

An introduction to the absorption method

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Abstract

Finding large transversals in Latin squares [Mon] and constructing designs [Kee14] constitute two landmark applications of the absorption method. In these notes, we will introduce the absorption method from scratch, beginning with the set-up of Dirac-type problems, and then build our way up to transversals and designs. These notes are work in progress.

1 What is the absorption method?

Suppose we are trying to construct an object satisfying a certain set of constraints. The absorption method gives us an angle of attack if the following two properties hold in our context.

- (A) It is significantly easier to construct some object satisfying 99% of the constraints.
- (B) There is a robust sense in which partial solutions can be *locally* modified to produce other partial solutions.

The above properties hold in a wide variety of contexts. For example, if the constraints come about in a structureless, uniform sort of way, a sensible approach towards (A) is simply *the probabilistic method*, i.e. considering a suitable notion of a randomly sampled object. If a random construction satisfies 100% of the constraints with positive probability¹, then of course there is no need for the absorption method. There are, however, several natural instances in which a random strategy gets us most of the way, and then gets stuck towards the end². This is where (B) comes in to somehow turn the approximate solution into an exact one.

When is (B) satisfied? Let's start with a non-example. Consider the task of constructing a proper 2-vertex-colouring of a cycle. Here, there is no local flexibility whatsoever: the effect of changing the colour of a vertex necessarily has to propagate through the whole cycle, and hence has *global* effects³. As for a positive example, we will see several throughout these notes, beginning with the following beautiful argument of Erdős from 1986 [Rei89], which appears to be the first application of the absorption method (to my knowledge), though the wide applicability of the method was not crystallised until pioneering work of Rödl, Ruciński, and Szemerédi [RRS06] from 2006.

Recall that a *tournament* is a complete graph, where each edge $\{i, j\}$ is assigned a direction $i \rightarrow j$ or $j \rightarrow i$. A tournament is transitive if its vertices can be ordered as $(1, 2, \dots, n)$ so that $i \rightarrow j$

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¹For example, as is the case whilst constructing an n -vertex graph with no cliques or independent sets of size $2 \log_2 n$.

²As a first example, the reader may consider the puzzle of the n -queens problem, i.e. the task of placing n mutually non-attacking queens on an $n \times n$ chessboard (see, for example, [SL22])

³As it should — whether we succeed or fail is of course entirely contingent on a global property: the parity of the number of the vertices.

if and only if $i < j$ (or equivalently, if a tournament is transitive if it contains no distinct i, j, k with $i \rightarrow j \rightarrow k \rightarrow i$).

Proposition 1.1 (Erdős, 1986). *For every k , there exists an N so that for all $n > N$ such that k divides n , the vertices of any n -vertex tournament can be partitioned into transitive sub-tournaments of size k .*

We need to first recall that any sufficiently large tournament contains a large transitive tournament. This can be seen from Ramsey's theorem by constructing an auxiliary red-blue edge colouring, but the following direct argument gives an even better bound.

Observation 1.2. *Suppose $n \geq 2^k$. Any n -vertex tournament contains a transitive sub-tournament on k vertices.*

Proof. By induction, suppose the assertion holds for smaller values of k . Fix some transitive tournament of size $n \geq 2^k$. Take some arbitrary vertex v , and notice v either has at least $n/2 \geq 2^{k-1}$ in-edges or out-edges, by the pigeonhole principle. Let's say v has many in-edges. Invoke the inductive hypothesis on the in-neighbourhood to find a transitive sub-tournament there of size $k-1$, and tack on v to the end of this tournament to find one of size k . The other case is of course symmetric. \square

Given the above, how should we approach [Proposition 1.1](#)? Let us first check [\(A\)](#). Say we took $N = N(k)$ to be 100×2^k . Then, by greedily plucking transitive sub-tournaments of size k one by one, we may saturate all but 1% of the original tournament with transitive sub-tournaments of the same size. So it feels indeed easier to satisfy 99% of the constraints.

How about [\(B\)](#)? Now suppose we took $N = 100 \times 2^{2k}$. Then we can repeat the same argument with transitive sub-tournaments of size $2k$ saturating 99% of the original tournament. Each transitive sub-tournament of size $2k$ splits into two disjoint ones of size k in a rich variety of ways, $\binom{2k}{k}$ ways to be exact. So there indeed are many partial solutions that can be obtained from one another by making "local toggles".

It's not actually clear how we can use these properties [\(A\)](#) and [\(B\)](#) to our advantage to fully solve the problem. The reader may want to stop and think for a moment, before we reveal the brilliant strategy of Erdős.

Proof of [Proposition 1.1](#). Given a large enough tournament T , let us first reserve $K := k2^{k-1}$ many disjoint transitive sub-tournaments T_i ($i \in [K]$) of size $2k-1$. Let us keep plucking disjoint transitive sub-tournaments of size k in the remainder (this can be done as long as there are 2^k vertices remaining, but we will stop earlier). The leftover must stay at being multiples of k (as K also is a multiple of k), so at some point, the size of the leftover is exactly K , so we can choose to stop the process at that moment. Let us arbitrarily pair up the leftover vertices with the T_i . The key observation that concludes the proof is the following: for each leftover vertex v , $v + T_i$ can be split into two transitive sub-tournaments, as v has at least $k-1$ neighbours in T_i with the same orientation of edges (in fact k , but $k-1$ is what we need here). \square

The above proof consists of three steps that appear one way or another in most applications of the absorption method.

The absorption method

- Step 1.** (Preparation) Find some flexible structure that satisfies the constraints in a rich variety of ways.
- Step 2.** (99% solution) In the remainder, saturate most of the constraints.
- Step 3.** (Absorption) Show that the leftover from Step 2 combines with the flexible structure from Step 1 to produce a construction that satisfies all of the constraints.

A motivated reader might want to think of the quantitative aspects of [Proposition 1.1](#). The Erdős argument certainly requires $N \gg 2^{2k-1}$, and one cannot do better than $N \gg 2^k$ without improving on [Observation 1.2](#). Can we improve on the constant factor in the exponent with a different argument and replace it with $1 + o(1)$? See [\[BS21\]](#) for an answer.

2 Perfect matchings in (hyper-)graphs and a digression on the switching method

Both the study of transversals in Latin squares [Mon] and the constructions of designs [Kee14] turn out to be expressible in the language of *hypergraph perfect matchings*. In this section, we give an overview of hypergraph perfect matchings, starting with the graph case, where simple "switching-methods" give satisfying answers, and the hypergraph case, where the said methods fail. We also discuss how the absorption method can in some sense be thought as a more robust implementation of the switching method, relying only on "local variability" to engineer some "global variability".

A *spanning subgraph* of a graph G is a subgraph that has the same vertex set as G and an edge set that is contained in $E(G)$. A decent chunk of extremal combinatorics seeks to characterise (hyper-)graphs that contain a certain kind of spanning subgraph. For example, a graph contains a tree as a spanning subgraph if and only if the graph is connected.

As a more substantial example, we have Hall's marriage theorem. Recall that if $S \subseteq V(G)$, the neighbourhood $N(S)$ denotes elements of $V(G)$ that are connected to some vertex in S .

Theorem 2.1 (Hall's marriage theorem). *A bipartite graph $G = (A, B)$ with $|A| = |B|$ has a perfect matching if and only if the following condition holds.*

(Hall's condition.) *For every $A' \subseteq A$, $|N(A')| \geq |A'|$.*

A direct corollary of Hall's marriage theorem is that it is always possible to give a short certificate that a bipartite graph does **not** contain a perfect matching⁴: one simply points to the set S with $|N(S)| < |S|$. This is very rare phenomenon in the study of spanning structures. For example, no analogous statement holds for spanning paths, or higher dimensional perfect matchings, subject to mainstream hypotheses in computer science.

To formalise this a bit more, a *tripartite hypergraph* $H = (A, B, C)$ is a collection of triples $E(H) := (a, b, c) \in A \times B \times C$ which we view as being the (hyper-)edges of H , and A, B and C are assumed to be disjoint. The definition of a perfect matching hasn't changed, it still is a collection of vertex-disjoint edges that together cover the vertex-set $A \cup B \cup C$. We call a tripartite graph *balanced* if $|A| = |B| = |C|$, an obvious necessary condition for the existence of a perfect matching.

Existence of perfect matchings in tripartite hypergraphs is one of Karp's original 21 NP-complete problems. What this means for the working combinatorialist is that there almost certainly is no nice characterisation of tripartite hypergraphs with perfect matchings, and moreover, in general, we expect that it is hard to prove (or give a certificate) that a given tripartite hypergraph does **not** contain a perfect matching. That said, many problems in combinatorics can be expressed as a hypergraph matching problem including the existence of transversals in Latin squares and the existence of designs, the two subjects that we are trying to build our way into. So, we certainly wish for a better understanding of hypergraph matchings, no matter how weak.

A widely useful criterion for when tripartite hypergraphs contain perfect matchings is given in the work of Aharoni–Haxell, and these results are interesting not least because they exemplify how topological methods can come into play for problems that seem entirely combinatorial in nature. Unfortunately, these methods and criteria have thus far not been very applicable in the study of transversals in Latin squares or designs, hence we will not say more about them here.

⁴In complexity-theoretic terms, the language of bipartite graphs with perfect matchings is in the class co-NP.

Let us set our targets a bit lower and consider the following (essentially trivial) corollary of Hall's marriage theorem.

Proposition 2.2. *If $G = (A, B)$ is a d -regular bipartite graph (each vertex is incident on exactly d -edges), then G has a perfect matching.*

Proof. Observe $|A| = |B|$ as $e(G)$ (number of edges of G) is equal to both $|A| \cdot d$ and $|B| \cdot d$. Also, for all $A' \subseteq A$, $e(A', N(A'))$ (number of edges between A' and its neighbourhood, $N(A')$) is equal to $d \cdot |A'|$, and is at most $|N(A')| \cdot d$, so $|N(A')| \geq |A'|$. \square

Most hypergraphs we consider here will be regular, so it would have been convenient to have any high-dimensional analogue of Proposition 2.2. Unfortunately, such a result cannot exist, even when we restrict our attention to *linear* hypergraphs, meaning those hypergraphs where any two vertices are contained in at most one common edge. In fact, such a result fails even when we restrict our attention to n -regular linear hypergraphs $H = (A, B, C)$ where $|A| = |B| = |C| = n$, which can be interpreted as the counter-intuitive assertion that there is no analogue of $K_{n,n}$ having a perfect matching for linear tripartite hypergraphs.

Example 2.3. *Consider a tripartite hypergraph $H = (A, B, C)$ where A, B, C are disjoint copies of $\mathbb{Z}/n\mathbb{Z}$ where n is an even integer and (a, b, c) is an edge if and only if $a + b + c = 0 \pmod{n}$.*

Proof. If H had a perfect matching, summing over all edges of the matching we'd obtain $3 \cdot \sum_{x \in \mathbb{Z}/n\mathbb{Z}} x = 0 \pmod{n}$, but $3 \cdot \sum_{x \in \mathbb{Z}/n\mathbb{Z}} x \equiv 3 \cdot (n/2) \equiv n/2 \not\equiv 0 \pmod{n}$, assuming n is even. \square

Considering disjoint unions of the above construction when $n = 2$, we can see that in general, a regular linear tripartite hypergraph can be quite far away from containing a perfect matching, the largest matching could miss half the vertices! We would expect though the situation would get less bad if the degrees of the hypergraph were larger. For example, any n -vertex d -regular graph (not necessarily bipartite) contains a matching covering all but $O(n/d)$ vertices, as can be deduced from theorems of Vizing, or Tutte (and this is optimal, as the graph could consist of disjoint unions of $O(n/d)$ odd-sized subgraphs).

A fundamental open problem of Alon–Kim–Spencer asks about the size of the largest matching in a general d -regular n -vertex linear hypergraph (of uniformity 3). Alon–Kim–Spencer showed that there is a matching covering all but $nd^{-1/2+o(1)}$ vertices (with techniques related to the Rödl nibble that we will discuss later on), but, in principle, it may be possible to find matchings covering all but $O(n/d)$ vertices. Even when $d = n$, proving such a result was a topic of extensive study, culminating in Montgomery's tour de force work [Mon] proving the following.

Theorem 2.4 (Montgomery, 2023+). *Any n -regular linear balanced tripartite hypergraph on $3n$ vertices contains a matching with $n - 1$ edges.*

A striking conjecture of Ryser is that if n is odd, $n - 1$ can be replaced with n in the above, meaning constructions like Example 2.3 can only exist for even values of n .

