Small Ramsey Numbers

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ABSTRACT: We present data which, to the best of our knowledge, includes all known nontrivial values and bounds for specific graph, hypergraph and multicolor Ramsey numbers, where the avoided graphs are complete or complete without one edge. Many results pertaining to other more studied cases are also presented. We give references to all cited bounds and values, as well as to previous similar compilations. We do not attempt complete coverage of asymptotic behavior of Ramsey numbers, but concentrate on their specific values.

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1. Scope and Notation

There is vast literature on Ramsey type problems starting in 1930 with the original paper of Ramsey [Ram]. Graham, Rothschild and Spencer in their book [GRS] present an exciting development of Ramsey Theory. The subject has grown amazingly, in particular with regard to asymptotic bounds for various types of Ramsey numbers (see the survey papers [GrRö, Neš, ChGra2]), but the progress on evaluating the basic numbers themselves has been unsatisfactory for a long time. In the last three decades, however, considerable progress has been obtained in this area, mostly by employing computer algorithms. The few known exact values and several bounds for different numbers are scattered among many technical papers. This compilation is a fast source of references for the best results known for specific numbers. It is not supposed to serve as a source of definitions or theorems, but these can be easily accessed via the references gathered here.

Ramsey Theory studies conditions when a combinatorial object contains necessarily some smaller given objects. The role of Ramsey numbers is to quantify some of the general existential theorems in Ramsey Theory.

Let $G_1, G_2, \ldots, G_m$ be graphs or $s$-uniform hypergraphs ($s$ is the number of vertices in each edge). $R(G_1, G_2, \ldots, G_m; s)$ denotes the $m$-color Ramsey number for $s$-uniform graphs/hypergraphs, avoiding $G_i$ in color $i$ for $1 \leq i \leq m$. It is defined as the least integer $n$ such that, in any coloring with $m$ colors of the $s$-subsets of a set of $n$ elements, for some $i$ the $s$-subsets of color $i$ contain a sub-(hyper)graph isomorphic to $G_i$ (not necessarily induced). The value of $R(G_1, G_2, \ldots, G_m; s)$ is fixed under permutations of the first $m$ arguments. If $s=2$ (standard graphs) then $s$ can be omitted. If $G_i$ is a complete graph $K_k$, then we may write $k$ instead of $G_i$, and if $G_i=G$ for all $i$ we may use the abbreviation $R_m(G; s)$ or $R_m(G)$. For $s=2$, $K_k-e$ denotes a $K_k$ without one edge, and for $s=3$, $K_k-t$ denotes a $K_k$ without one triangle (hyperedge).

The graph $nG$ is formed by $n$ disjoint copies of $G$, $G \cup H$ stands for vertex disjoint union of graphs, and the join $G+H$ is obtained by adding all the edges between vertices of $G$ and $H$ to $G \cup H$. $P_i$ is a path on $i$ vertices, $C_i$ is a cycle of length $i$, and $W_i$ is a wheel with $i-1$ spokes, i.e. a graph formed by some vertex $x$, connected to all vertices of the cycle $C_{i-1}$ (thus $W_i = K_1 + C_{i-1}$). $K_{n,m}$ is a complete $n$ by $m$ bipartite graph, in particular $K_{1,n}$ is a star graph. The book graph $B_i = K_2 + \overline{K}_i = K_1 + K_{1,i}$ has $i+2$ vertices, and can be seen as $i$ triangular pages attached to a single edge. The fan graph $F_n$ is defined by $F_n = K_1 + nK_2$. For a graph $G$, $n(G)$ and $e(G)$ denote the number of vertices and edges, respectively, and $\delta(G)$ and $\Delta(G)$ minimum and maximum degree in $G$. Finally, let $\chi(G)$ be the chromatic number of $G$. In general we follow the notation used by West [West].

Section 2 contains the data for the classical two color Ramsey numbers $R(k, l)$ for complete graphs, section 3 for much studied two color cases of $K_n-e$, $K_3$, $K_{m,n}$, and section 4 for numbers involving cycles. Section 5 lists other often studied two color cases for general graphs. The multicolor and hypergraph cases are gathered in sections 6 and 7, respectively. Finally, section 8 gives pointers to cumulative data and to other surveys.
2. Classical Two-Color Ramsey Numbers

2.1. Values and bounds for $R(k, l)$, $k \leq 10$, $l \leq 15$

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Table I. Known nontrivial values and bounds for two color Ramsey numbers $R(k, l) = R(k, l ; 2)$.

