $a, b \in \{0, 1\}$, $K_A, K_B \in \{A, B\}$. Note that $|S| = |T| = 4$. To win, the verifier checks this:

- $K_A = K_B = K$ and $a = b$.
- If $K = A$, then $x = a$, that is, if both provers answer A then the first component of he couple of answers of the provers is $x = a = b$.
- If $K = B$, then $y = b$, that is, if both provers answer B then the first component of he couple of answers of the provers is $y = a = b$.

This means that the winning cases are: $\phi[x, y, (x, A), (x, A)]$ and $\phi[x, y, (y, B), (y, B)]$.

Let us define a couple of strategies (f, g) used by the two players to answer as following: $f(0) = (0, A), f(1) = (1, A)$ and $g(0) = (0, A), g(1) = (1, A)$. Let us evaluate the probability to win this game. In our strategy, we always have $K_A = K_B = A$ in the second component of the answer. So, the two provers can win in two cases: $(0, 0)$ and $(1, 1)$. They also lose in two cases: $(0, 1)$ and $(0, 1)$. Hence, the winning probability of the game according to this couple of strategies is: $\Pr[\phi(x, y, (a, K_A), (b, K_B)) = 1] = \frac{2}{4} = \frac{1}{2}$.

Let us define another couple of strategies (s, t) such that $s(0) = (0, A), s(1) = (0, A)$ and $t(0) = (0, A), t(1) = (0, A)$. For this couple of strategies, the two provers can win in two cases: $(0, 0)$ and $(0, 1)$. They also lose in two cases: $(1, 0)$ and $(1, 1)$. Hence, the winning probability of the game according to this couple of strategies is: $\Pr[\phi(x, y, (a, K_A), (b, K_B)) = 1] = \frac{2}{4} = \frac{1}{2}$.

For all possible couple of strategies, the maximum value of the winning probability is $\frac{1}{2}$. Therefore, the value of the game G is:

$$\mathrm{val}(G) = \frac{1}{2}.$$

Now, let us compute $\mathrm{val}(G^2)$. Firstly, let us define the game G^2.

The sets of questions are respectively $X^2 = Y^2 = \{(0, 0); (0, 1); (1, 0); (1, 1)\}$. The verifier chooses randomly and uniformly the couple $(\bar{x}, \bar{y}) \in Q = X^2 \times Y^2 = \{(\bar{x}, \bar{y}) : \bar{x} \in X^2, \bar{y} \in Y^2\} = \{((0, 0), (0, 0)), \ldots, ((1, 1), (1, 1))\}$ where $\bar{x} = (x_1, x_2)$ and $\bar{y} = (y_1, y_2)$ are couples with $x_1, x_2, y_1, y_2 \in \{0, 1\}$. Note that $|Q| = 16$. The sets of answers are :$S^2 = \{(\bar{s}_1, \bar{s}_2) : \bar{s}_1, \bar{s}_2 \in S\} = \{((a, K_A), (a, K_A)) : a \in \{0, 1\}, K_A \in \{A, B\}\}$ and $T^2 = \{(\bar{t}_1, \bar{t}_2) : \bar{t}_1, \bar{t}_2 \in T\} = \{((b, K_B), (b, K_B)) : b \in \{0, 1\}, K_B \in \{A, B\}\}$. The verifier sends $\bar{x}$ to prover A and $\bar{y}$ to prover B. Answers of $\bar{x}$ is in S^2 and answers of $\bar{y}$ is in T^2. The verifier checks these rules:

- If $x_1 = y_2$ then both provers A and B win.

- If $x_1 \neq y_2$ then they lose.

[Jan: No, the verifier checks rules for G as before. These conditions are just for the strategy below.]

For that, let us define a couple of strategies (h, k) such that $h(\bar{x}) = h(x_1, x_2) = ((x_1, A), (x_1, B))$ and $k(\bar{y}) = k(y_1, y_2) = ((y_1, A), (y_2, B))$. [Jan: There is a typo here.]

According to this couple of strategies, both provers A and B win in these cases: [Jan: You have to explain why according to rules of the game.]

A	(0,0)	(0,0)	(0,1)	(0,1)	(1,0)	(1,0)	(1,1)	(1,1)
B	(0,0)	(1,0)	(0,0)	(1,0)	(0,1)	(1,1)	(1,1)	(0,1)

And they lose in these cases:

A	(0,0)	(0,0)	(0,1)	(0,1)	(1,0)	(1,0)	(1,1)	(1,1)
B	(0,1)	(1,1)	(0,1)	(1,1)	(0,0)	(1,0)	(0,0)	(1,0)

Then, the winning probability of the game G^2 according to the couple of strategies (h, k) is $\frac{8}{16} = \frac{1}{2}$.

For all couple of strategies, we assume that the winning probability is less or equal to $\frac{1}{2}$.

Thus, the value of the game G^2 is:

$$\operatorname{val}(G^2) = \frac{1}{2}.$$

Therefore, $\operatorname{val}(G)^2 \leq \operatorname{val}(G^2) \leq \operatorname{val}(G)$.

3.2.2 Parallel repetition theorem of two-prover games.. The parallel repetition theorem of two-prover games present an approximation upper bound of the value of n independent copies of the game G. Many main topics on the parallel repetition of prover game started to be treated from the early 1990s.

Feige and Lovász (1992) conjectured that for any two-prover game G with value smaller than 1 ($\operatorname{val}(G) < 1$), the value of the game G^n ($\operatorname{val}(G^n)$ decreases exponentially fast to 0.