We remark that linear tripartite hypergraphs $H = (A, B, C)$ with $n = |A| = |B| = |C|$ that are n -regular are often presented as *Latin squares*. An order n Latin square is an $n \times n$ array filled with n symbols so that no symbol repeats in any row or any column. Thinking of (A, B, C) as (rows, columns, symbols), and s being the symbol in row r and column c as (r, c, s) being an edge, we see that Latin squares and n -regular linear tripartite hypergraphs on $3n$ vertices are the same objects. Perfect matchings are often called *transversals* in the Latin square language. We motivated the study of perfect matchings through the graph theoretic lens in the above, but there are also strong design-theoretic motivations to study transversals in Latin squares, as

they have applications in error-correcting codes and the design of actual scientific experiments where the goal is to minimise unwanted correlations.

2.1 A digression on the switching method

We provide the short proof of Hall's marriage theorem, as it allows us to expose a close cousin of the absorption method, namely, the switching method.

Proof of Theorem 2.1. Let M be a matching of G (not necessarily perfect), and let $F := E(G) \setminus M$ be the unmatched edges. An M -alternating path is a path of G whose edges alternately come from F and M . An M -alternating path is an M -augmenting path if it starts and ends with vertices not matched by M . Given an augmenting path, we may swap the unmatched edges with matched edges, and find a matching M' with $|M'| > |M|$. So (the non-trivial direction of) Hall's marriage theorem reduces to showing that any non-perfect matching M in a graph G with Hall's condition has an M -augmenting path.

So let M be a matching of G and suppose $v \in A$ is unmatched. Consider the set of all vertices R_v that are reachable by an M -alternating path starting from v , and note that if R_v contains an unmatched vertex $w \in B$, we're done. Consider the sets $R_v \cap A$ and $R_v \cap B$. The key observation is that unless $R_v \cap B$ contains an unmatched vertex from B , it must be that $R_v \cap B$ and $R_v \cap A$ are in bijective correspondence with the pairing coming from M (the best way to see this is to draw a picture and track the iterative growth of R_v as we allow longer and longer alternating paths). Also, $R_v \cap B$ contains $N(v)$, as well as $N(R_v \cap A)$, as any G -neighbour of v or $R_v \cap A$ is certainly reachable by a M -alternating path from v . We then find a set of size $|(R_v \cap A) \cup \{v\}|$ whose neighbourhood has size $|R_v \cap B|$, contradicting Hall's condition, as desired. \square

The above proof of Hall's marriage theorem belongs in a wider class of proof strategies, which can be summarised as follows.

The switching method

- Step 1.** Find some object maximal with respect to some parameter which we are trying to optimize.
- Step 2.** Show that unless the object satisfies all the constraints, it can be improved by performing a sequence of modifications.

In the context of structural graph theory, the switching method is studied under the guise of "Kempe changes" (for example, in the proof of Vizing's theorem on edge-colourings or the 5-colour-theorem), and in the context of extremal graph theory, the switching method often manifests itself as the study of "Posá rotations" (we will see an illustration in the next section).

The third step in the absorption method is often realised by performing a sequence of *local* modifications, so the absorption method can really be thought of as a special case of the switching method. The proof of Hall's marriage theorem features a basic application of the switching method that requires no preparation, nor the 99% solution step, mainly because there is a tractable way in which we can reason about the space of *global* modifications we can perform. Indeed, neither the length of the augmenting path nor the size of the matching M being augmented had any role in the argument.

The absorption method is necessitated by the fact that in many contexts, there is no known tractable way of reasoning about global modifications⁵, yet there is a way of reasoning about local modifications.

⁵And moreover, there are compelling philosophical reasons for why there ought to not be a way to think about such global modifications in a tractable way, with evidence coming from computational complexity theory.

The selling point of the absorption method is that if we play our cards right in the preparation step, and if we furthermore facilitate what we have to do in the "modification stage" of the proof by dealing with 99% of the constraints already, then we can also find a way to deal with the remaining 1%. "Playing our cards right" often entails chaining up local objects that display local variability together to produce a global object that displays global variability. We already saw a basic manifestation of this phenomenon in the proof of [Proposition 1.1](#), and we will now turn our attention to slightly more involved examples.

3 Dirac-type theorems

We want to build our way up to understanding aspects of Montgomery’s theorem (Theorem 2.4), but to get there, we will first build more intuition on the absorption method. The absorption method was first codified by Rödl, Ruciński, and Szemerédi [RRS06] to generalise a classical theorem of Dirac to hypergraphs, and the set-up of these kinds of problems serve as a great learning ground. In particular, here, we will develop the idea of a *reservoir* and also a *cover-down*, which will be quite important later on.

Theorem 3.1 (Dirac’s theorem, 1950s). *If G is a n -vertex graph of minimum degree at least $n/2$, then G has a spanning (Hamilton) cycle, meaning a cycle that hits all vertices of the graph.*

Graphs with minimum degree less than $n/2$ need not even be connected, so Dirac’s theorem is sharp, as far as sufficient conditions for Hamiltonicity in terms of the minimum degree go.

The proof of Dirac’s theorem is fairly simple — just like the proof of Hall’s marriage theorem, it makes use of switchings, adapted to the context of path-like structures, where they are often called *rotations*.

Proof of Dirac’s theorem. As the minimum degree is at least $n/2$, and two vertices have at least one common neighbour, in particular, the graph is connected. We will show that for any maximal length path P , there is a cycle on the vertex set $V(P)$. Connectivity then implies the existence of a spanning cycle (why?).

Take a maximal length path P , then, and suppose u and v are its endpoints. All $\geq n/2$ neighbours of u and v have to be on the path P by maximality, and if $u \sim v$, we are happy. Otherwise, we do a rotation argument as follows. By the pigeonhole principle, there exist consecutive vertices of P , x and y (where x is the vertex closer to u) such that $x \sim v$ and $y \sim u$. Traversing the cycle as $u \rightarrow y$, following P until v , $v \rightarrow x$ and following P until u again closes a cycle on the same vertex set, as desired. \square

There is a rich literature on higher-dimensional generalisations of Dirac’s theorem in the literature, in terms of obtaining best-possible minimum degree conditions that imply the existence of a certain spanning subgraph. We will not attempt to give a survey of results, but a brief survey of the ideas that were generated as a result of this research programme.

As appealing as the proof of Dirac’s theorem is, it unfortunately does not seem to generalise to higher dimensions, or at least, nobody has figured out a way to make such an argument work yet. Up until the absorption method became prevalent through works of Rödl, Ruciński and Szemerédi [RRS06], the mainstream method for proving higher-dimensional generalisations of Dirac’s theorem were the regularity/blow-up method. This approach was pioneered by Komlós, Sarközy, and Szemerédi, and it entails working with a partition guaranteed by the Szemerédi regularity lemma, embedding most of the desired structure via a randomised algorithm, and then showing that there is a way to finish things off by reducing the remaining task to an application of Hall’s marriage theorem. There exist hypergraph generalisations of the Szemerédi regularity lemma, and extensions of the blow-up method by Keevash, but such an approach quickly becomes prohibitively technical, and moreover, it does not generalise to the set-up of transversals or designs (as the corresponding hypergraphs here are fairly sparse, making Szemerédi-type regularity lemmas inapplicable), so we will not say more about the blow-up methods here.

The development of the absorption machinery has led to a fairly satisfying theory of sufficient conditions for Hamiltonicity in dense hypergraphs, see for example the recent work of Lang and Sanhueza-Matamala [LSM24]. This theory, very roughly speaking, goes as follows. We know that any Hamiltonian graph needs to be (1) connected, and depending on the parity of

the number of vertices, (2) the existence of a perfect matching⁶, and (3) an odd-sized cycle is also forced. It turns out that any graph satisfying (1-3) in a very robust sense has to be Hamiltonian. The robustness property is formalised by asserting that almost all small-sized subsets inherit the properties (1-3), which often holds in dense and quasirandom settings. A version of this theory adapted to hypergraphs can concisely capture many high-dimensional extensions of Dirac's theorem in the literature. Although this theory is powerful, it does not tell us much about how to ensure the properties (1-3), which in some cases yield fairly difficult problems in extremal hypergraph theory, many of which are still unsolved.

In the simple context of Dirac's theorem though, the three properties are fairly simple to establish, allowing us to give a straightforward absorption proof of the following asymptotic relaxation of Dirac's theorem.

Theorem 3.2. *For every $\varepsilon > 0$, for n sufficiently large, any n -vertex graph G with $\delta(G) \geq (1 + \varepsilon)n/2$ has a Hamilton cycle.*

Of course this is weaker than Dirac's theorem, and the proof will be more convoluted than the simple rotation argument we just gave. Our motivation is as follows:

- Minor changes to the proof actually establish the sufficiency of (1-3) discussed above⁷, which significantly extends the minimum degree set-up considered in Dirac's theorem.
- Often, one can find a way to turn asymptotic results as [Theorem 3.2](#) into exact result, by performing what's called a *stability analysis*. In the set-up of Dirac's theorem, this is not particularly difficult, though in higher-dimensions this can get a bit tricky, though such a strategy was successfully pursued in many contexts.
- Recall that our real motivation is to learn the absorption method better, so that we can better understand transversals and designs, and the proof will demonstrate a transparent application of *the reservoir method*, which we will return to on several occasions.

To build some intuition for the proof, let us go back to [\(A\)](#) and [\(B\)](#), and see in what sense they hold in the context of [Theorem 3.2](#), starting with [\(A\)](#).

3.1 99% solution

We have the following easy proposition.

Proposition 3.3. *If $G = (A, B)$ is a bipartite graph with $|A| = |B| = n$ of minimum degree at least $n/2$, then G has a perfect matching.*

Proof. This can be seen by checking Hall's condition, or directly by considering a largest matching as follows. Supposing there exists vertices u, v that are unmatched, their entire neighbourhood must be contained in the vertex set of the largest matching. By the pigeon-hole principle, there must exist an edge of the matching that u and v are both adjacent to. This corresponds to an augmenting path on 3-edges, so performing a switch guarantees a larger matching, a contradiction. \square

Our proof will rely on relatively small subsets of G containing perfect matchings if $\delta(G) \geq (1 + \varepsilon)n/2$.

⁶We could also work with fractional perfect matchings here, which are weight functions on the edge set so that the sum of weights along the edges incident on any vertex is exactly 1.

⁷One should note that for higher-dimensional generalisations of this theory, one needs to work harder, in particular our argument does not generalise straightforwardly to higher dimensions, but the argument should still give a good introduction to start reading the work of Lang and Sanhueza-Matamala [\[LSM24\]](#)

Proposition 3.4. *Let v have $(1 + \varepsilon)|G|/2$ neighbours in G , and let $S \subseteq V(G)$ be a subset of size C , sampled uniformly at random. Then, with probability $1 - \exp(-\Omega(\varepsilon C))$, v has at least $(1 + \varepsilon/2)|S|/2$ neighbours in S .*

Proof. This is essentially direct by Chernoff's bound, though a slight nuance is that we consider a *hypergeometric distribution*, meaning S is sampled not independently, but subject to having a certain size. As one might expect, tail-bounds do not change much in this set-up, as one can formally show by applying Azuma's inequality or related tools. For example, a result of McDiarmid says that if a random variable is a function of a randomly sampled subset of a ground set of a certain size, and the value of the random variable changes only a little bit if an element of the input subset is interchanged, then we get strong concentration bounds as claimed above, see [LW17, Lemma 6.1] for a formal statement and the derivation from the classical Azuma martingale inequality. \square

Using the above and a union bound, we get the following corollary.

Corollary 3.5. *Let A, B be disjoint and random subsets of $V(G)$ each of size C where $\delta(G) \geq (1 + \varepsilon)n/2$. With probability $\geq 1 - 2C \exp(-\Omega(\varepsilon C))$, there exists a perfect matching between A and B .*

Let us imagine $C = (\log n)^2$, and that C divides n . In this case, given a n -vertex G with $\delta(G) \geq (1 + \varepsilon)n/2$, we may partition $V(G)$ randomly into sets of size C as $A_1, A_2, \dots, A_{n/C}$, and invoke Corollary 3.5 between every pair $G' = (A_i, A_{i+1})$ to find a perfect matching between the specified sets (the choice of $C = (\log n)^2$ allows us to comfortably take a union bound over all (A_i, A_{i+1}) (check this!)). Taking a union of all the perfect matchings, we have managed to cover G with $\log^2 n$ paths, or in another perspective, we found a Hamilton cycle, minus $(\log n)^2$ edges, which feels like good enough progress to say that (A) holds in the context of Theorem 3.2. We can go even further, and chain up these paths into a cycle that is *almost* spanning. First, we need a simple lemma stating we can set aside a random set through which all pairs of vertices are well-connected.

Proposition 3.6 (Reservoir exists). *Let G have minimum degree $\geq (1 + \varepsilon)|G|/2$, and let $S \subseteq V(G)$ be a subset of size C , sampled uniformly at random. Then, with probability $1 - |G|^2 \exp(-\Omega(\varepsilon C))$, the following property holds:*

P Every $u, v \in V(G)$ have at least $(\varepsilon/4)|S|$ common neighbours in S .

