The Pappus Configuration, Theorem and Graph

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Abstract

We consider Projective Geometry's Pappus configuration, to which Pappus' Theorem applies. We work at the level of graphs, selecting various conceptual classes of nice presentations for this graph: Projectively-natural, symmetric and Hamiltonian. We finally point forward to various natural successors to this configuration, fundamental Projective theorem and graph.

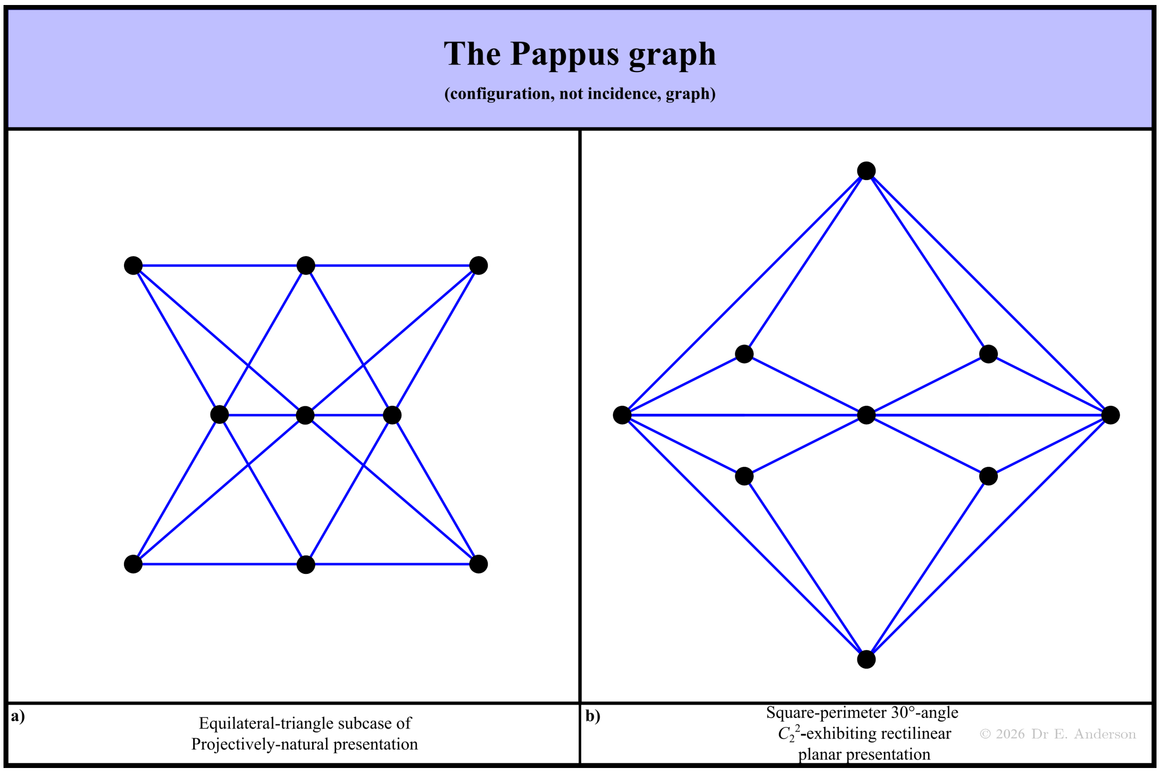

Figure 1:

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This Article is ⟨3⟩: accessible to third-year undergraduates.

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1 Introducing Pappus' configuration and theorem

1.1 Pappus' Theorem in the Euclidean plane

Pappus' Theorem [2, 19, 18, 50, 45] Work in the usual Euclidean plane. Let A, B, C be a collinear triple of points (yellow in Fig 2). And let A', B', C' be another (green). Then

$$AB' \cap BA' := I \text{ and 3-cycles} \tag{1}$$

are themselves a collinear triple (red).