We denote by $|S|$ and $|T|$ respectively the size of the sets of answers S and T of the game G. Thus, the answer size of the game G is $|S||T|$. Let us denote by c a universal constant and by s the expression $s(G) = \log |S||T|$ which represents the length of the answers. s can also represent the answer size. The parallel repetition theorem as formulated in Raz (1998, 2010) is stated as follows:

3.2.3 Theorem. *For any two-prover game G, with $\operatorname{val}(G) \leq 1 - \epsilon$, for $0 < \epsilon \leq 1$, the value of the game G^n is:*

$$\operatorname{val}(G^n) \leq (1 - \epsilon^c)^{\Omega(n/s)}.$$

Knowing that for all real number, $1 + x \leq e^x$ and for x closer to zero: $e^x = 1 + x + O(x^2)$ or simply $1 + x \approx e^x$, the bound of $\mathrm{val}(G^n)$ as expressed in (3.2.3) can be rewritten as follows:

$$\begin{aligned}\mathrm{val}(G^n) \leq& (1-\epsilon^c)^{\Omega(n/s)}\\ \leq& \left(e^{-\epsilon^c}\right)^{\Omega(n/s)}\\ =& \exp(-\epsilon^c\Omega(n/s)).\end{aligned}$$

Then, $\mathrm{val}(G^n) \leq \exp(-\epsilon^c\Omega(n/s))$. Or

$$\begin{aligned}\mathrm{val}(G^n) \leq& \exp(-\epsilon^c\Omega(n/s))\\ =& \exp(-\epsilon\epsilon^{c-1}\Omega(n/s))\\ =& \exp(-\epsilon)^{\epsilon^{c-1}\Omega(n/s)}\\ \approx& (1-\epsilon)^{\epsilon^{c-1}\Omega(n/s)}.\end{aligned}$$

Then, $\mathrm{val}(G^n) \leq (1-\epsilon)^{\epsilon^c\Omega(n/s)}$. [Jan: Typo in the last line.]

In some papers, the authors, for instance Rao (2011) expresses the upper bound of $\mathrm{val}(G^n)$ by using this expression: $\mathrm{val}(G^n) \leq (1-\epsilon/2)^{\epsilon^c\Omega(n/s)}$.

Feige and Lovász (1992) conjectured the parallel repetition theorem and gave some proofs for some special cases. The proof of the theorem (3.2.3) has been given by Raz (1998) and found an implicit constant $c = 32$. Holenstein (2007) simplified Raz's proof, proved the parallel repetition theorem in case of no-signaling strategies (strategies which do not imply communication) and gave an explicit bound on the maximal success probability of the product game G^n. This explicit bound is expressed as:

$$\mathrm{val}(G^n) \leq \left(1 - \frac{(1-\mathrm{val}(G))^3}{6000}\right)^{\frac{n}{\log(|A||B|)}}$$

. [Jan: Dot after math mode.] This means that the constant $c = 3$ in Thomas Holenstein's bound which is better than Ran Raz's expression. However, for the special case of the projection games. Rao (2011) improved the bound of this game by finding $c = 2$ and by expressing the function Ω without s. This bound is:

$$\mathrm{val}(G^n) \leq (1-\epsilon^2)^{\Omega(n)}.$$

According to Raz (2010), this bound was also known for the special case of XOR games.

To improve this bound from (3.2.3) to $(1-\epsilon)^{\Omega(n/s)}$ for the $n-$product game of two-prover games or for some special cases is one of the questions for which several researchers are looking for answers (Raz, 2010). This question is called the *strong parallel repetition problem*.

In case if the probability distribution on $X \times Y$ is a product distribution for games , Barak et al. (2009) showed that the value of free game is bounded as follows:

$$\mathrm{val}(G^n) \leq (1-\epsilon^2)^{\Omega(n/s)}$$

and if the game is a free projection game, then the value of the game is:

$$\mathrm{val}(G^n) \leq (1-\epsilon)^{\Omega(n)}.$$

Hence, the strong parallel repetition for the free projection game that is with product distribution is known. Note that the function Ω is not depending on s.

Similarly, Raz and Rosen (2012) studied the case where the probability distribution is uniform over the edges of an expander graph. The value of the repeated game is:

$$\operatorname{val}(G^n) \leq (1-\epsilon^2)^{c(\lambda).\Omega(n/s)}$$

where λ is the normalized spectral gap of the expander graph.

If in addition the game is a projection game, then the value of the repeated game is:

$$\operatorname{val}(G^n) \leq (1-\epsilon)^{c(\lambda).\Omega(n)}$$

which is a strong parallel repetition for a projection games on expander graph.

However, Raz (2011) gave a negative answer to the several research who are asking if it is possible to found a strong parallel repetition for two-prover games, that is to improve the bound value to $(1-\epsilon)^{\Omega(n/s)}$. A counterexample to strong parallel repetition used to disprove is an *odd cycle game* of size m which is a two-prover game with value $1-1/2m$. Thus, Raz showed that the value of the parallel repetition of this odd cycle game is at least $1-(1/m).O(\sqrt{n})$. Hence, for large $n = \Omega(m^2)$, the value of the parallel repetition (n times) of this odd cycle game is at least $(1-1/4m^2)^{O(n)}$. That is, the lower bound value of parallel repetition of two-prover games is at least $(1-\epsilon^2)^{O(n)}$ and can not reach $(1-\epsilon)^{\Omega(n/s)}$.

Since the odd cycle game is a projection game, a unique game, and a XOR game, this answers negatively most variants of the strong parallel repetition problem (Raz, 2011; Raz and Rosen, 2012). That is there exists a two-prover game (odd cycle game) which does not have a strong parallel repetition theorem.