Proof. Observe that any two vertices $u, v \in V(G)$ has at least $(\varepsilon/2)|G|$ common neighbours in G . The assertion about the random set S picking up an appropriate number of common neighbours for each pair of vertices then comes from a concentration and a union bound argument, same as the one we just saw before. \square

We will think of S as a "reservoir" of vertices that we can use to stitch up the paths we obtain in the argument spelled out after Corollary 3.5. With a bit of foresight, we prove a lemma that also takes as input two vertices u, v that are to be endpoints of a long path covering all vertices outside of S . As the reader might guess, we remark that the specific choice of the parameters is not particularly important, only the relationship between the parameters, and that they are at least polylogarithmic (so that a union-bound can be taken).

Lemma 3.7 (Cover-down step). *Let G have minimum degree $\geq (1 + \varepsilon)n/2$ where $n := |G|$ and let $S \subseteq V(G)$ be of size $C := n^{1/100}$ satisfying **P**. With probability $1 - o_n(1)$, the following holds. For any $u, v \in V(G) \setminus S$, there exists a path P with endpoints $\{u, v\}$, and $V(G) \setminus S \subseteq V(P)$.*

Proof. We know S satisfies **P**, so every pair of points have at least $\varepsilon n^{1/100}/4$ common neighbours in S

Let us suppose for simplicity that $n = n^{1/100} + (\log n)^2 \cdot t$ for some integer $t \sim n/(\log n)^2$.

Partition $V(G) \setminus S$ further into disjoint random sets A_1, \dots, A_t of size $(\log n)^2$ each (noting the graph restricted to the complement of S has minimum degree $(1 + \varepsilon/2)|G|/2$), and with high probability [Corollary 3.5](#) holds for each pair $(A, B) = (A_i, A_{i+1})$ simultaneously by a union bound.

Fix now an outcome of the random sampling satisfying these properties. We can then find a perfect matching in each $G = (A_i, A_{i+1})$ ($1 \leq i \leq t-1$), yielding a collection of $(\log n)^2$ vertex-disjoint paths partitioning $V(G) \setminus S$ (henceforth called spanning path forest). At the cost of increasing the number of paths to $(\log n)^2 + 2$, we can ensure that u and v are both endpoints of a *distinct* path in the spanning path forest, let's call it \mathcal{P} .

Let $\{x_i, y_i\}_{i \in I}$ be a pairing of the endpoints of \mathcal{P} except for u and v , so that if we "merge" each of the endpoints $\{x_i, y_i\}$, the resulting object would be a path with endpoints u and v (convince yourself such a pairing exists!). Now, we claim that there exists a collection of vertex disjoint paths $\{P_i\}_{i \in I}$, each on two edges, with endpoints $\{x_i, y_i\}_{i \in I}$ and the unique internal vertex in S . That $\{P_i\}_{i \in I}$ exists follows from the property of S : for each $\{x_i, y_i\}$, we can find a common neighbour that wasn't previously used on a "connecting path", as there are $\leq (\log n)^2$ connecting paths and $\geq \varepsilon n^{1/100}/4$ common neighbours, one can always find the next required connecting path. \square

The statement of [Lemma 3.7](#) contains a fairly important "cover-down" idea that will be reoccur both whilst studying transversals, and existence of designs. Applying the Lemma with $u \sim v$ being an arbitrary edge of G , we see that we can find a cycle that covers all but a few vertices of G , and moreover, the leftover vertices are restrained to a small subset that was pre-defined. We will later see a bootstrapping variation on this idea called "iterative absorption".

3.2 Absorption

How about [\(B\)](#)? This is where the odd-cycles come in. In the setting of [Theorem 3.2](#) we indeed have many odd-cycles, even triangles. Indeed, any vertex x must be contained in several triangles if the minimum degree is slightly more than half. We call a subgraph $T \subseteq G$ with $u, v, x \in V(T)$ a $(\{u, v\}, x)$ -absorber if T contains a spanning path, and $T \setminus \{x\}$ contains a spanning path, and both spanning paths have $\{u, v\}$ as its endpoints. Observe that for any triangle T with vertices u, v, x , is a $(\{u, v\}, x)$ -absorber. $(\{u, v\}, x)$ -absorbers being plentiful across G for any $x \in V(G)$ is the key "local variability" property we will use in the proof. We recommend the reader the challenge of constructing more delicate $(\{u, v\}, x)$ absorbers that contain no triangles, in fact, no short cycles at all.

Exercise 3.8. Show that for every k there exists a graph T and vertices $u, v, x \in V(T)$ so that T is a $(\{u, v\}, x)$ -absorber, T has at most $O(k^2)$ vertices, and the shortest cycle in T has length at least k .

The motivation for the above exercise is to justify our assertion that odd-cycles being abundant and connectivity being inherited by typical small induced subgraphs is all that is necessary to find Hamilton cycles (in addition to the perfect matchings).

Putting the individual local absorbers together, we can obtain a global absorber for a large reservoir. In general, chaining up local absorbers to obtain such a global property won't be so easy, but in the set-up of Dirac's theorem, it is fairly transparent how this takes place.

Definition 3.9. We call a subgraph $T \subseteq G$ with $u, v \in V(T)$, $S \subseteq V(T)$ a $(\{u, v\}, S)$ -absorber where $S \subseteq V(G)$ if $T \setminus S'$ contains a spanning path for each $S' \subseteq S$, and each such spanning

path has $\{u, v\}$ as its endpoints.

Lemma 3.10. *Let G have minimum degree $\geq (1 + \varepsilon)n/2$ where $n := |G|$ and let $S \subseteq V(G)$ be of size $\leq \gamma n$ where $\gamma \leq \varepsilon/100$. Then, there exists a subgraph T that is a $(\{u, v\}, S)$ -absorber for some $u, v \in V(G)$ where $|T| \leq 5|S|$.*

Proof. First find a collection of disjoint triangles where each triangle contains a unique element of S . Then connect the appropriate pairs of vertices with paths of length two so that the shape in Figure 1 emerges. The simple details are left to the reader.

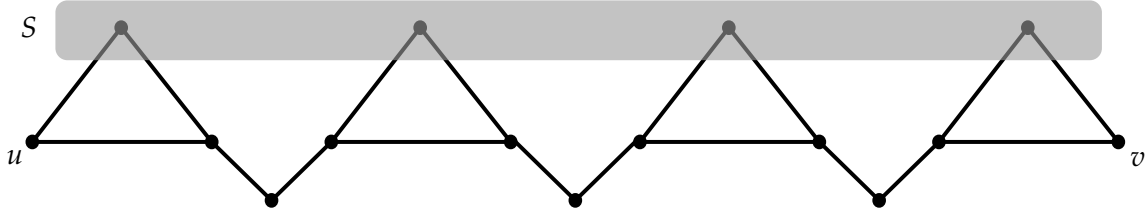


Figure 1: The construction of the $(\{u, v\}, S)$ -absorber. The reader should check that such an object exists under the specified minimum-degree condition whenever S is a subset of size at most $(\varepsilon/100)n$.

The reader should also check that for each subset $S' \subseteq S$ in the above, there exists the desired spanning path "absorbing" $S \setminus S'$. \square

3.3 Putting things together

Proof of Theorem 3.2. Set aside a set S of size $C := n^{1/100}$ with the property **P**, the existence of S is guaranteed by Proposition 3.6. By Lemma 3.10, there exists a subgraph T of size at most $5C$ that is a $(\{u, v\}, S)$ -absorber for some u, v . Applying Lemma 3.7 with the graph G with vertices of $T \setminus \{u, v\}$ deleted (observing this does not meaningfully change the minimum degree of G), and with $\{u, v\}$, we find a path P with endpoints $\{u, v\}$, fully saturating $G \setminus T \setminus S$, and using some vertices of S . The unused vertices of S , meaning $S' := S \setminus V(P)$, combine with T to find a $\{u, v\}$ path P' . $P' \cup P$ is then the desired Hamilton path. \square

3.4 Historical aside

The reservoir/cover-down style of absorption is not how the absorption method was originally popularised by Rödl, Ruciński, and Szemerédi (RRS) [RRS06]. They had a different notion of an "absorbing path", which can absorb vertices coming from anywhere along the graph, as opposed to just a predefined reservoir, as long as the set of vertices to be absorbed is small enough, compared to the size of the absorber. On the other hand, in the above construction, our absorber could absorb any subset of vertices, although they had to live in the reservoir. The reservoir perspective will be more useful later on, but obtaining a RRS-style absorber also isn't too difficult in the setting of Dirac's theorem.

Definition 3.11. Given an ambient graph G , we call a subpath P to be a γ -absorber if for all subsets S of $\leq \gamma|G|$ vertices, $S \cup P$ has a spanning path with the same endpoints as those of P .

Exercise 3.12. Let G be a graph of minimum degree $(1 + \varepsilon)|G|/2$. Show that there exists a $\gamma := \gamma(\varepsilon)$ so that G contains a γ -absorber path P of size at most $\varepsilon|G|/2$.

Hint: Sample a set of $f(\varepsilon)|G|$ random edges, check that for every vertex, some edges that form triangles with that vertex were sampled. Delete the edges around vertices of degree > 2 , and chain up the remainder into a path.

4 Concentration of measure, Rödl nibble, and addressing the "hierarchy issue" with quasirandomness

We are trying to build towards understanding Latin squares that have full transversals (of size n) and near transversals (of size $n - 1$). But before, we need to first be able to demonstrate that all Latin squares have transversals of size $0.99n$, which checks (A) and starts to make the absorption method potentially applicable. The most basic form of such a statement would be as follows. Recall that "Let $n^{-1} \ll \gamma$ " in the beginning of a statement means for any $\gamma > 0$, there exists n^{-1} sufficiently small so that the following statement holds.

Proposition 4.1. *Let $n^{-1} \ll \varepsilon$. Any $3n$ -vertex n -regular tripartite linear hypergraph (i.e. Latin square) has a perfect matching (i.e. transversal) covering all but εn vertices.*

We will prove results like the above via the *semi-random method*, or the *Rödl nibble*. The rough idea is we'll see (once we've built some intuition) that if we build a matching by a *random greedy strategy*, i.e. choosing an edge at random among all options that are disjoint with all previously selected edges, then we should get a desirable outcome. Analysing the random greedy strategy is however often tricky (though in many cases, including the above proposition, have been done, and isn't actually so technical with the above choice of parameters). The idea of the Rödl nibble is to group the random choices into big batches to ease the analysis. Think choosing εn random edges in the above (the bite). Then, do this about $1/\varepsilon n$ times and hope everything goes well (the nibbling). The gain is that the number of randomness stages to analyse has been reduced from n to $1/\varepsilon = O(1)$ — so the errors coming from the deviations from the mean have much less time to accumulate.

This is an immensely powerful trick and finds applications quite widely whenever one wishes to analyse a random greedy algorithm but is willing to compromise a little, see for example the work of Ford, Green, Konyagin, Maynard, Tao on long gaps between primes, or the work of Campos, Jenssen, Michelen, and Sahasrabudhe on "amorphous" sphere packings in high dimensions.

Something stronger about nearly-regular hypergraphs is true and follows from the Rödl nibble, and the *hierarchy* of parameters here is useful to internalise. A hypergraph is $(\delta \pm \gamma)n$ -regular if all degrees are in the range $[(\delta - \gamma)n, (\delta + \gamma)n]$.

Proposition 4.2. *Let $n^{-1} \ll \gamma \ll \delta, \varepsilon$. Any $3n$ -vertex $(\delta \pm \gamma)n$ -regular tripartite linear hypergraph (can be viewed as a partially filled Latin square) has a perfect matching covering all but γn vertices.*

The important thing in the above is that $\gamma \ll \delta$, so that the degrees are actually concentrated in a small space, and $\gamma \ll \varepsilon$ — if we are hoping the complete $(1 - \varepsilon)$ fraction of the target process, the "unpredictability" in the degrees should better be much better constrained than a γn space for $\gamma \ll \varepsilon$.

In reality, we will need to prove both a quantitative and qualitative strengthening of such a result so the absorption method can meaningfully be applied.

Firstly, we will need to be able to find transversals of size $(1 - n^{-\varepsilon})n$ for some small constant $\varepsilon > 0$ — this is because it will turn out that our definition of "local" switches will need to allow for chains of switches up to $\log n$ coordinates, something that hasn't appeared in the basic applications we have seen thus far (where switches have always been of order $O(1)$). This in turns translates to being able to deal with leftovers from the 99% part only when the leftover is $\ll n/\text{polylog}(n)$, which is the case when it is $\ll n^{1-\varepsilon}$. Thankfully, the probabilistic method does just give stronger bounds such as these, so we won't need to work extra hard for this.