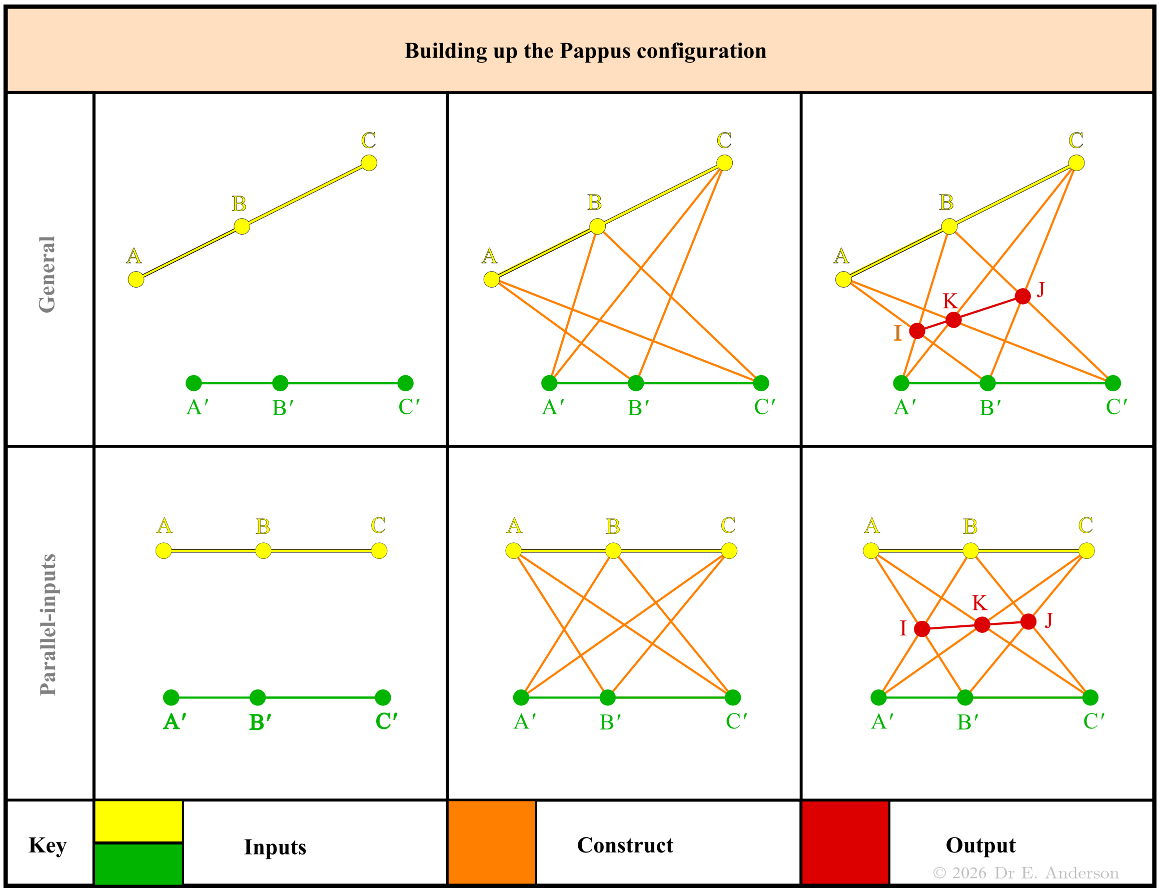

Figure 2:

Remark 1 Row 2 constructs this configuration Pappus in the Affinely-special case in which the 2 input triples are parallel. While row 1 of Fig 2 depicts a generic case.

Remark 2 One classical approach [23, 50, 45, 62] to proving this makes multiple uses of *Menelaus' Theorem.*[1]

1.2 Pappus' Theorem reappraised within Projective Geometry

Remark 2 This late Ancient Greek result harbours substantial Projective-Geometric significance. Though recognizing this had to await the 19th [7, 8, 9] and even 20th centuries [11, 28, 42]. In particular, it turns out to constitute one of the two main structural theorems of Projective Geometry.

[1] See whichever of [20, 14, 13, 39] for an introduction and [23, 25, 33, 62] for discussions and applications.

Projective Geometry [42, 21, 22, 12, 18, 26] is Geometry pared down to the study of *incidence*. At the level of planes, this is a binary relation on points-and-lines. Comprising whether points lie on lines and whether lines intersect each other.

Structure 1 An abstract Projective plane [55] is *Pappian* if Pappus' theorem holds universally throughout it. Elsewise it is *non-Pappian*.

1.3 Pointers to other styles of proof

Pointer 1 ⟨0-3⟩[2] One can proceed by multiple uses of [45] the basic *side-split lemma*. Alias *side-splitter*, *intercept* or *basic-proportionality lemma* or *theorem*, or one of the *theorems of Thales*. Or by an area-sum method [45]. Alongside Menelaus, these were all 'classically available' methods. A further pre-Projective approach [45] is to make multiple uses of Hud–Ceva's theorem in place of Menelaus'. In various senses Menelaus and Hud–Ceva are dual statements [62].

Pointer 2 ⟨3⟩ It is straightforward to obtain a Projective proof intrinsically within[3] 2-d ; see for instance [22, 18]. Or by using cross-ratios [47]. Or by composing projective transformations [38].

Pointer 3 ⟨2-3⟩ Algebraic approaches include use of homogeneous coordinates [45]. These are one of the most common types of Projectively-significant coordinates, analogous to Cartesian coordinates in Euclidean Geometry. This particular reference is further laced with Linear Algebra via its use of determinants. Though one can proceed instead using [45] ⟨3⟩ *Plücker relations*: a Projective notion. [4] These things said, proving Pappus' Theorem need not be a lengthy or technical affair, see e.g. [41] for a simple Coordinate Geometry proof.

Pointer 4 ⟨3⟩. Once various more substantial Projective theorems are available, Pappus' theorem drops out as a corollary. For instance from *Pascal's theorem*, by specializing its conic to a pair of intersecting lines [31]. Or from Desargues' theorem [42], by specializing its pair of triads to be in perspective.

1.4 Pedagogical aside

Pedagogical Remark 1 However that just *2 to 4* styles of proof for Pappus' theorem suffice up to ⟨3⟩ . Say a classical proof in ⟨2⟩, though in particular the most pedestrian – side-spliter – could be attempted in some earlier year. And a Projective proof in ⟨3⟩, alongside a Linear Algebra proof to illustrate the ongoing usefulness of the Linear Pillar of Geometry. Those following Stillwell's [42] Four Pillars of Geometry might pointedly want to extend your repertoire to a fourth Transformation Groups proof...

Pedagogical Remark 2 More proofs than this would be of particular interest when the Reader is doing 1) a graduate-level course in Projective Geometry. 2) A Ph.D. specializing in Projective Geometry. 3) Or a thesis or research project specifically on Pappus' theorem, or on some small set of Projective theorems that include Pappus'. Such as the Pappus–Desargues fundamental pair, or the Pascal–Brianchon dual pair [15, 23], which connects to Pappus' theorem as per Pointer 4. With some tongue in cheek, passing from Stillwell's 4 Pillars of undergraduate Flat Geometry to a larger number of Pillars beyond, includes the following. Geometrical invariants themselves come to constitute a Pillar, with various further Pillars [67, 68] providing first principles either for obtaining these or for obtaining the transformation group. As such, the graduate with reasons to study Pappus' theorem further might do well to next look into a cross-ratios proof...

[2] The current Encyclopedia [53] uses chevron brackets to denote "approximate year of study".

[3] A larger proportion of sources prove the other main theorem of Projective Geometry – Desargues' – by exiting from 2-d into 3-d .

[4] Brute-force Vector Algebra will also do [45] ⟨5⟩ .