Moreover, Dinur and Steurer (2014) used projection games to study parallel repetition by using analytical approach based on a matrix analysis argument. His [Jan: s/His/Their] result states that for every projection game G with $\operatorname{val}(G) \leq \rho$, we have:

$$\operatorname{val}(G^n) \leq \left(\frac{2\sqrt{\rho}}{1+\rho}\right)^{n/2}. \tag{3.2.3}$$

Dinur and Steurer (2014) establishes that this upper value bound (3.2.3) of an $n-$ fold parallel repetition of projection games G and $(1-\epsilon^2)^{O(n)}$ with improved bounds from Rao (2011) match when the value of the game G is closed to 1.

Notice that the good things of those approximations of the upper value of the parallel repetition, is that, the value of the game G^n is reduced exponentially.

In this work, we are mainly interested by the upper bound of the value of the parallel repetition. However, there exists some works which approximate the lower bound (Feige et al., 2007; Steurer, 2010; Raz, 2011). The table (3.2) adapted from Tamaki (2015) presents a summary of lower and upper bounds known of parallel repetition of some two-prover games.

[Jan: Typo in the first row of first table. What is "Projection on expander games"?]

Upper bounds of the value of G^n	Kind of game G	References
$(1-\epsilon^3 3)^{\Omega(n/s)}$	All provers	Raz (1998)
$(1-\epsilon^3)^{\Omega(n/s)}$	All provers	Holenstein (2007)
$(1-\epsilon^2)^{\Omega(n)}$	Projection, xor	Rao (2011); Raz (2010)
$\left(\frac{2\sqrt{\rho}}{1+\rho}\right)^{n/2}$	Projection	Dinur and Steurer (2014)
$(1-\epsilon^2)^{\Omega(n/s)}$	Free	Barak et al. (2009)
$(1-\epsilon)^{\Omega(n)}$	Free projection	Barak et al. (2009)
$(1-\epsilon^2)^{c(\lambda).\Omega(n/s)}$	Expander with spectral gap λ	Raz and Rosen (2012)
$(1-\epsilon)^{c(\lambda).\Omega(n)}$	Projection on Expander games	Raz and Rosen (2012)

Lower bounds of the value of G^n	Kind of game G	Reference
$1-(1/m).O(\sqrt{n})$	Odd cycle, value $1-1/m$	Feige et al. (2007)
$(1-1/4m^2)^{O(n)}$	Odd cycle, $n \geq \Omega(m^2)$	Raz (2011)
$1-O(\sqrt{\epsilon ns})$	Unique	Steurer (2010)

Table 3.2: Summary of known bounds

3.2.4 Parallel repetition of mutli-prover games. [Jan: s/mutli/multi]

Let $G(\phi, Q \subset X^1 \times \ldots \times X^k, A^1, \ldots, A^k, \mu)$ be a $k-$prover game, that is a prover game played with k players. For $1 \leq t \leq k$, the sets X^t and A^t represent respectively the set of questions and the set of their answers. The verifier ϕ is a predicate defined on $\left(\prod_{t=1}^{k} X^t, \prod_{t=1}^{k} A^t\right)$, that is $\phi[(x^1, \cdots, x^k), (a^1, \cdots, a^k)] = 1$ for a winning case and the other for the losing case. The distribution measure μ is a function defines from Q to $(0, 1]$.

The $n-$fold parallel repetition of the game G is the $k-$prover game $G^n(\phi^n, Q^n \subseteq (X^1)^n \times \ldots \times (X^k)^n, (A^1)^n, \ldots, (A^k)^n, \mu^n)$, where $(X^1)^n, \ldots, (X^k)^n$ are sets of $n-$tuple of questions, $(A^k)^n, \ldots, (A^k)^n$ are sets of $n-$tuple of answers.

Let us denote by x_i^t a element of the set X^t where superscripts $1 \leq t \leq k$ denote the players and subscripts $1 \leq i \leq n$ denote coordinates in parallel repetition.

Elements of Q^n are n-tuple of $k-$tuple (of questions). $((x_1^1, \cdots, x_1^k), (x_2^1, \cdots, x_2^k), \ldots, (x_n^1, \cdots, x_n^k)) \in_{\mu^n} Q^n$ which is identifying to the $k-$tuple $((x_1^1, \cdots, x_n^1), (x_1^2, \cdots, x_n^2), \ldots, (x_1^k, \cdots, x_n^k))$. Elements of Q^n are chosen randomly in accordance with the probability distribution μ^n. Let $\bar{x}^t$ represent a $n-$tuple $(x_1^t, \cdots, x_n^t)$ belongs to $(X^t)^n$. So, the distribution measure μ^n is a function defined as:

$$\begin{aligned} \mu^n : & Q^n \subseteq (X^1)^n \times \ldots \times (X^k)^n \times \longrightarrow (0,1] \\ & (\bar{x}^1, \ldots, \bar{x}^k) \longmapsto \mu^n(\bar{x}^1, \ldots, \bar{x}^k) = \prod_{i=1}^{n} \mu(x_i^1, \cdots, x_i^k). \end{aligned}$$

And the verifier is a predicative defines as follows:

$$\begin{aligned}\phi^n :&(X^1)^n \times \ldots \times (X^k)^n \times (A^1)^n \times \ldots \times (A^k)^n) \longrightarrow \{0,1\}\\ &(\bar{x}^1,\ldots,\bar{x}^k,\bar{a}^1,\ldots,\bar{a}^k) \longmapsto \phi^n(\bar{x}^1,\ldots,\bar{x}^k,\bar{a}^1,\ldots,\bar{a}^k) = \bigwedge_{i=1}^{n} \phi[x_i^1,\cdots,x_i^k,f_i^1(\bar{x}^1),\cdots,f_i^k(\bar{x}^k)]\end{aligned}$$

where $\bigwedge$ represents the logical connective "AND" (conjunction) and f_i^t are strategies.