Secondly, we will need to deal with a certain *hierarchy issue*. Recall the basic premise of the absorption method: we first do some preparation to build some flexible structure \mathcal{F} , do 99%

of the task, and show that the leftover combines with \mathcal{F} to produce a full solution. In both applications of the method we've seen, it was important that the leftover was comparable, or a fair bit smaller than the flexible structure \mathcal{F} , and this is a fairly general phenomenon. That is, if we are working in a n -vertex graph, find a "flexible absorber" \mathcal{F} of size an , \mathcal{F} is only able to "absorb" sets of size up to bn for $b \ll a$.

The reader might want to stop and think for a moment about the hole in the strategy of applying something like [Proposition 4.2](#) after a flexible absorber is set aside in the beginning of the argument.

The issue is, when we are setting aside \mathcal{F} of size an , assuming a worst-case condition, γ in [Proposition 4.2](#) will become at least as large as a , so then ε will become $\varepsilon \gg a$. So if we naively set an absorber aside and hope everything will be okay, we will be disappointed in the end as we will end up with a leftover much larger in size than the absorber we set aside, rendering the absorber effectively useless.

How we deal with this issue in the set-up of transversals vs. designs will be quite different – but in both cases, we need a *regularity-boost* idea. Something that we do or observe after the absorber has been set aside, to tame the hierarchy of our parameters once again. In the setting of the Latin square hypergraph, this will boil down to noticing some *quasirandomness* properties random subgraphs of Latin squares have, which using the standard theory of quasirandomness (here we opt for that of Thomason (i.e. jumbledness)) will allow us to say that even in the worst case, setting aside an absorber won't damage the hierarchy all that much. See [Section 4.3](#) for details.

Before we can analyse the nibble and prove an appropriate strengthening of [Proposition 4.2](#) compatible with our absorption strategy, we need to first review the concentration of measure toolkit.

4.1 Toolkit for concentration

The simplest one of all is Markov's inequality that says for a non-negative random variable X , we have $\mathbb{P}(X \geq a) \leq \frac{\mathbb{E}[X]}{a}$ where $a > 0$ is arbitrary. This one really is quite transparent: for example, it says probability that X is more than twice its expectation is at most $1/2$. As this considers only the expectation and nothing else, we call it a first-moment bound. If we are in a position where we can reason about $\mathbb{E}[(X - \mathbb{E}[X])^2]$, then we can apply Markov to the random variable $(X - \mathbb{E}[X])^2$, and get more powerful bounds in terms of the variance, a second-moment bound (also called Chebyshev's inequality). If our random variable breaks up into a sum of nice little independent chunks X_i with $P(X_i = 1) = p_i$ and $P(X_i = 0) = 1 - p_i$, computing the second-moment is actually very easy. But why stop there, at that point we can compute for any t , $\mathbb{E}[e^{tX_i}]$, the moment generating function, and apply Markov to that. Point is that if $\sum X_i = X$, e^{tX} can be expressed as a product e^{tX_i} , and the expectation of that product splits into the expectation of the individual pieces if the X_i are independent. So we have:

Lemma 4.3 (Chernoff bound). *Let $X := \sum_{i=1}^m X_i$ where $(X_i)_{i \in [m]}$ is a sequence of independent indicator random variables with $\mathbb{P}(X_i = 1) = p_i$. Then, for any $0 < \gamma < 1$, we have that*

$$\mathbb{P}(|X - \mathbb{E}[X]| \geq \gamma \mathbb{E}[X]) \leq 2e^{-\mathbb{E}[X]\gamma^2/3}$$

We use the following corollary of Chernoff's bound often: that if R is a p -random subset of an n -element set (p -random means each element sampled independently with probability p), then with high probability we have that $|pn - |R|| \leq \log n \sqrt{n}$.

Now onto more complicated random variables with dependencies. We have a product probability space $\Omega = \prod_{i=1}^n \Omega_i$ (this simply means we have n independent trials) and $X: \Omega \rightarrow \mathbb{R}$ is a random variable. It's important to digest what's being said here, we are saying **X is some random variable that's determined by n independent trials**, but that's all we're assuming.

X is called **C-Lipschitz** if $|X(\omega) - X(\omega')| \leq C$ whenever ω and ω' differ in at most 1-coordinate. We will refer to the following standard bound as McDiarmid's inequality.

Lemma 4.4 (McDiarmid's inequality). *Let X be C-Lipschitz random variable on a product probability space with n coordinates. Then, for any $t > 0$,*

$$\mathbb{P}(|X - \mathbb{E}(X)| > \gamma \mathbb{E}[X]) \leq 2e^{-\frac{\gamma^2 \mathbb{E}[X]^2}{nC^2}}.$$

McDiarmid applies more generally than Chernoff, but if $\mathbb{E}[X] = o(n)$, (where n is the number of coordinates in our product probability space), it starts to perform much worse quantitatively. It can be proved in a similar way to Chernoff's bound. The dependency on n can be a deal-breaker in many situations we want to apply McDiarmid's inequality. In such situations, Talagrand's inequality comes to the rescue, whose proof is non-trivial, and makes crucial use of a "certifiability" assumption.

Lemma 4.5 (Talagrand's inequality). *Let X be a non-negative r.v. determined by n independent trials, and satisfying the following for some $r, c > 0$.*

1. X is C-Lipschitz.
2. *For any s , and sample ω if $X(\omega) \geq s$, that's because there are at most rs -trials that we can point to as a "certificate". More precisely, there are $\leq rs$ indices of ω , so that for all other samples ω' that agree with ω on those $\leq rs$ indices, $X(\omega') \geq s$ also.*

Then, for all $t > \sqrt{\mathbb{E}(X)}$, if $\mathbb{E}(X)$ is sufficiently large and $\beta < 1/8c^2r$, we have:

$$\mathbb{P}(|X - \mathbb{E}(X)| > t) \leq 2e^{-\frac{\beta t^2}{\mathbb{E}(X)}}.$$

Note how the dependency on n just vanished under the mild certifiability assumption, bringing us back to the quantitative strength of Chernoff, just magic!

What about random variables that are not determined by n independent trials, but dependent trials? For example, this would be the case any time we want to analyse a random greedy process. We have some randomness at each step, but the randomness is also highly restricted by potentially bad choices we've made in the past. These kind of situations can turn into head-scratchers real fast, but the canonical way to deal with them is to reason about how much the information coming in at step i would change our prediction of X at any given step, and apply Azuma's inequality (the canonical martingale inequality):

Lemma 4.6 (Azuma's inequality). *Let X be a r.v. determined by **not necessarily independent** outcomes of n trials, T_1, \dots, T_n , such that for any $i \in [n]$, and any two possible sequences of outcomes*

$$t_1, \dots, t_{i-1}, t_i$$

and

$$t_1, \dots, t_{i-1}, t'_i$$

we have

$$\left| \mathbb{E} \left[X \mid \bigwedge_{1 \leq j \leq i} T_j = t_j \right] - \mathbb{E} \left[X \mid \bigwedge_{1 \leq j \leq i-1} T_j = t_j \text{ and } T_i = t'_i \right] \right| \leq c_i$$

then

$$\mathbb{P}(|X - \mathbb{E}(X)| > t) \leq 2e^{t^2 / (2 \sum_{i \in [n]} c_i^2)}$$

Azuma and McDiarmid are incomparable. Azuma lets us deal with dependencies across trials, and McDiarmid lets us get rid of the dependence on the number of trials, assuming independence and certifiability.

Exercise. Derive McDiarmid's inequality from Azuma's inequality.

4.2 Defining and analysing the nibble

Recall that every bipartite d -regular graph has a perfect matching. Can we recover (an approximation of) this fact with the probabilistic method? It's not going to work if each vertex on one side chooses a neighbour uniformly at random. This doesn't even work for $K_{n,n}$ — with high probability, something like a third of vertices will not be seen by the candidate matching, i.e. there will be a lot of clashes (exercise!). Something that seems a lot more promising is the "random greedy algorithm". That is, at stage i , pick a random edge among all those edges that don't intersect with the previously chosen edges. This one works for trivial reasons in $K_{n,n}$, but does it work well for some arbitrary d -regular $2n$ -vertex bipartite graph? (We may even imagine $d = \text{poly}(n)$ for simplicity.) In particular, can such an algorithm keep going, with high probability, for $(1 - o(1))n$ steps? The answer in this case is yes, and it can be shown by setting things up properly for an application of Azuma's inequality — but this is fairly delicate to set things up properly and control the potential deviations in the conditional expectations *dynamically* along the whole trajectory of the random process. But it can be done, see [SL22] for an example in a simplified setting.

The idea of nibble is extremely simple: let us do something in-between the stupid random algorithm of randomising all at once fully independently and the delicate random greedy algorithm: Let's randomise in small batches (bites) and slowly, but still just in $O(1)$ steps, eat away our graph with a partial matching until it's mostly gone. The idea is often associated to Rödl's work on constructing "approximate" designs, but goes back further than that to work of Ajtai, Komlós, Pintz, Spencer, and, you've guessed it, Szemerédi. It seems that Desmond Tutu has also discovered the basic idea independently, as the following quote suggests:

The nibble method

- "There's only one way to eat an elephant: one bite at a time."

Digesting the following definition is important for our framework.

Notation Given real numbers a, b, c , we write $a = b \pm c$ to denote that $b - c \leq a \leq b + c$. We say a graph G is $(1 \pm \gamma)d$ -regular if $d_G(v) = (1 \pm \gamma)d$ for each $v \in V(G)$. We use standard notation for "hierarchies" of constants, writing $x \ll y$ to mean that there is a non-decreasing function $f : (0, 1] \rightarrow (0, 1]$ such that all the relevant subsequent statements hold for $x \leq f(y)$. Hierarchies with multiple constants are defined similarly, with the functions chosen from right to left, for example, for $x \ll y \ll z$.

With Tutu's idea, we can easily prove the following, which is a baby case of the nibble:

Proposition 4.7. Suppose $d \geq n^{1/100}$, and suppose $1/n \ll \gamma \ll \varepsilon \leq 1$. Let G be a $2n$ -vertex bipartite graph that is $(1 \pm \gamma)d$ -regular (all degrees are in this range). Then, G has a matching of size $(1 - \varepsilon)n$.

Recall the \ll notation defined above: this is saying for every ε , if γ is sufficiently small w.r.t. to ε , and n is sufficiently large w.r.t. everything else, the assertion holds. We suppress the literal dependencies to highlight the hierarchy, which is what matters the most.

Proposition 4.7 can be derived from Hall's marriage theorem very easily, with linear dependence between γ and ε , and not much of an assumption about n or d in relation to γ and ε . So why are we bothering with these trivialities? It's conceptually interesting (and has non-trivial applications) that a random algorithm can recover this, and as we will see, the proof generalises to higher dimensions, whereas Hall's marriage theorem does not.

We can derive the above from:

Lemma 4.8. Suppose $d \geq n^{1/1000}$, and suppose $1/n \ll \gamma_1 \ll \gamma_2, \beta \leq 1$. Let G be a $2n$ -vertex bipartite graph that is $(1 \pm \gamma_1)d$ -regular. Then, G has a set of edges M such that the following all hold.

1. $|M| = (1 \pm \gamma_2)\beta n$
2. $|V(M)| = (1 \pm \gamma_2)(1 - e^{-\beta})(2n)$
3. $G \setminus V(M)$ is a $(1 \pm \gamma_2)e^{-\beta}d$ -regular graph.

Note above M is not necessarily a matching but close enough as it spans almost twice its size as a vertex set. M will simply be a set of edges with each edge sampled with probability β/d , which is why the $e^{-\beta}$ terms pop up naturally.

Exercise. Derive **Proposition 4.7** from **Lemma 4.8**. How should we select β in terms of the ε ? Should we select the same β each time? How should we set up the $\gamma_1, \gamma_2, \gamma_3, \dots$. How many times should we plan on applying **Lemma 4.8** as a function of ε ? Is it an issue that the M that the lemma gives isn't a matching? Should we clean up all the clashing edges in one step, or all at once?

Proof of Lemma 4.8. We will select $p = \beta/d$ and create M by sampling each edge of G at random, independently, with probability p . We will show that with positive probability, it satisfies 1., 2. and 3.