1.5 Call-signs for the Pappus configuration's objects

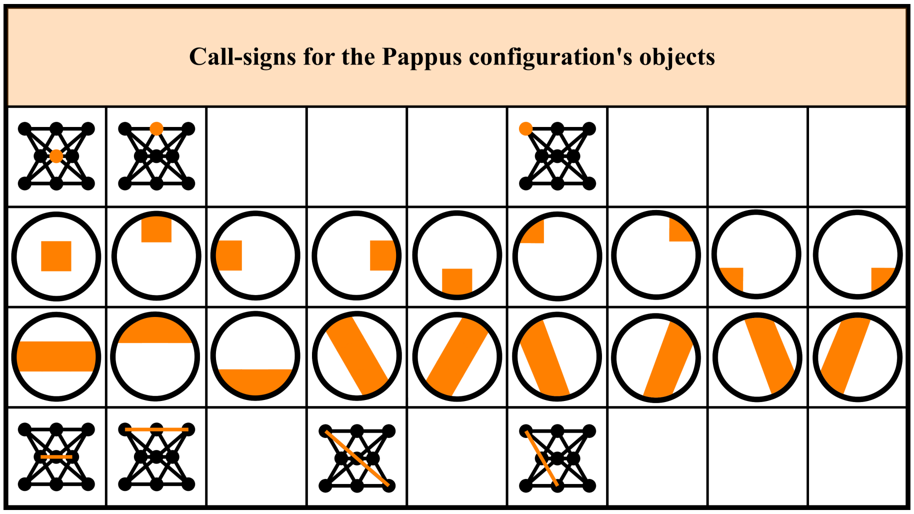

Figure 3:

Remark 1 We root the following notation, applicable to all nondegenerate Pappus configurations by Topological equivalence, on the following special case. The equilateral-triangles case of the affinely-special Pappus configuration. This is a patch of the tessellation [32] of the plane by equal-sized equilateral-triangle tiles. While Coxeter [17] uses a symmetrical Affine presentation of Pappus, superposing our figure reveals that his triangles are slightly taller than our equilateral ones...

Notational Remark 1 The Pappus objects highlighted in fireopal are then simplified, while all the unselected objects previously cast in jet are now jettisoned. These 'call-signs' are presented inside circles, since our main use of them shall be to label the nodes of the Pappus incidence graph in the sequel Article [58]. This notation follows on from S. Sánchez' devising of call-signs for the Fano objects [51, 55]. We will also on occasion pick out the input and output objects by colouring the corresponding call-sign shapes to match Fig 2.

1.6 The Pappus configuration's symmetries

Exercise 1 These form a group of order

$$108 \; = \; 2^2 \times 3^3 \; .$$

Or, including the duality generator, of order

$$216 \; = \; 6^3 \; = \; 2^3 \; \times \; 3^3 \; .$$

Justify this count.

Pointer 5 Working out which group this is – i.e. relators as well as generators – lies beyond the scope of the current Encyclopedia. See Coxeter's articles [29, 30] for details ⟨6-8⟩ .

2 Introducing the Pappus graph

2.1 The Projectively-natural presentation

Remark 1 Graphs associated with Geometrical figures are Topological-level constructs. So we can recycle the above nice equilateral-triangles subcase of the Pappus configuration to form a nice presentation for the corresponding Pappus configuration graph. See Fig 1.a). This is not to be confused with the aforementioned Pappus incidence graph...

2.2 Some basic counts and properties

Remark 2 So the Pappus graph has

$$V(\text{Pappus}) = N = 9 , \tag{2}$$

$$E(\text{Pappus}) = 18 . \tag{3}$$

This corresponds to an average of exactly 4 edges per vertex.

Remark 3 The Pappus graph's degree sequence is

$$\deg(\text{Pappus}) = 3^4 \, 4^2 \, 5^2 \, 6 . \tag{4}$$

The Pappus graph is consequently neither *regular* [52]: of a single degree. Nor a *cone* [52]: with

$$\geq 1 \text{ degree-}(V - 1) = 8 \text{ vertices} .$$

It does however have a sole vertex with greater degree strength than the others: 6 . Which we subsequently prefer to place centrally in forming nice presentation.

Remark 4 It is straightforward to show that the Pappus graph is *planar* [27, 40]. Given Fig 1.a)'s presentation 'in the wild', 4 identical tucks of the degree-3 vertices will do. The square-perimeter 30^{o} angle presentation of this is exhibited in Subfig b).

Remark 5 The Pappus graph then clearly has

$$F(\text{Pappus}) = 10$$

internal faces Or a total of

$$F_{\text{T}}(\text{Pappus}) = 11$$

faces including the external face.

In the first interpretation,

$$V - E + F = 9 - 18 + 10 = 1 = \chi\left(\mathbb{D}^2\right) :$$

the Euler characteristic of the disc. In the second interpretation,

$$V - E + F_{\text{T}} = 9 - 18 + 11 = 2 = \chi\left(\mathbb{S}^2\right) .$$

Where $\mathbb{D}^2$ is the disc and $\mathbb{S}^2$ is the sphere.