There are two results: win or lose. All k provers win when $\bigwedge_{i=1}^{n} \phi[x_i^1,\cdots,x_i^k,f_i^1(\bar{x}^1),\cdots,f_i^k(\bar{x}^k)] = 1$, that is when all provers win simultaneously in all n coordinates. The verifier treats independently each of the n copies.

As all provers are allowed to agree on a strategy but not to communicate each other during the game, the strategy in this case is a $k-$tuple of functions $(F^1, F^2, \ldots, F^k)$ where for $1 \leq t \leq k$, every F^t is a $n-$tuple function $(f_1^t, f_2^t, \ldots, f_n^t)$. f_i^t is strategy used by the prover t to give the answer a_i^t of the question x_i^t for $1 \leq i \leq n$. This function f_i^t is defined as:

$$\begin{aligned}f_i^t :&(X^t)^n \longrightarrow A^t\\ &\bar{x}^t \longmapsto f_i^t(\bar{x}^t) = a_i^t\end{aligned}$$

Thus, the value of the parallel repetition of the multi-prover game G denoted by $\text{val}(G^n)$ is the optimal winning probability of provers over all possible strategies. This value is expressed as follows:

$$\text{val}(G^n) = \max_{F^1,F^2,\ldots,F^t} \Pr\left[\bigwedge_{i=1}^{n} \phi\left(x_i^1,\cdots,x_i^k,f_i^1(\bar{x}^1),\cdots,f_i^k(\bar{x}^k)\right) = 1\right].$$

Given the value of the multi-prover game G, can we estimate or approximate the value of the parallel repetition of the multi-prover game G using the value of G?

For a two-prover game, there are so many advanced studies about that, we can cite the works of Feige and Lovász (1992); Verbitsky (1996); Raz (1998); Holenstein (2007); Barak et al. (2009); Raz (2010); Rao (2011); Dinur and Steurer (2014). Nevertheless, express $\text{val}(G^n)$ in terms of power of $\text{val}(G)$ or bound it with the power of $\text{val}(G)$ does not seem to be easy.

Another question that we can ask is: does the value of parallel repetition of a multi-prover game decay exponentially like for a two-prover game?

For some multiplayer games, for instance free game and anchored[1] game, the exponentially decay bounds for parallel repetition are known (Barak et al., 2009; Bavarian et al., 2015). A recent work of Dinur et al. (2016) gives an exponentially decay bound for the parallel repetition for expander games.

Expander game is based on expander graph (see (3.1.2)). Given a base game G, a related connected graph G, a spectral gap of the graph G denoted by λ, then the value of the repeated

[1] Related to quantum parallel repetition. Before being repeated in parallel, the base game G is modified to an equivalent game $\tilde{G}$.

game, $\text{val}(G^n)$ goes down exponentially in n for sufficiently large n. Dinur et al. (2016) expresses it as follows:

$$\text{val}(G^n) \leq \exp\left(-\frac{c\epsilon^5\lambda^2 n}{\log|A|}\right) \tag{3.2.4}$$

where $|A|$ is the answer size of the game and c a constant.

An expander game is merely the extension of free and anchored games. All kind of expander games are linked by the connectedness property. Hence, the free and anchored games are connected games.

As $0 < \epsilon \leq 1$, ϵ^5 is very smaller than ϵ. The upper bound value (3.2.4) of the parallel repetition of the expander game can be expressed as:

$$\begin{aligned} \text{val}(G^n) &\leq \exp\left(-\frac{c\epsilon^5\lambda^2 n}{\log|A|}\right) \\ &= \exp\left(-\epsilon^5\right)^{\frac{c\lambda^2 n}{\log|A|}} \\ &= \left(1-\epsilon^5\right)^{\frac{c\lambda^2 n}{\log|A|}} \\ &= \left(1-\epsilon^5\right)^{\Omega(n/s)} \end{aligned}$$

where $s = \log|A|$ and $\Omega(n/s) = \frac{c\lambda^2 n}{\log|A|}$ with λ a constant.

A general bound of the value of parallel repetition of a multi-prover game is given by Verbitsky (1996) by using the Hales-Jewett theorem. Despite the fact that the rate of convergence of this general bound value of Oleg Verbitsky is slow, this boundary remains the only best result that gives a general parallel repetition bound for all multiplayer games (Hązła et al., 2016; Dinur et al., 2016). In the next chapter, we present the connection between Hales-Jewett theorem and the parallel repetition of multi-prover games. [Jan: Don't use et al. for citing.]

4. Connection between parallel repetition of multi-prover games and Hales-Jewett theorem.

This chapter presents the relationship between parallel repetition of multiple provers with the density Hales-Jewett theorem. We give a parallel repetition bound using the density Hales-Jewett. Firstly, we show that the density Hales-Jewett theorem implies parallel repetition. Secondly, we show that the parallel repetition implies the density Hales-Jewett theorem.

4.1 Hales-Jewett theorem implies parallel repetition.

In both versions of Hales-Jewett theorem (see (2.4.2) and (2.4.3)), the concept which emphasizes this theorem is the *combinatorial line.* The combinatorial line is the umbilical cord between the Hales-Jewett theorem and the parallel repetition. In section (2.4), we have already explain in a detailed way and define what the combinatorial is. Let us recall some notions about a combinatorial line and the formulation of the Hales-Jewett theorem.