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References for Table I. HW+ abbreviates HWSYZH.
We split the data into the table of values and a table with corresponding references. In Table I, known exact values appear as centered entries, lower bounds as top entries, and upper bounds as bottom entries. For some of the exact values two references are given when the lower and upper bound credits are different.

(a) The task of proving $R(3, 3) \leq 6$ was the second problem in Part I of the William Lowell Putnam Mathematical Competition held in March 1953 [Bush].

(b) Greenwood and Gleason [GG] in 1955 established the initial values $R(3, 4) = 9$, $R(3, 5) = 14$ and $R(4, 4) = 18$.

(c) Kéry [Kéry] in 1964 found $R(3, 6) = 18$, but only recently an elementary and self-contained proof of this result appeared in English [Car].

(d) All the critical graphs for the numbers $R(k, l)$ (graphs on $R(k, l)−1$ vertices without $K_k$ and without $K_l$ in the complement) are known for $k = 3$ and $l = 3, 4, 5$ [Kéry], 6 [Ka2], 7 [RK3, MZ], and there are 1, 3, 1, 7 and 191 of them, respectively. All $(3, k)$-graphs, for $k \leq 6$, were enumerated in [RK3], and all $(4, 4)$-graphs in [MR2]. There exists a unique critical graph for $R(4, 4)$ [Ka2]. There are 430215 such graphs known for $R(3,8)$ [McK], 1 for $R(3,9)$ [Ka2] and 350904 for $R(4, 5)$ [MR4], but there might be more of them. The graphs constructed by Exoo in [Ex9, Ex12, Ex13, Ex14, Ex15, Ex16, Ex17], and some others, are available electronically from http://ginger.indstate.edu/ge/RAMSEY.

(e) In [MR5], strong evidence is given for the conjecture that $R(5, 5) = 43$ and that there exist exactly 656 critical graphs on 42 vertices.

(f) Cyclic (or circular) graphs are often used for Ramsey graph constructions. Several cyclic graphs establishing lower bounds were given in the Ph.D. dissertation by J.G. Kalbfleisch in 1966, and many others were published in the next few decades (see [RK1]). Harborth and Krause [HaKr] presented all best lower bounds up to 102 from cyclic graphs avoiding complete graphs. In particular, no lower bound in Table I can be improved with a cyclic graph on less than 102 vertices. See also item 2.3.k and section 5.16 [HaKr].

(g) The claim that $R(5, 5) = 50$ posted on the web [Stone] is in error, and despite being shown to be incorrect more than once, this value is still being cited by some authors. The bound $R(3, 13) \geq 60$ [XieZ] cited in the 1995 version of this survey was shown to be incorrect in [Piw1]. Another incorrect construction for $R(3, 10) \geq 41$ was described in [DuHu].

(h) There are really only two general upper bound inequalities useful for small parameters, namely 2.3.a and 2.3.b. Stronger upper bounds for specific parameters were difficult to obtain, and they often involved massive computations, like those for the cases of $(3,8)$ [MZ], $(4,5)$ [MR4], $(4,6)$ and $(5,5)$ [MR5]. The bound $R(6, 6) \leq 166$, only 1 more than the best known [Mac], is an easy consequence of a theorem in [Walk] (2.3.b) and $R(4, 6) \leq 41$.

(i) T. Spencer [Spe3], Mackey [Mac], and Huang and Zhang [HZ1], using the bounds for minimum and maximum number of edges in $(4,5)$ Ramsey graphs listed in [MR3, MR5], were able to establish new upper bounds for several higher Ramsey numbers, improving
on all of the previous longstanding best results by Giraud [Gi3, Gi5, Gi6].

(j) Only some of the higher bounds implied by 2.3.* are shown, and more similar bounds could be derived. In general, we show bounds beyond the contiguous small values if they improve on results previously reported in this survey or published elsewhere. Some easy upper bounds implied by 2.3.a are marked as [Ea1].