2.3 Grid and tessellation presentations

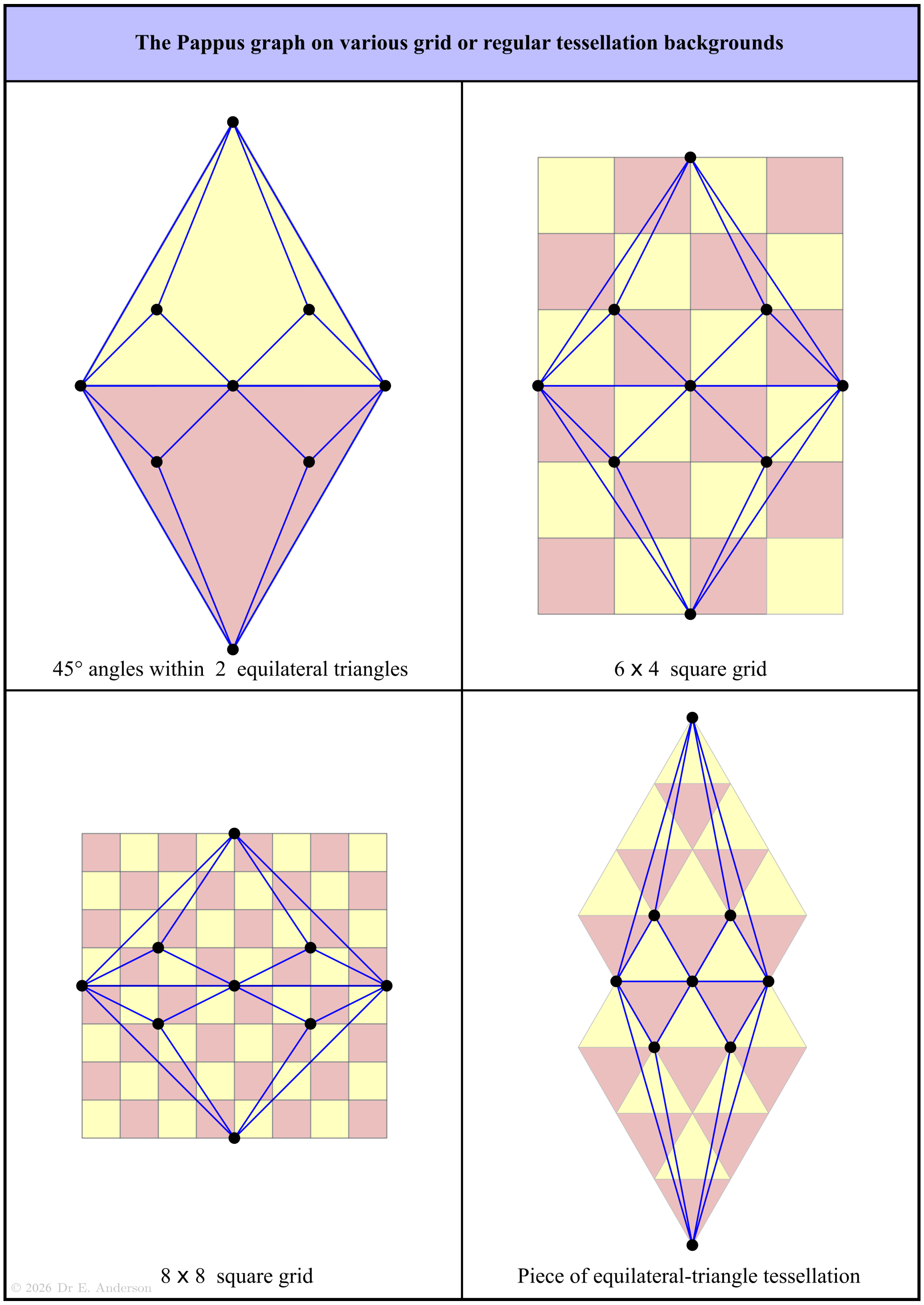

Figure 4:

Remark 6 We provide four of these in Fig 4.