Some basic calculations:

- $\mathbb{E}[|M|] = p \cdot e(G)$ (linearity of expectation) which is $= (1 \pm \gamma_1)pnd$. By independence, we can apply Chernoff to deduce $\mathbb{P}(|M| \neq (1 \pm 2\gamma_1)\beta n) \leq 2e^{-\beta n \gamma_1^2/3} = o_{n,d}(1)$.
- For any $v \in V(G)$, we have

$$\mathbb{P}(v \in V(M)) = 1 - (1 - p)^{d_G(v)} \simeq 1 - e^{-pd_G(v)} = 1 - e^{-\beta(1 \pm 3\gamma_1)} = 1 - e^{-\beta}(1 \pm 5\gamma_1)$$

- For any subset $S \subseteq V(G)$, consider $I_S = \sum_{v \in S} I_{v \in V(M)} = |S \cap V(M)|$. If S is restricted to come from just one of the sides of the bipartition, I_S is a sum of Bernoulli random variables, as the random trials determining $I_{v \in V(M)}$ for distinct v occurs on disjoint sets of edges which we sample independently! So we can apply Chernoff for sets of the form $S = N(v)$, which will be key to maintain regularity. So for any v we have:

$$\mathbb{P}(|N(v) \setminus V(M)| \neq (1 \pm 10\gamma_1)e^{-\beta}) \leq e^{-\text{poly}(d)}$$

- By the same reasoning as above, we can deduce that

$$\mathbb{P}(|V(M)| \neq (1 \pm \gamma_2)e^{-\beta}(2n)) \leq e^{-\text{poly}(d)}$$

So with high positive probability, M satisfies all of the above, and for each v (check the union bound makes sense!). \square

Exercise. What if the graph wasn't bipartite, but still $(1 \pm \gamma)d$ -regular. Then Chernoff doesn't apply everywhere it should. How should we proceed? Does McDiarmid work? If we go for Talagrand, how can we think of the random variables so that they are "certifiable"?

Exercise. Try to make everything above explicit, without relying on the \ll notation.

Exercise. Why was the $d = \text{poly}(n)$ crucial throughout? Can we omit this assumption somehow? Hint: Use the Lovász local lemma.

Exercise. Can we do away with the nibble, and analyse the "edge-by-edge" greedy random process, using Azuma's inequality? Does this give better bounds?

4.3 Fixing the hierarchy issue: The actual strong 99%-lemma that we need

Here we give a tripartite generalisation of a nibble type statement that deals with the "hierarchy issue" discussed earlier on in this section. Given a nearly regular, linear hypergraph, the nibble applies to find a almost spanning matchings, following the analysis given in the previous section (adapted to higher uniformities). It should not come as a surprise that if one samples the vertices of a regular hypergraph with probability p independently, the resulting hypergraph will be nearly regular with small deviations (exercise: prove this via McDiarmid's inequality), and hence contain almost spanning matchings also. In this section, we state a result that allows one to integrate an adversarially chosen set into such an argument, with the idea being that after we set aside an absorber, the leftover set is potentially adversarially chosen (recall the earlier discussion).

This requires some additional assumptions on top of linearity and regularity. To see this, consider a regular linear tripartite hypergraph (A, B, C) that is the disjoint union of several Latin squares. If we sample A' and B' as p -random subsets, but take $C' \subseteq C$ of size pn as an adversarially chosen subset (chosen after A' and B' are sampled), we cannot even expect there to be any edges in the resulting hypergraph on (A', B', C') .

However, it turns out that if the original regular hypergraph satisfies a certain definition of "quasirandomness" (which naturally holds for "complete" linear tripartite hypergraphs, i.e. Latin squares), then the above degeneracy doesn't happen. That is, it holds that for typical choices of A' and B' , *any* choice of C' yields some (A', B', C') that essentially gives a nearly regular graph (at least in average degree – after which the low degree vertices can be cleaned). This is reminiscent of the similar story in 2-graph quasirandomness that allows one to control edge counts $e(A, B)$ for *any* A, B – and as it turns out, there is a way to reduce 3-graph quasirandomness to 2-graph quasirandomness in this specialised set-up (though generally, defining hypergraph quasirandomness is notoriously tricky).

We now give some definitions towards "quasirandomness", or "typicality", which are natural generalisations of graph quasirandomness ($\sim pn$ -regular graphs with common neighbourhoods being $\sim p^2n$, or equivalently, $\sim p^4n^4$ cycles).

For a 3-uniform, 3-partite hypergraph H , vertices u, v and a subset $U \subseteq V(H)$, we define the **pair degree** of (u, v) into U as the number of vertices in U which are in the neighbourhood of

both u and v , i.e. the number of vertices z in U such that there exists $v, w \in V(H)$ such that $\{u, z, v\}$ and $\{v, z, w\}$ are both edges of H . For a 2-uniform, bipartite graph H , vertices u, v , and a subset $U \subseteq V(H)$, we define the **pair degree** of (u, v) into U as the number of mutual neighbours of u and v in U .

We say that a r -partite r -uniform hypergraph H (where r will be either 2 or 3) is (γ, p, n) -**regular** if every part has $(1 \pm \gamma)n$ vertices and every vertex has degree $(1 \pm \gamma)pn$. We say that H is (γ, p, n) -**typical** if, additionally, every pair of vertices x, y in the same part of H have pair degree $(1 \pm \gamma)p^2n$ into every other part of H . We say that a hypergraph is **linear** if through every pair of vertices, there is at most one edge.

Observation 4.9. *Tripartite hypergraphs that are $(0, 1, n)$ -typical and linear are exactly the hypergraphs that correspond to order n Latin squares.*

One result we need is the following, which is proved by the above nibble idea if we keep track of the parameters.

Lemma 4.10. *Let $1/n \ll \gamma, \delta$. Every (γ, δ, n) -regular linear tripartite hypergraph has a matching covering all but at most $n^{1-1/500} + 3\gamma n$ vertices.*

Proof. Following the outline of the previous bipartite nibble argument, one can adapt this to the tripartite case, replacing applications of Chernoff's bound with Talagrand's inequality.

For an explicit proof, I recommend the Molloy–Reed book, or Luke Postle's lectures on Youtube. \square

We also need an elementary property of typical bipartite graphs that gives us "global average degree" control of subgraphs from "local pair degree control". Typical graphs have the following well-known pseudorandomness condition, which dates back to work of Thomason [Tho89]. Note that for the rest of the section, we assume that bipartite graphs come with a partition of their vertex set as (A, B) and similarly tripartite hypergraphs come with a partition (A, B, C) .

Lemma 4.11. *Let G be a (γ, δ, n) -typical bipartite graph. Then for every $A' \subseteq A, B' \subseteq B$, we have $e(A', B') = \delta|A'||B'| \pm 5\sqrt{(\delta + \gamma)n^3} \pm \gamma n^2$.*

The above lemma is deep, though the proof itself is actually a fairly straightforward counting argument.

Exercise. Prove Lemma 4.11.

Combined with the nibble, we can deduce the following, which will let us find a large matching even after an absorber is removed:

Lemma 4.12. *Let $H = (A, B, C)$ be a $(0, 1, n)$ -typical tripartite hypergraph. Let $p \geq n^{-1/650}$. Let A', B', C' be p -random subsets of A, B, C respectively, not necessarily independent. Set $R := A' \cup B' \cup C'$. With high probability the following holds. Let $q \leq 5p$. For any $X \subseteq V(H) \setminus R$ with $|X \cap A|, |X \cap B|, |X \cap C| = (1 \pm n^{-0.25})qn$, there is a matching in $R \cup X$ covering all but at most $n^{1-10^{-4}}$ vertices of $R \cup X$.*

Exercise. Prove Lemma 4.12, using Lemma 4.11, Lemma 4.10, and McDiarmid/Chernoff inequalities. See the nibble section on [MP25] for a solution.

5 Latin squares with full transversals / perfect matchings

Armed with the nibble, we have fairly flexible approximate results, so it's about time we start discussing how to turn approximate results into exact results.

Recall the set-up: $H = (A, B, C)$ is a linear tripartite n -regular hypergraph, or equivalently a Latin square, or a $(0, 1, n)$ -typical tripartite hypergraph. Montgomery's theorem states that H contains a matching with $n - 1$ edges, and we cannot hope for any better in general, because of [Example 2.3](#), i.e. Cayley tables of even cyclic groups. So far, it should be fairly non-obvious how we ought to apply an absorption strategy that would get us so close to a perfect matching, but stop one short of it. Wrapping our minds around this will require us to build some intuition. A good place to build this intuition will be some restricted class of Latin squares where we can guarantee perfect matchings / full transversals. These restricted Latin squares belong to one of two categories:

1. **The random Latin square** (with probability $1 - o(1)$). In other words, the fraction of Latin squares which do not contain transversals goes to 0 as $n \rightarrow \infty$. This was proved by Kwan in 2020 by way of introducing a method to reason about substructure counts in typical Latin squares, and combining this method with an absorption argument, which we will shortly discuss ⁸. Kwan's results were strengthened later by Bowtell–Montgomery, who proved that a random Latin square can be partitioned into transversals. ⁹
2. **Cayley tables of groups with "the Hall–Paige condition"**. We will momentarily explain the said condition, but here it turns out that the main content comes from the Cayley tables of nonabelian simple groups, which have the Hall–Paige condition, and thus contain perfect matchings.

We will now digress a bit, with the goal of making it clear that in some sense, both classes above are in fact members of the same deterministic notion of a "simple" Latin square. The philosophy behind this definition will be quite important as we go on to the proof of Montgomery's theorem.

Which Cayley tables can contain perfect matchings? Let us first make it clear the definition of the tripartite hypergraph that associates with a given finite group G . Here we have $H = (A, B, C) = (G, G, G)$, and $(a, b, c) \in A \times B \times C$ is an edge if and only if $abc = 0$ in G . We could have also defined edges with the relation $ab = c$, but this gives an isomorphic hypergraph. It'll often be more convenient to have more symmetry between A, B, C , hence our convention.

Now suppose a Cayley table has a perfect matching. Note that this by definition gives us two bijections on G , ϕ and ψ , satisfying $g\phi(g)\psi(g) = 0$ for all $g \in G$. Let H be any normal subgroup of G so that G/H is abelian (of course G is normal in G so H exists). Then, combining all these equations together in G/H , where we are allowed to rearrange the terms, we obtain that $\prod g \prod \phi(g) \prod \psi(g) = 0$, but of course all this is saying is $\prod g = 0$ in G/H . To obtain the most possible information from this identity, we should select H so that G/H is the abelian quotient carrying the most amount of information. The canonical way to do this is to take H to be the commutator subgroup G' , i.e. the subgroup generated by the commutator elements, i.e. those elements of the form $[g, h] = ghg^{-1}h^{-1}$. Key thing to recall here is that $gh = [g, h]hg$, so to pretend as though the operation commutes, we have to insert these commutators all around

⁸In a nutshell, Kwan's method gives a formal way to say that counts of a $O(1)$ -sized subhypergraph in a random Latin square is similar to the count of the same subhypergraph in a binomial random hypergraph with n vertices and $\sim n^2$ edges under certain assumptions. Kwan's method relies on Keevash's results on existence of designs – in particular, on the fact that a sufficiently sparse binomial random hypergraph can be completed to a full Latin square, with high probability. We may discuss this again when we move on to designs.

⁹This is a striking result, as it spectacularly contradicts a conjecture of Euler that asserts no such Latin square can exist when $n \equiv 2 \pmod{4}$ (that had previously been contradicted in the 1960s by constructive strategies).

the place, and modding the subgroup generated by such elements, we truly obtain something where everything commutes.

In conclusion, we obtain that if the Cayley table of G contains a perfect matching, then we have that product of all elements of G is trivial in $G/G' =: G^{\text{ab}}$ (the abelianization of G), i.e. that product of all elements of G is a member of G' the commutator subgroup. This condition is called the **Hall–Paige** condition.

Proposition 5.1. *The following properties are all equivalent for a finite group G , and hence we can call all of them the Hall–Paige condition.*

1. $\prod G$ is in G' .
2. There exists an ordering of the group elements so that $g_1 g_2 \cdots g_n$ is the identity in G .
3. The Sylow 2-subgroups of G are either trivial or non-cyclic.

Proving the above would be bit of a digression, but it isn't a difficult proposition – especially in the case of abelian groups.

Exercise. Check [Proposition 5.1](#) for abelian groups.

Exercise. Describe the structure of abelian groups with the Hall–Paige condition in terms of their cyclic product decomposition. Do their Cayley tables contain perfect matchings? You may want to focus on the case of an odd order cyclic group, and \mathbb{F}_2^n . Also the following observation is helpful: the Cayley tables of H and K having perfect matchings imply that so does the Cayley table of $H \times K$.

Exercise. Check that large abelian groups with the Hall–Paige condition contain transversals by reducing this to Montgomery's theorem.