Let $k, n \in \mathbb{Z}^+$, $[k] = \{1, 2, \ldots, k\}$ and an $x-$string $w(x) = a_1a_2 \ldots a_n \in ([k] \times \{x\})^n \backslash [k]^n$. That is, in $w(x) = a_1a_2 \ldots a_n$, at least one of the symbol a_i contains the symbol x called wildcard. Let $w(x; i)$ be the string obtained by replacing x by i.

The *combinatorial line* is the set of k strings $\{w(x; i) \ : \ i \in \{1, 2, \ldots, k\}\}$, that is the set $\{w(x; 1), w(x; 2), \ldots, w(x; k)\}$.

The Hales-Jewett theorem is given in (2.4.2). As the name stipulates, the Hales-Jewett was proved by Hales and Jewett in 1963. The formulation is based on colouring of a set and on the existence of a monochromatic combinatorial line.

Furthermore, there is a density formulation of Hales-Jewett theorem on which this section is mainly constructed. Given a subset A of $[k]^n$, the density of A is defined and denoted as $\delta(A) = \frac{|A|}{k^n}$. By simplicity, δ denotes the density of A, that is $\delta = \delta(A)$.

Thereby, the density version of Hales-Jewett theorem states that for any positive number k and real number δ, there exists a large enough number n (depending on k and δ) such that any subset of $[k]^n$ with density δ contains a combinatorial line. In the following, essentially we use the density version of Hales-Jewett theorem. Whenever we say the Hales-Jewett theorem, we mean the density version of Hales-Jewett theorem.

We denote by $\Delta_{k,n}$ the maximum density of a subset W of $[k]^n$ without a combinatorial line. Δ_k, n was discussed in (2.4.7). The number $\Delta_{k,n}$ is called density Hales-Jewett number.

The density version of the Hales-Jewett theorem is equivalent to $\lim\limits_{n \longrightarrow \infty} \Delta_{k,n} = 0$ for $k \geq 2$ (Furstenberg and Katznelson, 1991). Let us show it.

- The density version of the Hales-Jewett theorem implies $\lim\limits_{n \longrightarrow \infty} \Delta_{k,n} = 0$. We assume that the density version of the Hales-Jewett theorem is true, that is $\forall k, \delta, \exists DHJ(k,\delta) \in \mathbb{N}/\forall n \geq DHJ(k,\delta)$ and $\forall S \subseteq [k]^n, |S| \geq \delta k^n$, S contains a combinatorial line. This means that there is a subset $W \subseteq [k]^n$ which does not contain a combinatorial line with density $|W| < \delta k^n \Longleftrightarrow |\frac{|W|}{k^n} - 0| < \delta \Longleftrightarrow |\Delta_{k,n} - 0| < \delta$. So, $\lim\limits_{n \longrightarrow \infty} \Delta_{k,n} = 0$.

- $\lim\limits_{n \longrightarrow \infty} \Delta_{k,n} = 0$ implies the density version of the Hales-Jewett theorem. $\lim\limits_{n \longrightarrow \infty} \Delta_{k,n} = 0$ is equivalent to $\forall, \delta > 0, \exists N_0 \in \mathbb{N}/\forall n \geq N_0, \Delta_{k,n} < \delta$ fro a fixed k. $\Delta_{k,n}$ is the density of the largest subset of $[k]^n$ without a combinatorial line. Hence, $\forall n \geq N_0, \forall S \subseteq [k]^n$ with $|S| \geq \delta k^n$ contains a combinatorial line.

This result shows that a subset of $[k]^n$ with constant density will necessarily contain a combinatorial line when n increases. ‘

The density Hales-Jewett number converges to 0 when n converges to infinity. Equally, the Raz theorem (3.2.3) shows that the value of a parallel repetition of a game (non-trivial) decreases exponentially fast to 0 when n converges to infinity. Note that the convergence of the Raz theorem is fast than the convergence of the density Hales-Jewett number.

The following Oleg Verbitsky theorem shows that the density Hales-Jewett theorem implies the parallel repetition of multi-prover games.

4.1.1 Theorem (Verbitsky (1996)). *Let G be a non-trivial multi-prover game with $|Q| = r$ the size of question set. Then,* $\mathrm{val}(G^n) \leq \Delta_{r,n}$.

Knowing that the density Hales-Jewett number converges to 0 when n converges to infinity, then we obtain the following consequence.

4.1.2 Corollary. Let G be a non-trivial multi-prover game. Then, $\lim\limits_{n \longrightarrow \infty} \mathrm{val}(G^n) = 0$.

The theorem (4.1.1) has been proved by Verbitsky (1996) for two-prover games. His proof can be extended for multi-prover games in our case, that is, for k players with $k \geq 2$. To establish the truth of this theorem, Oleg Verbitsky used the proof by contradiction. The general idea is: given a subset K of Q^n for which the provers win for a given strategy, we must show that K is the subset of Q^n without a combinatorial line. So, we assume that there is a combinatorial line and then we show that there is contradiction.

Let us adapt our proof from the proof of Verbitsky (1996) to show the theorem (4.1.1) for multi-prover games, that is, we extend the proof of Oleg Verbitsky from two-prover games to multi-prover games.