2.4 Ramsey presentations

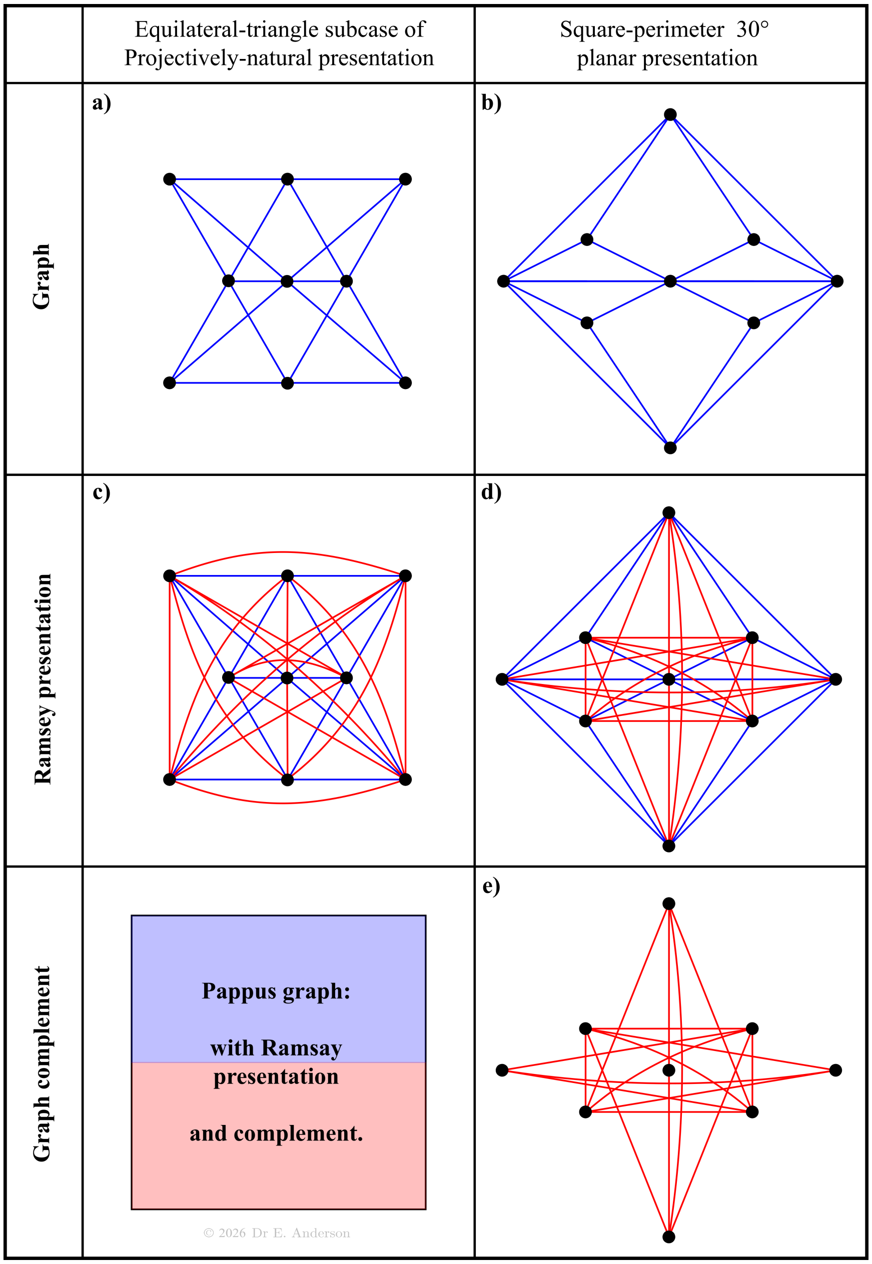

Figure 5:

Structure 1 See Subfigs 5.c-d) for the corresponding *Ramsey presentations* on each of the already-encountered presentations in Subfigs a-b)'s blue chassis. This builds in a simple graph's non-edges in red: on an equal footing with the edges in blue.

Remark 7 One can then peel off the blue to leave the red to subsequently unfold, revealing the structure of one's incipient graph's complement. See row 3 for the peeled version, and Fig 6 for unfolded versions.

2.5 The Pappus graph is edge-critical and heterocomplementary

Structure 2 A simple graph G is *edge-critical* if

$$E(\mathrm{G};\,N) \;=\; E_{\mathrm{crit}}(N) \;=\; \frac{V\,(V\,-\,1)}{4}\;. \tag{5}$$

This corresponds to a graph G and its complement $\overline{\mathrm{G}}$ having the same number of edges. This can only happen if

$$V \;=\; 0,\,1 \;\;(\bmod\,4)\;. \tag{6}$$

Structure 3 A graph is *homocomplementary* if it is isomorphic to its own complement. Otherwise it is *heterocomplementary*.[5]

Diagnostic 1 The above simple graph edge-criticality conditions (5, 6) are necessary but not sufficient for a graph to be homocomplementary.

Remark 8 In fact, generically, edge-critical simple graphs are not self-complementary.

Diagnostic 2 A more detailed necessary but not sufficient condition for homocomplementarity is that the graph and its complement share degree sequence.

Remark 9 From (2, 3), the Pappus graph turns out to be edge-critical:

$$E_{\mathrm{crit}}(9) \;=\; \frac{V\,(V\,-\,1)}{4} \;=\; \frac{9\,(9\,-\,1)}{4} \;=\; \frac{9\,\times\,8}{4} \;=\; 18 \;=\; E(\,\mathrm{Pappus};\,9\,)\;.$$

And yet to be generic in the heterocomplementary sense rather than homocomplementary. For

$$\deg\left(\overline{\mathrm{Pappus}}\right) \;=\; 2\,3^2\,4^2\,5^4\;. \tag{7}$$

And this does not match (4). So our noted high-degree vertex having no balancing low-degree vertex suffices to dash any hope of the Pappus graph being in the more distinguished class of the heterocomplementary graphs.

Principle 1 Suppose that

$$E(\mathrm{G};\,N) \;>\; E_{\mathrm{crit}}(N)\;. \tag{8}$$

Then it is usually easier to understand the structure of $\overline{\mathrm{G}}$ than that of G . It is usually also more straightforward to name graphs via whichever of themself or their complement has smaller size (= edge number E) . For edge-critical graphs, there is no a priori reason for one to be more suitable than the other. See [61] for some further selection principles in this critical edge case.

[5] The alias *self-complementary* has so far been more widely used.

2.6 A few properties of the Pappus complement

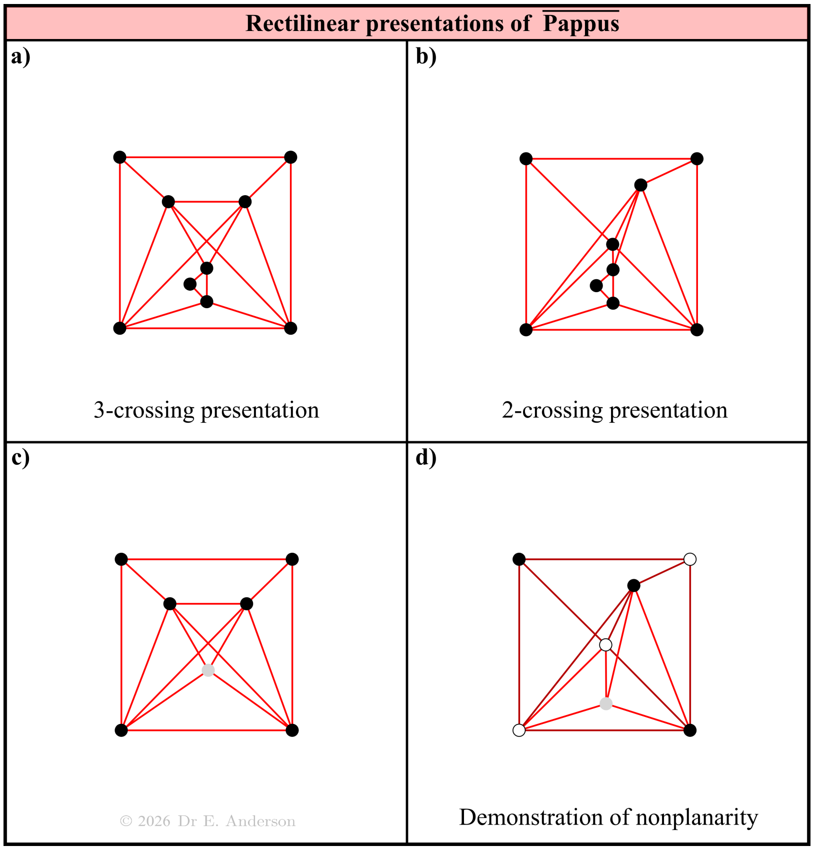

Figure 6:

Remark 10 We unfold row 3 of Fig 5's presentation of $\overline{\text{Pappus}}$ to quickly obtain a 3-crossing presentation in Fig 6.a). And then get it down to 2 crossings in Subfig b).