A solution to the above exercises shows that the Hall–Paige condition has some explanatory power, at least over abelian groups. Hall and Paige boldly conjectured in 1955 that the Hall–Paige condition is a necessary and sufficient condition for an arbitrary (even nonabelian) Cayley table to contain a perfect matching. In 2009, Wilcox found a clever but fairly elementary way to reduce the Hall–Paige conjecture to the case of simple groups. To see why such a thing ought to be possible in principle, you can try to show that if $H \leq G$ is normal, and the Cayley tables of H and G/H both have perfect matchings, then so does G (exercise). As simple groups have been classified, this has made it possible to prove the Hall–Paige conjecture by going through them one by one and verifying that they have transversals. Evans and Bray accomplished this. A different proof for large groups (no CFSG reliance) was given in a remarkable paper by Eberhard–Mrazovic–Manners, who determined even the number of perfect matchings up to $1 + o(1)$ terms in Cayley tables with the Hall–Paige condition (it's extremely non-obvious that such an asymptotic formula should exist for the number of transversals!).

In these notes we will discuss an absorption-based proof for the Hall–Paige conjecture, based on [MP25], which also will serve as a good model towards understanding Montgomery's theorem, which uses related techniques. A consequence of [MP25] is that for "generic" subsets $A, B, C \subseteq G$, the induced subhypergraph of the Cayley table of G has a perfect matching if and only if $\prod A \prod B \prod C \in G'$.

Exercise. Assuming that subsets $S \subseteq G$ with $|S| = |G| - o(|G|)$ are "generic", deduce Montgomery's theorem that Latin squares contain near perfect matchings in the specific case of Cayley tables from the result stated in the above paragraph.

6 Absorbers and simple Latin squares

In this section, we give a certain "quasirandomness" condition for Latin squares. We call the resulting Latin squares "simple". It turns out that random Latin squares are simple with high probability, and so are the Cayley tables of nonabelian simple groups. We will show (sufficiently large) simple Latin squares have perfect matchings.

Our notion of "simple" will simply come from a combinatorial desire to want to make an absorption argument work. To do this, let us try to pin down exactly what we want from this magical absorber that we are trying to construct.

Definition 6.1. Let $T \subseteq V(H)$, where H is some tripartite hypergraph. We call T a β -**absorber** (for H) if for all $L \subseteq V(H) \setminus T$ such that L is balanced with respect to the tripartition of H and $|S| \leq \beta \cdot |V(H)|$, $H[T \cup L]$ admits a perfect matching.

Note that T itself must be balanced with respect to the tripartition. Indeed, this we see by simply invoking its property with $S = \emptyset$ to deduce that $H[T]$ has a perfect matching.

Exercise. Supposing H is a Cayley table of an abelian group, show that H does not contain any non-trivial β -absorbers with $\beta > 0$.

Despite the harrowing nature of the previous exercise, it will turn out that for "simple" Latin squares, we can actually find non-trivial absorbers. And using the nibble machinery introduced in the previous sections (recall [Lemma 4.12](#)) – we will see that these absorbers let us turn almost perfect matchings into full perfect matchings.

Lemma 6.2. Let $p \leq 1/100$ and let n be sufficiently large. Let H be a Latin square of order n . Suppose that with probability at least $1/5$, a p -random subset $R \subseteq V(H)$ contains some $T \subseteq R$ that is a $(\log n)^{-10}$ -absorber. Then, (with probability 1), H contains a perfect matching.

Of course, there is a lot of slack in the choice of parameters above. The important thing is that [Lemma 4.12](#) leaves a leftover of size $n^{1-\varepsilon}$ for positive $\varepsilon > 0$, so our absorber will need to be able to integrate leftovers of this size. As it turns out, we can deal with leftovers of size as large as $\sim 1/(\log n)$, so that's no problem. We wish to find the absorber inside a p -random random set, to fix up the "hierarchy issue" raised in the nibble section, and for this any choice such as $p = 1/100$ is compatible with the hypothesis $q \leq 5p$ of [Lemma 4.12](#). And [Lemma 4.12](#) already holds with high probability, so all that we care here is that we can find the absorber with positive probability — then the random set we set aside with positive probability satisfies the conclusion of [Lemma 4.12](#) and contains a absorber as well, so by the union bound and the probabilistic method we can fix a random set R satisfying both of these properties.

Exercise. Fill in the details of deriving [Lemma 6.2](#) from [Lemma 4.12](#).

6.1 Reduction to building a reservoir

To find an absorber for H , we will show that it suffices to find an absorber for some $S \subseteq H$ that is much smaller than H , as long as S is randomly chosen. First, we give our definition for what it means to absorb a specific set.

Definition 6.3. Let $T, S \subseteq V(H)$, where H is some tripartite hypergraph, and let $k \in \mathbb{N}$. We say that T **k -absorbs** S if for all balanced (w.r.t the tripartition) subsets $S' \subseteq S \setminus T$ with $|S'| = k$, $S' \cup T$ admits a perfect matching.

Here, we view S as a *reservoir* of flexible vertices, similar to the proof of Dirac's theorem that we discussed earlier on. The restriction on $|S'|$ will make it somewhat easier to construct T — but it's not an important weakening of the statement as we will see. The following proposition justifies this reduction, and the proof idea is a *cover-down* which we have already seen before.

Proposition 6.4. Let $p \leq 1/200$ and let n be sufficiently large. Let H be a Latin square of order n . Suppose that with probability at least $1/5$, a p -random subset $R \subseteq V(H)$ has the following property:

P For all $S \subseteq V(H)$ with $|S| \leq n/(\log n)^5$ and $k \in \mathbb{N}$ with $|k| \leq |S|/10$, there is some $T \subseteq R$ that k -absorbs S .

Then, with probability at least $1/10$, a p -random set R also has the property that there exists some $T' \subseteq R$ that is a $(\log n)^{-10}$ -absorber.

Sketch. The idea is to apply **P** with S also a random set of size $n/(\log n)^{10}$, sampled disjointly with R , and $k := |S| - |S|/(\log n)^7$, and find some T that k -absorbs S . With high probability, every vertex of H will send $\Omega(p^2n) = \Omega(n)$ edges into S , call this property (*). Subject to that, we claim that $S \cup T$ is a $(\log n)^{10}$ -absorber for H . Indeed, take some L of size $\leq n/(\log n)^{10}$. First, by repeatedly invoking (*), there exists a matching M_1 on $|L|$ edges saturating L , with the other vertices of the matching contained in S (note the set of such vertices is balanced, as L is balanced). We cannot absorb $S \setminus V(M_1)$ via T just yet, simply because $k \gg |S \setminus V(M_1)|$. So we need to shrink S some more, and we can do this simply by finding another matching M_2 , disjoint with M_1 , of the appropriate size, just by repeatedly invoking (*), so that $k = |S \setminus (V(M_1) \cup V(M_2))|$. By property of T , there exists a matching M_3 on vertex set $T \cup (S \setminus (V(M_1) \cup V(M_2)))$. Overall, $M_1 \cup M_2 \cup M_3$ is a matching on vertex set $L \cup T$ as needed. \square

6.2 Definition of simple Latin squares

So what we really need to understand is when **P** holds. It will be the case that for simple Latin squares, **P** holds. We now define simple Latin squares. The intuition will be that in perfect Latin squares, we can 1-absorb any pair of vertices in a robust and local way. We will later show that this local flexibility can be turned into the global flexibility that **P** requires, by applying the technique of distributive absorption.

Definition 6.5. Let H be a Latin square of order n , and let x, y be two vertices of H . We call $\{x, y\}$ an **K-exchangeable pair** if there exists a collection of n/K disjoint subsets $T \subseteq V(H)$ of size $\leq 100K$ with the property that T 1-absorbs $\{x, y\}$.

Observe that a fixed set 1-absorbing $\{x, y\}$ implies that x and y have to come from the same part of the tripartition of the ambient Latin square. So when we think about exchangeability, it is natural to restrict our attention to one of the parts of the tripartition of a Latin square $H = (A, B, C)$, and by convention, we will simply look at C .

Definition 6.6. We call a Latin square $H = (A, B, C)$ **K-simple** if all pairs $x, y \in C$ form a K -exchangeable pair.

The following lemma shows that focusing only on C does not cost us much.

Lemma 6.7. Let $H = (A, B, C)$ be a K -simple Latin square. Then, all pairs $x, y \in B$ are $10K$ -exchangeable. Similarly, all pairs in A are $10K$ -exchangeable.

Proof. □

6.3 From 1 in 2 absorbers to 1 in 100 absorbers

Definition 6.8. Let H be a Latin square of order n , and let X be a subset of vertices of H . We call X a **K-exchangeable set** if there exists a collection of n/K disjoint subsets $T \subseteq V(H)$ of size $\leq K$ with the property that T 1-absorbs X .

Lemma 6.9. Let $K' \gg K$. Let $H = (A, B, C)$ be a K -simple Latin square. Let $X \subseteq \square$ for some $\square \in \{A, B, C\}$ of size $\leq K$. Then, X is a K' -exchangeable set.

Proof. □

6.4 Distributive absorption

The following was first shown by Montgomery [Mon19] in 2019.

Proposition 6.10. Let $\ell \leq k$ be positive integers. There exists a bipartite graph, with bipartition $(X \cup Y, Z)$ where X and Y are disjoint, $|X| = k + \ell$, $|Y| = 2k$ and $|Z| = 3k$ such that:

- a) Maximum degree is at most 40.
- b) Given any subset $X' \subset X$ with $|X'| = k$, there is a perfect matching between $X' \cup Y$ and Z .

Proof. The following proof is copied from [BS21] which follows the work of Montgomery.

Fix some $Z_1 \subseteq Z$ of size $2k$ and place independently 20 random perfect matchings between Y and Z_1 . Let the graph Q_0 be the union of these matchings. Given subsets $A \subset Y$ and $B \subset Z_1$, and a random matching M , the probability that *all* vertices of B get matched by M to a vertex in A is $\binom{|A|}{|B|} / \binom{2k}{|B|}$. Thus, for any $t \leq k/2$, the probability there is some set $B \subset Z_1$, of size t with neighbourhood of size less than $2t$ in Q_0 , is by a simple union bound over possible choices for B and all possible choices for a set of size $2t$ containing its neighbourhood at most

$$\binom{2k}{t} \binom{2k}{2t} \left(\binom{2t}{t} / \binom{2k}{t} \right)^{20} \leq \left(2e^3 \left(\frac{k}{t} \right)^3 \left(\frac{t}{k} \right)^{20} \right)^t = \left(2e^3 \left(\frac{t}{k} \right)^{17} \right)^t \leq 2^{-11t}.$$

Taking the sum over all $t \leq k/2$ we see that the probability that such a B of arbitrary size smaller than $k/2$ exists is at most 2^{-10} . An identical calculation shows that the probability there is an $A \subset Y$ with $|A| \leq k/2$ and neighbourhood of size less than $2|A|$ is at most 2^{-10} . The probability that there are two subsets $A \subset Y$ and $B \subset Z_1$, with $|A| = |B| = \lceil k/2 \rceil$ and no edges between A and B is at most

$$\binom{2k}{\lceil k/2 \rceil}^2 \left(\binom{\lfloor 3k/2 \rfloor}{\lceil k/2 \rceil} / \binom{2k}{\lceil k/2 \rceil} \right)^{20} \leq (4e)^k \left(\frac{3}{4} \right)^{10k} \leq 2^{-k/2}.$$

Since $2^{-1/2} + 2^{-10} + 2^{-10} < 1$ there exists a graph G satisfying all three of these properties. Duplicate $k + \ell$ of the vertices in Y to get X , and then duplicate k of the vertices in Z_1 to get the set Z_2 and set $Z = Z_1 \cup Z_2$. We claim that this new bipartite graph with bipartition $(X \cup Y, Z)$ has the desired properties. For a), since $Y \cup Z_1$ induces 20 matchings and we duplicated every vertex at most once the maximum degree is indeed at most 40.

Now, take any set $X' \subset X$ of size k . To show b) we will verify Hall's condition between Z and $X' \cup Y$. For $A \subset Z$, let A' be the larger of the sets $A \cap Z_1$ and $A \cap Z_2$, so that $|A| \geq |A'| \geq |A|/2$.

If $|A'| \leq k/2$. Then by the first property we ensured for G we know A' has at least $2|A'| \geq |A|$ neighbours inside Y , and hence so does A inside $X' \cup Y$, as desired. Otherwise, $|A'| > k/2$

so by our second property of G there can be at most $k/2$ vertices in Y which are not adjacent to any vertex of A' . Since we obtained X by duplicating vertices of Y the same holds about non-neighbours of A' inside X . In particular, all but at most k vertices of $X' \cup Y$ are adjacent to some vertex in A' so we are done unless $|A| > 2k$.