Proof. Let G be a $k-$prover game (non-trivial), that is $G(\phi, Q \subseteq X^1 \times \ldots \times X^k, A^1 \times \ldots \times A^k, \mu)$ where X^t and A^t represent respectively the set of questions and the set of answers of the player t, for $1 \leq t \leq k$. The set Q is a subset of the set $X^1 \times \ldots \times X^k$ where elements are chosen uniformly according to the probability distribution μ.

Let $|Q| = r$, with $Q = \{q_1, \dots, q_r\}$ where $q_j = (q^1_j, \dots, q^k_j)$, $q^t_j \in X^t$ for $j \leq r$. The superscript t highlights the component (player), while the subscript j denotes the number (order) of questions. For instance the question q^t_j is the $j-$th question addressed to the player number t. For the parallel repetition G^n, let us consider $F^1, \dots, F^k$ like the k optimal strategies of the game where each strategy is an $n-$tuple function of strategies, that is $F^t = (f^t_1, \dots, f^t_n)$. We denote by K the set of success questions using these strategies in G^n. The set K can be expressed as:

$$K = \{(s_1, \dots, s_n) \in Q^n : \bigwedge_{i=1}^{n} \phi \left[s^1_i, \dots, s^k_i, f^1_i(s^1_1, \dots, s^1_n), \dots, f^k_i(s^k_1, \dots, s^k_n)\right] = 1\}.$$

Note that for $1 \leq i \leq n$, $s_i \in Q = \{q_1, \dots, q_r\}$. s^t_i denotes an $i-$th question in parallel repetition addressed to the player t. This question can be any of the $t-$th component of the set q_j.

As K is the set of success questions, then the value of the game G^n is: $\mathrm{val}(G^n) = \frac{|K|}{r^n}$.

In this stage, we can not say that $\Delta_{r,n} \geq \frac{|K|}{r^n}$ because we do not know if the set K does not contain any combinatorial lines. Let us show that K is a set without a combinatorial line.

Let us suppose by contradiction that there is a combinatorial line $L = \{\bar{b}_1, \dots, \bar{b}_r\} \subseteq K$. In this case, the game G should be trivial.

Let $C = C_1 \dots C_n$ be an $r \times n$ matrix whose r rows are $\bar{b}_1, \dots, \bar{b}_r$ and n columns $C_1 \dots C_n$ each are either $(q_j, q_j, \dots, q_j)^T$ for some $j \leq r$ or $(q_1, q_2, \dots, q_r)^T$. By definition of a combinatorial line, there exists at least one column $C_l = (q_1, q_2, \dots, q_r)^T$. We assume that L is ordered so that the intersection of the row $\bar{b}_j$ and the column C_l of the matrix is the element q_j. The element $q_j = (q^1_j, \dots, q^k_j)$ has k components. So, the matrix C can be expanded to the $kr \times n$ matrix D by replacing each matrix element q_j with the column $(q^1_j, \dots, q^k_j)^T$. There are kr rows of the matrix D and n columns. Thus, let us denote by $\bar{x}^1_1, \dots, \bar{x}^k_1, \dots, \bar{x}^1_r, \dots, \bar{x}^k_r$ the rows of the matrix D where $\bar{x}^t_j \in (X^t)^n$.

Since L is a combinatorial line, let us use one of the strategy of the matrix element in the column C_l which is in the form $(q_1, q_2, \dots, q_r)^T$. Note that q_j is a $k-$tuple. Let us define strategies $f^1, f^2, \dots, f^k$ in the game G by $f^t(q^t) = f^t_l(\bar{x}^t_{nt})$ where $x^t_{n_t} = q^t$ for $1 \leq t \leq k$.

For arbitrary $q_j = (q^1_j, \dots, q^k_j) \in Q$, we have:

$$\phi(q^1, \dots, q^k, f^1(q^1), \dots, f^k(q^k)) = \phi(q^1_j, \dots, q^k_j, f^1_l(\bar{x}^1_j), \dots, f^k_l(\bar{x}^k_j)) = 1$$

As $b_j \in K$, strategies $F^1, \dots, F^k$ win in the $l-$th copy of G. That is the game G is trivial.

Hence, there is a contradiction with our assumption that K contains a combinatorial line.

Therefore, K does not contain a combinatorial line and $\Delta_{r,n} \geq \frac{|K|}{r^n}$.

It results that $\mathrm{val}(G^n) \leq \Delta_{r,n}$. □

Let $\nu_{Q,n} = \max_G \mathrm{val}(G^n)$ where the maximum is over all non-trivial games G with $|Q| = r$ the size of the set of questions Q. The Oleg Verbitsky's theorem (4.1.1) is applicable to $\nu_{Q,n}$, that is $\nu_{Q,n} \leq \Delta_{r,n}$. Then, $\lim\limits_{n \longrightarrow \infty} \nu_{Q,n} = 0$.

4.2 Parallel repetition implies Hales-Jewett theorem.

To show that the parallel repetition implies the Hales-Jewett theorem, let us firstly define a set of questions on which will be constructed some multi-prover games.

4.2.1 Definition. Let $k \geq 2$ and $Q_k \subseteq \{0,1\}^k$ a question set of size k. An *k-prover question set* is a question set Q_k where the $t-$th question contains 1 in the $t-$th position and 0 in the remaining positions. This question set can be expressed as:

$$Q_k = \left\{(q^1, \ldots, q^k) : |\{t : q^t = 1\}| = 1\right\}.$$

An extensional definition of the question set Q_k is: $Q_k = \{(1,\ldots,0),(0,1,\ldots,0),\ldots,(0,\ldots,1)\}$. $|Q_k| = k$ and the elements of the question set Q_k are equivalent to the elements of the canonical basis, that is $Q_k = \{e_1, e_2, \ldots, e_k\}$ where $e_l = (\delta_{1l}, \delta_{2l}, \ldots, \delta_{kl})$, δ_{ml} is the Kronecker delta which equals to 1 if $l = m$ and 0 whenever $l \neq m$ for $1 \leq l, m \leq k$.