Subfig d) suffices to demonstrate nonplanarity: it contains, as a subgraph, the utilities graph

$$\text{Utilities} \;=\; K_{3,\,3} \, :$$

the complete bipartite graph with equal parts of size 3 . Where the second symbol denotes complete-bipartite with 2 pieces of order 3 . By Kuratowski's theorem [40], this is indeed one of the 2 irreducible forbidden subgraphs in a planar graph. The other is the complete graph K_5 .

Exercise 2$^-$ Check that Subfig 6.a)'s graph is indeed isomorphic to Subfig 5.e)'s.

3 The Pappus graph is a double irreducible

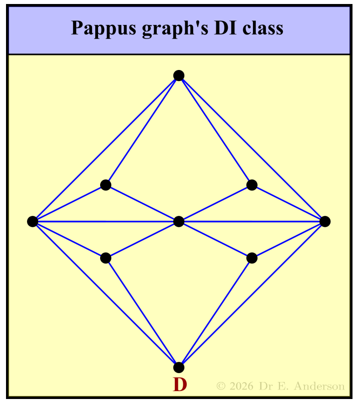

Figure 7:

Remark 1 $I($ Pappus $)$ is cubic and thus has no degree-1 or -2 vertices. Thus it is both foliation irreducible and homeomorph irreducible. Which combination we term double irreducible: class D [54], which we denote with a yellow background, as in Fig 7.

4 Notions of traversability

4.1 The basic notions

Remark 1 The Pappus graph is immediately not *Eulerian*, since it contains odd-degree vertices.

Remark 2 The Pappus graph is straightforwardly *Hamiltonian*.

Remark 3 Consult Chapters 41 and 42 of the freely available [52] if you are not sure what these two notions of traversability mean, or what their basic conceptual content is.

4.2 ZIPHoN treatment

Remark 4 Since the Pappus graph is also planar, one can investigate its Hamiltonian properties using the *ZIPHoN theorem*[6] By this result, every Hamiltonian cycle splits the graph into 2 outerplanar strips. Each containing an equal amount T of triangulating triangles.

Notational Remark 1 We colour in one outerplanar strip in yellow, leaving the other in white. This includes modelling yellow and white as individually-meaningless and yet mutually-distinguishable labels. By which such strips are invariant under colour exchange. Due to this, one can w.l.o.g. never colour the outer face. We finally mark the bounding Hamiltonian cycles using thick emerald edges.

Remark 5 For the Pappus graph,

$$T = 7 .$$

Fig 8 produces 3 such strips, while also indicating some of the forcings by which no more cases are possible.

Remark 6 Our exhaustive case location procedure is to start with a fan of 4 triangles. This fails to give any cases as per row 1. We next consider a continuous fan of 3 triangles, giving the second rows' case. We next consider a contiguous pair, one with a degree-6 vertex and the other not. This

[6] Zero-index planar Hamiltonian necessity theorem [51, 52, 63]. Alias Grinberg's theorem [24, 34, 40].