By taking a subset of A of size $2k$ we can see from the previous paragraph that the set B of vertices in $X' \cup Y$, not adjacent to any vertex in A has size at most k . By symmetry (note that X' is simply a set of k duplicates of vertices in Y , same as Z_2 is for Z_1) we can repeat the above argument with B in place of A to conclude there are at least $|B|$ vertices in Z adjacent to some vertex in B . In particular, $|A| \leq 3k - |B|$, which is also the number of vertices adjacent to some vertex of A , as desired. \square

6.5 Putting everything together: P holds for simple Latin squares

Lemma 6.11. *Let $p \leq 1/200$ and let n be sufficiently large. Let H be a simple Latin square of order n . With probability at least $1/5$, a p -random subset $R \subseteq V(H)$ has the following property:*

P For all $S \subseteq V(H)$ with $|S| \leq n/(\log n)^5$ and $k \in \mathbb{N}$ with $|k| \leq |S|/10$, there is some $T \subseteq R$ that k -absorbs S .

Proof. \square

7 Checking simplicity under randomness and nonabelian simplicity

Brief notes here, I hope to eventually expand on these.

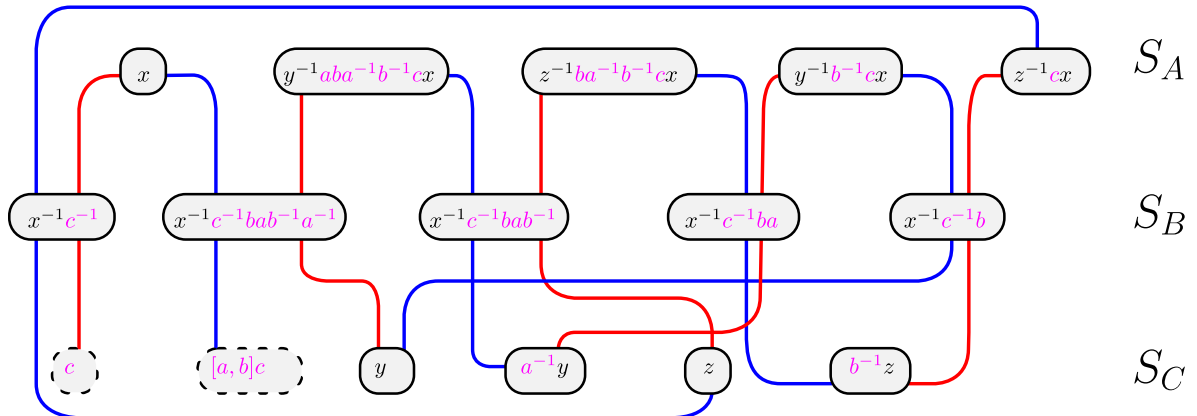
7.1 Simplicity under nonabelian simpleness

The following was conjectured by Ore in 1951, but only established in 2010.

Theorem 7.1 (Liebeck–O’Brien–Shalev–Tiep). *Every element of a finite nonabelian simple group is a commutator, i.e. can be written of the form $[gh] = ghg^{-1}h^{-1}$.*

This allows us to say that checking K -exchangeability of pairs $c, [a, b]c$ where $[a, b]$ is an arbitrary commutator is enough. Somehow, it turns out that establishing exchangeability when two elements are just a commutator apart turn out to be much easier.

Here is a figure justifying pairs $\{c, [a, b]c\} \subseteq C$ are $O(1)$ -exchangeable, where black letters should be seen as "free" variables, and pink letters are "constants". The reader can check that



for differing choices of x, y, z , sets of vertices as encoded by the diagram above produce enough disjoint solutions to verify K -exchangeability, for $K \geq 10^5$. See [MP25] for a rigorous treatment.

7.2 Simplicity under randomness

We go back to the "grid representation" of a Latin square here as this makes pictures easier to draw. The idea will be to consider a much simpler toy model for a Latin square, where the entry on each of the n^2 grid points is one of $\{1, 2, \dots, n\}$ with equal probability. It feels as though from the perspective of the count of small subconfigurations in the Latin square, the top model should be a somewhat accurate representation. Indeed, this correspondence was established in a paper of Kwan [Kwa20] – we won't give much detail for that here, and just proceed to establish exchangeability in the toy model. Given x, y which we think of as "constant" symbols, we will be interested in two disjoint 2×2 subsquares with the following pattern of symbols.

$$\begin{array}{cc} x & a \\ b & c \end{array} \quad \begin{array}{cc} y & a \\ b & c \end{array}$$

Note that when we draw a diagram like the above, the rows and columns we consider aren't necessarily adjacent in the Latin square – the only relationships that matter are the relationships of "being in the same row as" or "being in the same column as".

Also, here, a, b, c should be thought of as "free variables", and x, y should be thought of as constants, for which we are trying to find 1-absorbers for. The expected number of such configurations for fixed x, y is n^3 , in the toy model. We also have concentration via Chernoff and thus can take a union bound over all linear sized sets, which can be translated to check the exchangeability definition, due to the following two sets of matchings we can consider:

$$\begin{array}{cc} \mathbf{x} & \mathbf{a} \\ b & \mathbf{c} \end{array} \quad \begin{array}{cc} y & \mathbf{a} \\ \mathbf{b} & c \end{array}$$

$$\begin{array}{cc} x & \mathbf{a} \\ \mathbf{b} & c \end{array} \quad \begin{array}{cc} \mathbf{y} & a \\ b & \mathbf{c} \end{array}$$

Crucially, these two selection of matchings have the same row and columns set, and the symbol sets are either $\{a, b, c, x\}$ or $\{a, b, c, y\}$, meaning that the only two things that vary are x and y , meaning that the corresponding structure 1-absorbs the set $\{x, y\}$.

8 Near-transversals in Cayley tables

Our next goal will be to prove the following special case of Montgomery's theorem.

Proposition 8.1. *Let $H = (A, B, C)$ be a (large) Cayley table. Then H has a near-transversal, that is, a transversal that misses one row, column, and a symbol.*

Perhaps surprisingly, the above does not immediately follow from the Hall–Paige conjecture. The methods we discuss will be robust enough to derive the analogous result for balanced and "random-like" induced subgraphs of Cayley tables, of the form $H' = (R, C, S)$ where $R, C, S \subseteq A, B, C$ (respectively). Meaning we can derive something like the following:

Proposition 8.2. *Let G be a finite group and let $A, B, C \subseteq G$ be "random-like" and "dense" subsets with $|A| = |B| = |C|$. Then the linear tripartite hypergraph $H = (A, B, C)$, where (a, b, c) is an edge iff $ab = c$, contains a matching of size $|A| - 1$.*

The above result has a strong consequence for abelian groups G . The point here is that if additionally the identity $\sum A + \sum B = \sum C$ holds, then once we find a matching of size $|A| - 1$, for the final remaining a, b, c outside the matching, the relation $a + b = c$ must hold (why?), meaning we get a perfect matching. This is the abelian case of the so-called random Hall–Paige conjecture from [MP25]. It turns out that an analogous result holds for non-abelian groups as well, though this requires more work, as all we can derive in this case is that $ab \equiv c \pmod{G'}$ where G' is the commutator subgroup.

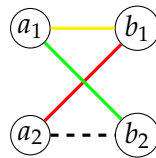
Once we prove Proposition 8.1, we will afterwards discuss how to remove the assumption of the Latin square corresponding to a Cayley table, to prove Montgomery’s theorem. For now, let us make the most out of the assumption that the Latin square is a Cayley table. These techniques turn out to be relevant for Montgomery’s theorem as a key idea there will be to work with an "approximate equivalence relation" on the ground set so that once we squint and think of the corresponding "approximate quotient", the resulting general (possibly non-associative and non-group-like) Latin square will "approximately" behave like a Cayley table.

The proof we give here is essentially from [MP25], however, we discuss things from a slightly different perspective to highlight the role of the so-called "quadrangle property" more vividly, so as to make the connection with the upcoming argument of Montgomery [Mon] a bit more natural.

A property that a Latin square will have if it also is a Cayley table is the following. Suppose we have found entries r, y, g satisfying the following row-sameness and column sameness relations:

$$\begin{array}{cc} r & y \\ g & \circ \end{array}$$

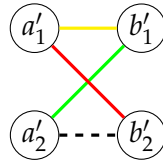
Then, the value of \circ is uniquely determined by a, b and c only. To clarify this a bit further, we find it more convenient to switch to a graph theoretic perspective and associate to each Cayley table $H = (A, B, C)$ a edge-coloured complete bipartite graph $H = (A, B)$ where the colour of an edge $(a, b) \in A \times B$ is simply $c := ab$. Now suppose that we found 4 vertices as indicated below where $a_1, a_2 \in A$ and $b_1, b_2 \in B$.



Let us suppose r, y, g stand for the labels of the red, yellow, and green edges, so we have the identities $a_1 b_1 = y$, $a_2 b_1 = r$ and $a_1 b_2 = g$. Then, $a_2 b_2 = (a_2 b_1)(a_1 b_1)^{-1}(a_1 b_2) = ry^{-1}g$. Crucially, the value of $ry^{-1}g$ depends only on r, y, g , and not on a_i, b_i . In other words, any 3-edge path that starts on the set A with colour sequence r, y, g has that the colour of the 4th edge closing the cycle is determined only by r, y, g . This property is called the **quadrangle condition** for a Latin square. Not only is the quadrangle condition a necessary condition for a Latin square to be a Cayley table, but it is also a sufficient condition.

Exercise. Prove that a Latin square arises as a Cayley table of a finite group if and only if the quadrangle condition holds. The direction we haven't proved above is that if the quadrangle condition holds for a Latin square, then the rows, columns, and the symbols can be identified with a finite group G with bijections ϕ , ψ , and χ (in a way we get to choose) so that if (r, c) entry in the Latin square is s , then $\phi(r)\psi(c) = \chi(s)$. (This was first observed by Brandt in 1927, see [GL20] for a solution, and also a fascinating result on how an approximate version of the quadrangle condition implies the existence of "approximate group structure")

Note that in the quadrangle condition, we insist that the first edge of the path (with colour sequence r, y, g) lives in A . In particular, if we find a different subgraph looking like the following: Then it is not necessarily true that $a'_2 b'_2 = ry^{-1}g$, instead in this case we obtain $a'_2 b'_2 = gy^{-1}r$. Of



course in abelian groups, there is no difference. The reader might want to think about whether this stronger asymmetric quadrangle condition implies that the underlying Cayley graph is necessarily abelian.

Now let's think about how any of this will get us some "local flexibility" so we can build the absorber. Suppose we fix the colour $b = ry^{-1}g$, and found two disjoint 4-cycles on vertex sets $\{a_1, a_2, b_1, b_2\}$ and $\{a'_1, a'_2, b'_1, b'_2\}$. Consider the following two distinct matchings we can consider on the union of the two 4-cycles.



Observe that the above indicated matchings witness that the 4-cycles 1-absorb the set $\{\{a_2, b_2\}, \{a'_2, b'_2\}\}$, where we abuse notation a bit because S is not anymore a subset of $V(H)$, but a set of subsets, so let us recast the definition so that it makes sense to say things like "1-absorbs" $\{\{a_2, b_2\}, \{a'_2, b'_2\}\}$.

Definition 8.3. Let $T \subseteq V(H)$, where H is some tripartite hypergraph, let S be a family of subsets of $V(H)$, and let $k \in \mathbb{N}$. We say that T **k -absorbs** S if for all subsets $S' \subseteq S$ (disjoint with T) with $|S'| = k$, $\bigcup_{s \in S'} s \cup T$ admits a perfect matching.

Note we removed the balancedness assumption above also compared to the previous definition, so it follows that S has to be contained fully in one of the parts of the tripartition of H .

The definition of K -exchangeable essentially stays the same, it's just that x and y are allowed to be sets of vertices now. Subject to the natural new meaning of k -absorbing families of sets (instead of families of singletons), the following is the key concept.

Definition 8.4. Let H be a Latin square of order n , and let X, Y be two subsets of $V(H)$. We call $\{X, Y\}$ an **K-exchangeable pair** if there exists a collection of n/K disjoint subsets $T \subseteq V(H)$ of size $\leq 100K$ with the property that T 1-absorbs $\{X, Y\}$.

Using simply the quadrangle property, we can fiddle a bit to deduce the following.

Lemma 8.5. Let H be a Cayley table, and let a, b, a', b' be such that there exists a $v \in V(H)$ such that $\{v, a, b\}$ and $\{v, a', b'\}$ are both edges of H . Then, $\{a, b\}, \{a', b'\}$ is a 1000-exchangeable pair.

From this point onwards, the story closely mirrors the story of the exchangeable pairs from the previous section; the only difference being that our initial assumption is an exchangeability of pairs of pairs, where the pairs range over tuples from a group that are mutually in an edge together. In particular, by first having a version of the above lemma that gives sets 1-absorbing a set of 100 exchangeable pairs, and the combining this with the robustly matchable bipartite graph, one can obtain a statement like the following.