(k) We have recomputed the upper bounds in Table I marked [HZ1] using the method from the paper [HZ1], because the bounds there relied on an overly optimistic personal communication from T. Spencer. Further refinements of this method are studied in [HZ2, ShZ1, Shi2]. The paper [Shi2] subsumes the main results of the manuscripts [ShZ1, Shi2]. The upper bound \( R(10,12) \leq 81200 \) in Table I [Yang] was obtained by Yang using the method of [HWSYZH] (abbreviated in the table as HW+).

### 2.2. Bounds for \( R(k,l) \), higher parameters

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Table II. Known nontrivial lower bounds for higher two color Ramsey numbers \( R(k,l) \), with references.
(a) The construction by Mathon [Mat] and Shearer [She1] (see also items 2.3.i, 6.2.k and 6.2.l), using the data obtained by Shearer [She3] for primes up to 7000, implies in particular the following diagonal lower bounds: \( R(11,11) \geq 1597 \), \( R(13,13) \geq 2557 \), \( R(14,14) \geq 2989 \), \( R(15,15) \geq 5485 \), and \( R(16,16) \geq 5605 \). Similarly, \( R(17,17) \geq 8917 \), \( R(18,18) \geq 11005 \) and \( R(19,19) \geq 17885 \) were obtained in [LSL], though the first two of these bounds follow also from the data in [She3]. The same approach does not improve on the bound \( R(12,12) \geq 1639 \) [XSR2].

(b) The upper bounds of 88, 99, 110, 121 133, 145, 158 on \( R(3,k) \) for \( 15 \leq k \leq 21 \), respectively, were obtained in [Les]. The lower bounds marked [XXR], [XXER], [XSR2], 2.3.e and 2.3.h need not be cyclic. Several of the Cayley colorings from [Ex17] are also non-cyclic. All other lower bounds listed in Table II were obtained by construction of cyclic graphs.

(c) The graphs establishing lower bounds marked 2.3.g can be constructed by using appropriately chosen graphs \( G \) and \( H \) with a common \( m \)-vertex induced subgraph, similarly as it was done in several cases in [XXR].

(d) Yu [Yu2] constructed a special class of triangle-free cyclic graphs establishing several lower bounds for \( R(3,k) \), for \( k \geq 61 \). All of these bounds can be improved by the inequalities in 2.3.c and data from Tables I and II.

(e) Unpublished bound \( R(4,22) \geq 314 \) [LSLW] improves over 282 given in [SL]. [LSLW] includes also \( R(4,25) \geq 458 \). Not yet published bounds \( R(3,23) \geq 139 \) [XWCS] and \( R(4,17) \geq 200 \) [LWXS] improve over 137 and 182 obtained in [WSLX2] and [LSS1], respectively.

(f) Two special cases which improve on bounds listed in earlier revisions: \( R(9,17) \geq 1411 \) is given in [XXR] and \( R(10,15) \geq 1265 \) can be obtained by using 2.3.h.

(g) One can expect that the lower bounds in Table II are weaker than those in Table I, in the sense that some of them should not be that hard to improve, in contrast to the bounds in Table I, especially smaller ones.

2.3. General results on \( R(k,l) \)

(a) \( R(k,l) \leq R(k-1,l) + R(k,l-1) \), with strict inequality when both terms on the right hand side are even [GG]. There are obvious generalizations of this inequality for avoiding graphs other than complete.

(b) \( R(k,k) \leq 4R(k,k-2) + 2 \) [Walk].

(c) Explicit construction for \( R(3,3k+1) \geq 4R(3,k+1) - 3 \), for all \( k \geq 2 \) [CleDa], explicit construction for \( R(3,4k+1) \geq 6R(3,k+1) - 5 \), for all \( k \geq 1 \) [ChCD].

(d) Explicit triangle-free graphs with independence \( k \) on \( \Omega(k^{3/2}) \) vertices [Alon2, CPR]. For other constructive results in relation to \( R(3,k) \) see [BBH1, BBH2, Fra1, Fra2, FrLo, Gri, KlaM1, Loc, RK3, RK4, Stat, Yu1]. See also (p) and (q) below.
(e) The study of bounds for the difference between consecutive Ramsey numbers was initiated in [BEFS], where the bound $R(k, l) \geq R(k, l - 1) + 2k - 3$, for $k, l \geq 3$, was established by a construction. Let $\Delta_{k, l} = R(k, l) - R(k, l - 1)$. Only easy bounds on $\Delta_{k, l}$ are known, in particular $3 \leq \Delta_{3, l} \leq l$ for $k = 3$. Contrary to some claims about $\Delta_{k, l}$, it is not even known whether $\Delta_{k, k+1}/k \to \infty$ as $k \to \infty$, see [XSR2].