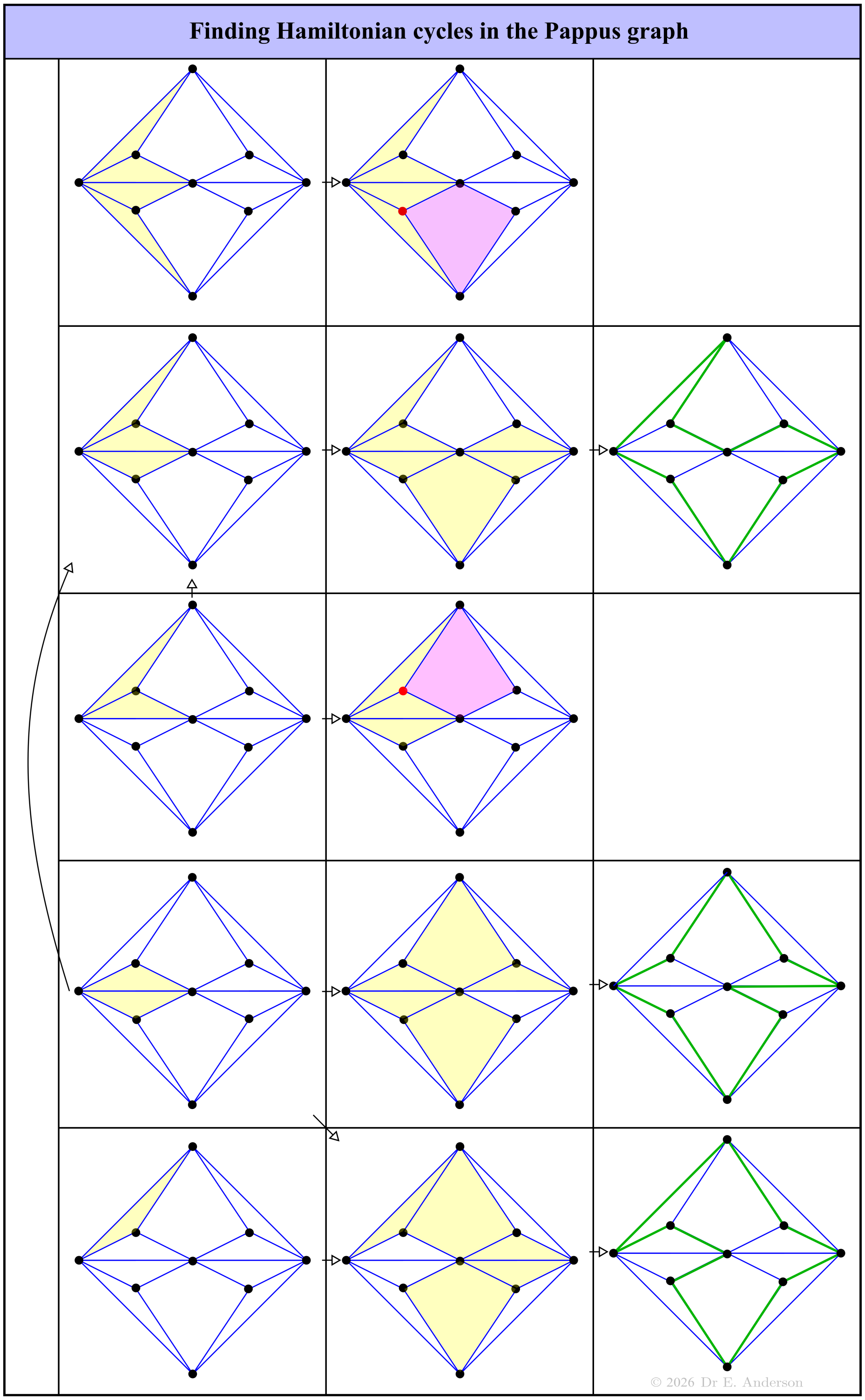

Figure 8:

is forced either to return to the previous or to give the third row's case. A contiguous pair with both sharing the degree-6 vertex gives our last case. All other cases – 1 or 0 triangles within such a fan – just either become impossible. Or return previous cases, under colour reversal if needs be.

4.3 Manifestly Hamiltonian presentations

Remark 7 Corresponding manifestly-Hamiltonian presentations of the Pappus graph are given in Fig 9.

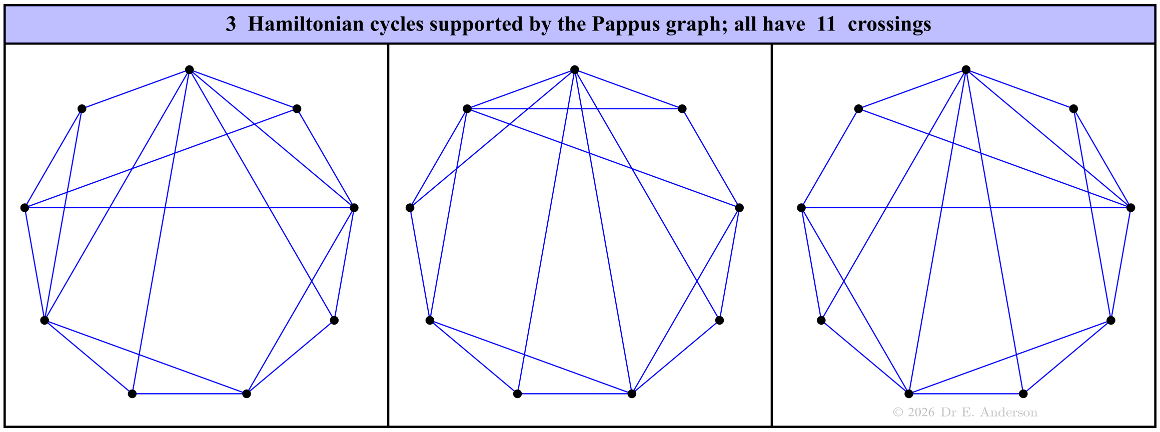

Figure 9:

Exercise 3$^-$ Show that these graphs are isomorphic to each other and to Subfig 1.b)'s graph.

Remark 8 The idea here is to use a manifest regular N-polygon perimeter in place of picking out a non-obviously realized N-cycle in emerald.

Remark 9 We finally make use of both the inner face and the outer face to retain manifest planarity in Fig 10.

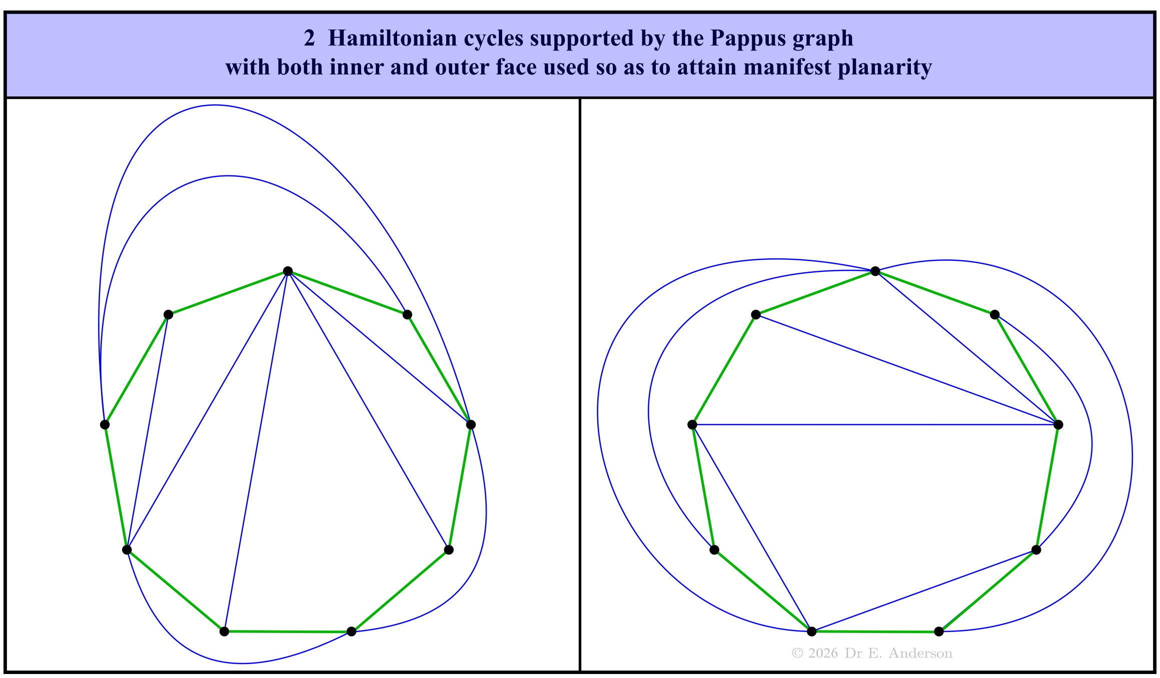

Figure 10:

5 Notions of colourability

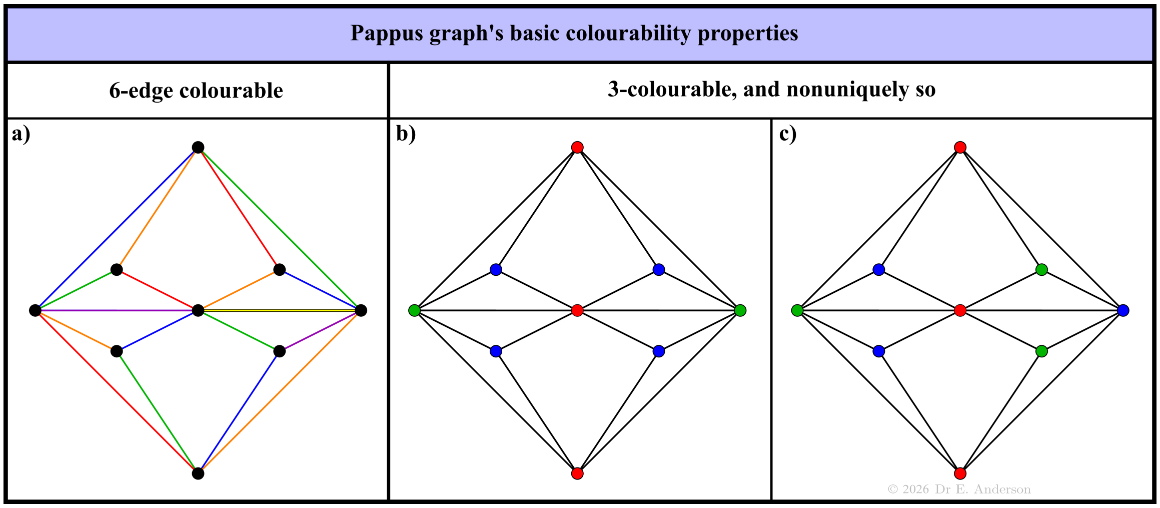

Figure 11:

Remark 1 Since the Pappus graph has a degree-6 vertex, it is $\geq$ 6-edge colourable. In fact, it is precisely 6-edge colourable, as per Fig 11.a).

Remark 2 Since the Pappus graph contains triangles, it is $\geq$ 3-colourable. And since it is planar, it is $\leq$ 4-colourable by the famous 4-colour theorem. In fact, it is 3-colourable, as per Subfig b).

Remark 3 See e.g. [27, 40] or Chapter 47 of the freely-available [52] for an introduction to these notions of colorability. The first two of these are also useful first references for the 4-colour theorem. See [35] for a more advanced account of colourability.

Remark 4 With the Graph Atlas [37] tabulating unique colourability as well, we draw out Subfig c) to demonstrate that the Pappus graph does not have this further property.

Exerecise 4$^-$ Establish Remark 1 and 2's colourability properties.

6 Pointers to allied material

Pointer 6 A more systematic study would start with Pappus' law's simpler configuration. This shall be covered within our article on the simplest Projective graphs [64]. Where no Projective plane conditions, or adjectives, are required. This shall for instance also cover the Pasch configuration [10] and scissor [42] graphs.

Pointer 7 A subsequent systematic study 6 should also cover degenerate cases, such as Pappus' little theorem. And other variants, such as including the intersection point(s).

Pointer 8 Incidence is the central notion in Projective Geometry. The *incidence graph* for the Pappus configuration shall first be covered in 5; Graph Theorists often call incidence graphs *Levi graphs*. They and Geometers often call the Pappus incidence graph the Pappus graph. Whereas the current Article takes this name to mean the Pappus configuration graph; an older alias for configuration graphs is *Menger graphs* [17].

Pointer 9 The Pappus configuration is double-tied in third place [36] for (one notion of) Projective configuration. The smallest is the Fano plane: $N = 7$ [55]. Next there is a unique projective configuration for $N = 8$: Möbius–Kantor's [17]. And then Pappus arrives, accompanied by 2 other 9's. [66] shall more eventually cover the 8 and the 2 other 9's as graphs; for now see [36, 44, 46] at the level of configurations.

Pointer 10 The *Desargues configuration* is then 1 of the 10 10's. The corresponding *Desargues' theorem* [5, 16, 22, 19, 26, 31, 41, 38] is *the other* fundamental theorem of Projective Geometry. The Desargues configuration, theorem and graph are covered in [59]. Again, this is not to be confused with a more famous incidence graph, which is covered instead in [60].

Non-Desarguian Projective planes [43] are more often mentioned than non-Pappian ones. In fact, for finite planes, Pappus' theorem implies Desargues'. So conversely in the finite realm, non-Desarguian planes are guaranteed to be non-Pappian. And many Discrete Mathematics ventures confine themselves to finite cases.

Pointer 11 The Dandelin–Gallucci property and theorem [49] in 3-d are closely related to Pappus' Theorem. This makes use of the projective notion of transversality [62] in the context of the generic triple of lines supported in 3-d .

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