The following theorem highlights that there exists a game such that the parallel repetition of this game implies the density Hales-Jewett theorem. This result announced as theorem (4.2.2) links the existence of a combinatorial line in a set with the parallel repetition value of a certain game.

4.2.2 Theorem (Hązła, Holenstein, and Rao (2016)). *Let $k \geq 3$, $n \geq 1$ and $S \subseteq [k]^n$ with density $\delta = |S|/k^n$ such that S does not contain a combinatorial line.*

There exists a $k-$prover game G_S with question set Q_k and with answer alphabets, $A^t = 2^{[n]} \times [n]$ such that:

- $\mathrm{val}(G_S) \leq 1 - 1/k.$
- $\mathrm{val}(G_S^n) \geq \delta(S).$

Thus, from the theorem (4.2.2) we can deduce the value of the $n-$fold parallel repetition G_S^n when S is the maximum subset of $S \subseteq [k]^n$ without a combinatorial line, that is when the density of S is $\Delta_{k,n} = |S|/k^n$ where $k \geq 3$, $n \geq 1$. This result given as theorem (4.2.3) is complementary to Oleg Verbitsky theorem (4.1.1).

4.2.3 Theorem. *Let $k \geq 3$, $n \geq 1$ and $S \subseteq [k]^n$ with density $\Delta_{k,n}$. We have:* $\mathrm{val}(G_S^n) \geq \Delta_{k,n}$.

For this game G_S, according to the theorems (4.1.1) and (4.2.3), we conclude that $\mathrm{val}(G_S^n) = \Delta_{k,n}$.

To prove the theorem (4.2.2), we need to construct a game which satisfies the conditions on theorem (4.2.2). So, let us construct a game G_S as defined by Hązła et al. (2016) based to the subset S of the set $[k]^n$.

Let $k \geq 3$, $n \geq 1$ and $S \subseteq [k]^n$ with $\delta(S) = \frac{|S|}{k^n}$. The game G_S with question set Q_k which we will define must satisfy the following requirements:

- If S does not contain a combinatorial line, then G_S is non-trivial.
- $\mathrm{val}(G_S^n) \geq \delta(S)$.

As $|Q_k| = k$ and $|[k]| = k$, there is a natural bijection between the question tuples in Q_k and $[k]$. So, the game G_S is played as this. The verifier chooses the number of a special prover $t \in [k]$ and sends 1 to the special prover and 0 to all other provers. The answer set of the game G_S is the same for all provers: $A^t = 2^{[n]} \times [n]$ where the power set $2^{[n]}$ denotes the set of all subsets of $[n]$. Note that the set $2^{[n]}$ is equivalent to the set $\{1, 2, \ldots, 2^n\}$. Thus, answers from provers are in the form $(T^1, z^1), \ldots, (T^k, z^k)$. The verifier checks the following conditions and accepts if all of them are met:

- The sets $T^1, T^2, \ldots, T^k$ form a partition of $[n]$.
- $z^1 = z^2 = \ldots = z^k = z$.
- $z \in T^t$
- Let $\bar{s} = (s_1, s_2, \ldots, s_n)$ be the string over $[k]^n$ such that $s_i = e$ if and only if $i \in T^e$ for $1 \leq i \leq n$. Then, $\bar{s} \in S$.

From the definition of the game G_S we can deduce the following propositions given and proved by Hązła et al. (2016). So, the proofs of these propositions are adapted from this latter paper.

4.2.4 Proposition. If S has a combinatorial line, then the game G_S is trivial .

Proof. We assume that $S \subseteq [k]^n$ has a combinatorial line. Let $\bar{b} = w(x) = (b_1, \ldots, b_n)$ an $x-$string for which the combinatorial line is $L(\bar{b}) = \{w(x;i) : i \in [k]\} \subseteq S$ and let fix a position $z \in [n]$ with $b_z = x$. Note that $b_1, \ldots, b_n \in [k] \cup \{x\}$. For $p \in [k] \cup \{x\}$, let us define a set $B(p)$ as: $B(p) = \{j : b_j = p\}$. The set $B(p)$ is the set of coordinates j in which b_j equals to p. Now, let us define the strategy for which prover e will use to answer questions:

$$f^e(q^e) = \begin{cases} (B(e), z) & \text{if } q^e = 0, \\ (B(e) \cup B(x), z) & \text{if } q^e = 1. \end{cases}$$

Thus, the verifier checks the four conditions. The four conditions are all satisfied. In effect, the first condition will be always accepted by the verifier because the sets $B(1), \ldots, B(k), B(x)$ from a partition. All z^e are equal, that is $z^1 = \ldots = z^k$, then the second condition is satisfied. Because the prover t responds with $(B(t) \cup B(x), z)$ and $z \in B(x)$, then $z \in T^t$: the third condition is satisfied. The fourth condition is also satisfied because $\bar{s} = \bar{b}$ and $\bar{s} = \bar{b} = w(t) \in L(\bar{b}) \subseteq S$. □