Lemma 8.6. Let $p \leq 1/200$ and let n be sufficiently large. Let H be a Latin square arising from a Cayley table of order n . With probability at least $1/5$, a p -random subset $R \subseteq V(H)$ has the following property:

P For all $S \subseteq \binom{V(H)}{2}$ with $|S| \leq n/(\log n)$ and there exists some $v \in V(H)$ such that S consists of sets of the form $f \setminus \{v\}$ where f is an edge incident on v , $k \in \mathbb{N}$ with $|k| \leq |S|/10$, there is some $T \subseteq R$ that k -absorbs S .

The reason of the awkward presentation of which pairs we get to switch between as a function of the shadows of the vertex neighbourhoods is the following. It would be natural to say something like, S is a set of ordered pairs with the property that each pair (x, y) has a fixed product $c = xy$. It's just that if $H = (A, B, C)$ is the ambient hypergraph, whether xy , or xy^{-1} or $x^{-1}y$ should be fixed depends on whether (x, y) lives inside $A \times B$ or $A \times C$ or $B \times C$ – whereas the relationship of living in the shadow of a neighbourhood together compactly captures this exchangeability relationship without having to make reference to the underlying tripartition.

8.1 Cover-down with pairs

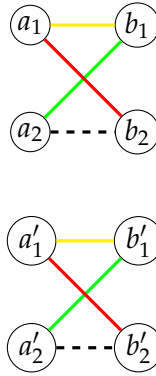
In the previous analogue of Lemma 8.6 with singletons instead of pairs, i.e. Lemma 6.11, using the statement to finish the proof with an application of the nibble was relatively straightforward. Here, when we do the "cover-down" step, not only will we have to worry about matching an arbitrary leftover to a randomly chosen S (which was always possible due to Chernoff-type reasons), but we will have to do this in a way that respects some inherent pairing in S , in the sense that whenever x is used in the matching, the pair of x will also have to be used in the matching. It should generally be impossible to do such a thing, because some Cayley tables don't have full transversals. However, it turns out that there is a way to do find such a matching that nearly respects the pairing, in that there remains at the end only 3 vertices, one from each part, so that their pairs are used in the matchings but the vertices themselves aren't.

In class, we discussed how such a matching can be found by gradually building up the matching $O(1)$ steps at a time. I will eventually add more detailed notes and figures surrounding this.

9 Exchangeable colour classes

To recap, thus far we have seen that K -simple Latin squares have transversals (which, together with an inductive argument of Wilcox, imply that Cayley tables of group with the Hall–Paige

condition have transversals), and furthermore, all Cayley graphs have near transversals. In the proofs, small sub-configurations like the below one had a major role in the arguments.



We saw whilst working with random Latin squares that for any two colours c and c' , we have that a random Latin square contains many configurations a_i, b_i like the above where c and c' are the colours of the edges a_2b_2 and $a'_2b'_2$, respectively. This allowed us to deduce that all pairs of colours are K -exchangeable, meaning that random Latin squares are K -simple, with high probability, meaning that they contain (full) transversals.

On the other hand, we saw that in Cayley graphs, configurations like the above imply that the colours of a_2b_2 and $a'_2b'_2$ must be the same. In fact, this property, i.e. the quadrangle condition, is a defining property of Cayley tables. (To prevent a potential confusion – this does not preclude Cayley tables from being K -simple – because we are allowed to consider other, more complicated, configurations to find 1-absorbers between pairs of colours, as pointed out in Section 7.1).

The possibility of the quadrangle condition holding prevents us from having an argument that finds 1-absorbers between arbitrary pairs of colours in general. However, in the previous section, we saw that the quadrangle condition itself can be thought of as a condition that ensures the existence of 1-absorbers for the pairs of edges a_2b_2 and $a'_2b'_2$. This notion of a "local flexibility" between pairs satisfying an algebraic identity (such as having the same product) was also a compatible input to the absorption machinery – allowing us to find a near transversal in all Cayley graphs.

We now arrive at what is perhaps the crux of the proof of Montgomery's theorem [Mon] which gives a way to interpolate between these two extremes of the quadrangle condition holding (as in Cayley graphs) or failing dramatically (as is the case for random Latin squares). The key idea will be to group together (identify) colours between which there are many 1-absorbers, and then show that after this identification is performed, the quadrangle condition holds between the colour clusters. Afterwards, the proof like the one we saw in the previous section allows one to deduce the existence of a near transversal, as though the arbitrary Latin square was a Cayley table.

First, let's formalise something that has been implicit in the discussion already.

Definition 9.1. Let $H = A \times B$ be a properly coloured bipartite graph. A **basic switcher** is a 8-vertex configuration as depicted below, i.e. distinct vertices $a_1, a_2, b_1, b_2, a'_1, b'_1, a'_2, b'_2$ with $a_i, a'_i \in A$ and $b_i, b'_i \in B$ where for any $(i, j) \in \{1, 2\}^2$ except for $(i, j) = (2, 2)$, we have that a_ib_j and $a'_ib'_j$ has the same colour, but these colours are otherwise distinct. We also call the same structure a $a_2b_2, a'_2b'_2$ -**switcher** if we wish to highlight the role of these special coordinates. We emphasise again that a_2b_2 and $a'_2b'_2$ may or may not have the same colours.

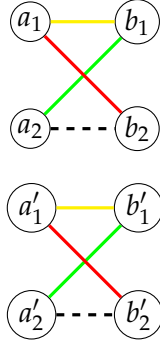


Figure 2: A basic switcher, also a $a_2b_2, a'_2b'_2$ -switcher. Recall the previous section on near transversals in Cayley graphs for justification of the "switcher" terminology.

Exercise. This has been implicit in the discussion, but to check their understanding, a reader might want to verify/recall that a $a_2b_2, a'_2b'_2$ -switcher is (in the corresponding 3-uniform hypergraph) a 1-absorber for the sets $\{\{a_2, b_2\}, \{a'_2, b'_2\}\}$, and if c, c' are the colours of $\{a_2, b_2\}, \{a'_2, b'_2\}$, respectively, also a 1-absorber for the set $\{\{c\}, \{c'\}\}$. Check also that the latter makes sense even when $c = c'$.

The following definition is key.

Definition 9.2. Let $H = A \times B$ be a properly coloured bipartite graph with colours in set C . By the **exchangeability graph**, we denote the auxiliary weighted graph $\text{Aux}(H)$ (where loops are allowed) on vertex set C , and the weight of an edge c, c' (where potentially $c = c'$) is the number of basic switchers that are c, c' -switchers in H . We denote this weight by $w(c, c')$.

Exercise. Show that the sum of the weights $w(c, c')$ on $\text{Aux}(H)$ where H comes from a Latin square (i.e. underlying bipartite graph is complete, and each colour class is a perfect matching), is roughly $(1 + o(1))n^5$.

From now on H always comes from a Latin square.

To have a sense of the utility of the notion of an exchangeability graph, let us assume we find colours c_1, c_2, \dots, c_k where for each i we have $c_i \sim_{\text{Aux}(H)} c_{i+1}$. Let us further assume that the weights on the edges were large enough that we could somehow extract a 1-absorber for each pair c_i, c_{i+1} disjointly (other than on the vertices c_i , of course). Then, the union of such absorbers gives us a 1-absorber between c_1 and c_k (why?). So the rough intuition for now is that the exchangeability graph has some weak transitivity properties that captures the notion of K -exchangeability from before. Let's make all this more precise.

Observation 9.3. For any vertex v of a properly coloured bipartite graph, there exists at most $O(n^4)$ basic switchers that contain v . The same holds for colours: for each colour c , there are at most $O(n^4)$ basic switchers that contain the colour c .

Observation 9.4. For any colours c, c' , the weight of the edge c, c' on $\text{Aux}(H)$ is $O(n^4)$. Furthermore, for any v , the number of basic switchers between c and c' that use the vertex v is $O(n^3)$. Analogous statement holds when the vertex v is replaced by some colour c'' .

Lemma 9.5. Let $w(c, c') \geq \epsilon n^4$ for two colours c and c' with $c \neq c'$. Then, $\{c, c'\}$ are K -exchangeable for some $K = \Omega(1/\epsilon)$.

Proof. We need to find n/K disjoint (except on c, c') 1-absorbers for $\{c, c'\}$, and they will be of order at most 20, satisfying the definition of K -exchangeability. Note that each c, c' -switcher gives rise to a 1-absorber for $\{c, c'\}$, as shown in the earlier exercise. Take a maximal collection of disjoint c, c' switchers of order 20, and suppose there are less than n/K many. Together, they span at most $20n/K$ vertices and colours. Through all of these vertices and colours, there exist at most $O(20n^4/K) \ll \epsilon n^4$ basic c, c' -switchers. So there must remain one that is disjoint with all these, giving a contradiction. \square

Asking for $\Theta(n^4)$ weight, and the above greedy argument, is a bit too much for recovering the notion of exchangeability, at least in certain occasions, as the following exercise serves to demonstrate.

Exercise. Using similar heuristics to those used in Section 7.2, convince yourself that in a random Latin square H , each edge of $\text{Aux}(H)$ (including the loops) has approximately the same weight of $\Theta(n^3)$.

The reason why random Latin squares have exchangeability between any pair of colours despite edges having weight only around $\Theta(n^3)$ is that these switchers can also be shown to be fairly well distributed across the graph – so one does not need to rely on the crude "take a maximal collection" trick from Lemma 9.5 (instead we can simply union bound over all linear sized subsets which contain many switchers w.h.p.).

That said, we should not get too discouraged that the crude analysis does not recover that all pairs of colours are K -exchangeable for $K = O(1)$ in random Latin squares, as we will still be able to recover that almost all pairs of colours are K -exchangeable – and that will be enough to run a strategy like the one in the previous section (in particular, the techniques in Section 8.1 still go through). Before justifying that we can recover exchangeability for almost all pairs, let us make a bit clearer what our objectives are, and why they are enough to reduce the situation to the Cayley table case. We are trying to find colour classes where within a class every pair of colours are exchangeable, and we are trying to *cover* the space of colours with such "exchangeable classes". With that in mind, let us make the following (provisional) definition, which we will later have to revise.

Definition 9.6. Let $H = A \times B$ be a properly coloured bipartite graph with colours in set C . Let $C' \subseteq C$. We say that C' is **strongly exchangeable** if for all $c, d \in C'$, we have that there are $\Omega(n)$ disjoint 1-absorbers for $\{c, d\}$ in H .

Given the above definition, our objective is roughly summarised below (a detail oriented reader might want to see Theorem 5.4 from [Mon] for a formal statement).

Theorem 9.7 (informal). *Let $H = A \times B$ be a properly coloured bipartite graph with colours in set C . Then, there are colour classes C_1, C_2, \dots so that:*

- (3) *Each $C_i \subseteq C$ is strongly exchangeable.*
- (3) *The C_i are "essentially" disjoint (the quotations are doing a lot of work here)*
- (3) *All the switcher weight is captured within the classes. Formally, let \mathcal{F} consist of all $c, d \in C$ so that there is no C_i such that $c, d \in C_i$. Then*

$$\sum_{(c,d) \in \mathcal{F}} w(c, d) = o(n^5).$$

We remark that in the special case when H is a Cayley table, the cosets of the commutator subgroup form a partition satisfying the above goal, as shown in [MP25]. However, in the general case, it will be much more accurate to think of the C_i as a *cover* for the edges of $\text{Aux}(H)$ rather than a partition of the vertices of $\text{Aux}(H)$, that is, C .

Once we achieve (3), we will have a situation for almost all basic switchers, the colours of the edges corresponding to a_2b_2 and $a'_2b'_2$, c and c' respectively, will be in a same class (note we can't say "the" same class due to the vagueness in (2)). Thanks to (1), we will be able to find separately (in a disjoint way) as 1-absorber for the colours $\{c, c'\}$. When combined with the basic switcher, this gives rise to a 1-absorber for the pairs of edges $\{\{a_2, b_2\}, \{a'_2, b'_2\}\}$ (this is quite important, so the reader should check this claim carefully!) – just like the situation we had when we had the quadrangle condition (in the Cayley table case, we didn't need the additional 1-absorber for $\{c, c'\}$, because c and c' were the same exact colour anyways!)

To prove Theorem 9.7, it will be very helpful to partition the edges of $\text{Aux}(H)$ into 4 categories: very light edges, light edges, moderate edges, and heavy edges. The weight cut-offs for this definition will be something like:

$$w_0 = \varepsilon n^3, w_1 = (n \log n)^3, w_2 = \frac{n^4}{(\log n)^3}$$

So edges of weight below w_0 are very light, between w_0 and w_1 are light, between w_1 and w_2 are moderate, and above w_2 are heavy. Observe that we don't care about the very light edges as they contribute at most a εn^5 term to the sum in (3). On the other hand, we discussed that in a typical Latin square, $\text{Aux}(H)$ consists of a complete graph with loops where every edge is a light edge. What to do then? Or more generally, what to do when all edges of $\text{Aux}(H)$ are light edges, but the underlying graph is not necessarily complete?

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