4.2.5 Proposition. If the game G_S is trivial, then S has a combinatorial line.

Proof. We assume that the game G_S is trivial. As the game G is trivial, there is a k-tuple of strategies for which the provers always win. Let $f^1, \ldots, f^k$ be this k-tuple of strategies. The form of the answer of the prover e to the question $q \in \{0, 1\}$ is similar as in the definition of the game G_S and is defined as: $(T^e_q, z^e_q) = f^e(q)$ where $e \in [k]$. As the game is trivial we have $z^1_0 = z^2_0 = \ldots = z^k_0 = z^1_1 = z^2_1 = \ldots = z^k_1 = z$. For any two $e \neq e'$, $T^e_0 \cap T^{e'}_0 = \emptyset$. If $t \neq e$ and $t \neq e'$, the verifier will reject. $z \notin T^1_0 \cup \ldots \cup T^k_0$, because if $z \in T^e_0$, the verifier rejects if $t \neq e$. Therefore, the word $\bar{b} = w(x)$ (combinatorial line) is defined as:

$$b_i = \begin{cases} e & \text{if } i \in T^e_0, \text{ for } e \in [k], \\ x & \text{otherwise.} \end{cases}$$

For a fix $t \in [k]$, let us show that $w(t) \in S$. By picking the special prover t, the verifier checks that the sets T^e form a partition. In this case the answer of the prover t is $T^t_1 = [n] \setminus \left(T^1_0 \cup \ldots \cup T^{t-1}_0 \cup T^{t+1}_0 \cup \ldots T^k_0\right)$. For every t, $w(t) \in S$. Hence, $L(\bar{b}) \subseteq S$. □

4.2.6 Proposition. The value of G^n_S is at least $\delta(S)$

Proof. For $1 \leq e \leq k$, let q^e be the question. Let $n \geq 1$ and G^n be the n-fold parallel repetition. Note that question q^e in the game G^n_S is an n-tuple defined as: $q^e = (q^e_1, q^e_2, \ldots, q^e_n)$ where for a fixed $i \in \mathbb{N}$ there is necessary one special t for which $q^t_i = 1$ and other $q^e_i = 0$. In other words, (q^t_i) forms a $k \times n$ matrix where in each column there is at most one element equals to 1. But, for a fixed t there is at least one special i for which $q^t_i = 1$. In other words, in a line of the $k \times n$ matrix there is at least one one, that is the cardinality of the set $\{i \in [n] : q^e_i = 1\}$ is at least one.

Let $T^e = \{i \in [n] : q^e_i = 1\}$. in coordinate (column) i the prover e responds with (T^e, i). For $1 \leq e \leq k$ and $1 \leq i \leq k$, let $(a_i = t)$ where $q^t_i = 1$, that is $a_1, \ldots, a_n$ form a sequence of special provers. Then for a fixed i, sets $T^1, \ldots, T^k$ form a partition of $[n]$. Equally, $z^1_i = \ldots = z^k_i$. Also, $i \in T^{a_i}$. Finally, $\bar{s} = (a_1, \ldots, a_n) \in S$. Let us compute the value of G^n_S. The string a_i can take k different values. So the probability for a_i to be a string of $\bar{s}$ is $\frac{1}{k^n}$. Now, the probability of $\bar{s}$ to be in S is: $\Pr(\bar{s} \in S) = \frac{|S|}{k^n} = \delta(S)$. Hence, $\mathrm{val}(G^n_S) \geq \delta(S)$.

□

5. Conclusion

In this study, the relationship between parallel repetition and the density version of the Hales-Jewett theorem was analysed. We have shown that this umbilical cord which connects them is the combinatorial line. This study consisted of three parts following our thesis statements.

In the first place, we have started by investigating on [Jan: Delete "on"] the Van der Waerden's theorem, the Szemerédi's theorem, the Hales- Jewett theorem [Jan: No space after hyphen.] and the density version of the Hales-Jewett theorem. We have proved 4 implications: the density version of the Hales-Jewett theorem implies the Hales-Jewett theorem and the Szemerédi's theorem, the Hales-Jewett is a generalisation of the Van der Waerden's theorem and the Szemerédi's theorem is only the density version of the Van der Waerden's theorem.

Also, we have generalized [Jan: s/generalized/presented] some notions on prover games and on its parallel repetition. A summary of some known boundary of the value of a parallel repetition of two-prover games was given. We have given a proof which shows that the n-th power of the value of a game G is less or equal to the value of the n-fold parallel repetition G^n. [Jan: Add: "Furthermore, we showed that those two values do not have to be equal".] To support it we have constructed an example.

Lastly, we have extended the proof of Oleg Verbitsky from two provers to multiple provers by showing that the value of the parallel repetition of multi-prover games is bounded above by the density Hales-Jewett number. Specifically, we have shown that the density version of the Hales-Jewett theorem implies the parallel repetition. Inversely, we have constructed a game which shows that the value of the parallel repetition of multi-prover games is bounded below by the density Hales-Jewett number. In other words, we have established that the parallel repetition implies the density version of the Hales-Jewett theorem for a multi-prover game that we have constructed. [Jan: Please cite appropriate papers and make clear that this is not your original work.]

A general exponential decay bound like the Raz theorem for parallel repetition of multi-prover games is still not known. Future research may focus on: generalizing this bound for multi-prover games or simplifying the Raz proof, and showing or disproving the existence of the general exponentially decay [Jan: s/decay/decaying] bound. Equally, exact general expressions of the Van der Waerden number, the density Szemerédi's number and the density Hales-Jewett number are not known and form open problems for research. Even showing the existence of these numbers is still a problem. [Jan: It is not an open problem, but the proofs are difficult.] Further work should also focus on understanding and summarizing papers that apply parallel repetition to hardness of approximation and exploring in depth the parallel repetition of quantum games.

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