(f) By taking a disjoint union of two critical graphs one can easily see that $R(k, p) \geq s$ and $R(k, q) \geq t$ imply $R(k, p + q - 1) \geq s + t - 1$. Xu and Xie [XX1] improved this construction to yield better general lower bounds, in particular $R(k, p + q - 1) \geq s + t + k - 3$.

(g) For $2 \leq p \leq q$ and $3 \leq k$, if $(k, p)$-graph $G$ and $(k, q)$-graph $H$ have a common induced subgraph on $m$ vertices without $K_{k-1}$, then $R(k, p + q - 1) > n(G) + n(H) + m$. In particular, this implies the bounds $R(k, p + q - 1) \geq R(k, p) + R(k, q) + k - 3$ and $R(k, p + q - 1) \geq R(k, p) + R(k, q) + p - 2$ [XX1, XXR], with further small improvements in some cases, like the term $k - 2$ instead of $k - 3$ in the previous bound [XSR2].

(h) $R(2k - 1, l) \geq 4R(k, l - 1) - 3$ for $l \geq 5$ and $k \geq 2$, and in particular for $k = 3$ we have $R(5, l) \geq 4R(3, l - 1) - 3$ [XXER].

(i) If the quadratic residues Paley graph $Q_p$ of prime order $p = 4t + 1$ contains no $K_k$, then $R(k, k) \geq p + 1$ and $R(k + 1, k + 1) \geq 2p + 3$ [She1, Mat]. Data for larger $p$ was obtained in [LSL]. See also 3.1.c, and items 6.2.k and 6.2.l for similar multicolor results.

(j) Study of Ramsey numbers for large disjoint unions of graphs [Bu1, Bu9], in particular $R(nK_k, nK_l) = n(k + l - 1) + R(K_{k-1}, K_{l-1}) - 2$, for $n$ large enough [Bu8].

(k) $R(k, l) \geq L(k, l) + 1$, where $L(k, l)$ is the maximal order of any cyclic $(k, l)$-graph. A compilation of many best cyclic bounds was presented in [HaKr].

(l) The graphs critical for $R(k, l)$ are $(k - 1)$-vertex connected and $(2k - 4)$-edge connected, for $k, l \geq 3$ [BePi]. This was improved to vertex connectivity $k$ for $k \geq 5$ and $l \geq 3$ in [XSR2].

(m) All Ramsey-critical $(k, l)$-graphs are Hamiltonian for $k \geq l - 1 \geq 1$ and $k \geq 3$, except $(k, l) = (3, 2)$ [XSR2].

(n) Two color lower bounds can be obtained by using items 6.2.m, 6.2.n and 6.2.o with $r = 2$. Some generalizations of these were obtained in [ZLLS].
In the last seven items of this section we only briefly mention some pointers to the literature dealing with asymptotics of Ramsey numbers. This survey was designed mostly for small, finite, and combinatorial results, but still we wish to give the reader some useful and representative references to more traditional papers looking first of all at the infinite.

(o) In 1947, Erdős gave a simple probabilistic proof that $R(k, k) \geq c \cdot k^{2k/2}$ [Erd1]. Spencer [Spe1] improved the constant $c$ to $\sqrt{2}/e$. More probabilistic asymptotic lower bounds for other Ramsey numbers were obtained in [Spe1, Spe2, AlPu].

(p) The limit of $R(k, k)^{1/k}$, if it exists, is between $\sqrt{2}$ and 4 [GRS, GrRo È, ChGra2].

(q) In a 1995 breakthrough Kim proved that $R(3, k) = \Theta(k^{2}/\log k)$ [Kim].

(r) Other asymptotic and general results on triangle-free graphs in relation to $R(3, k)$ can be found in [Boh, AlBK, AKS, Alon2, CleDa, ChCD, CPR, Gri, FrLo, Loc, She2].

(s) Explicit constructions yielding lower bounds $R(4, k) \geq \Omega(k^{8/5})$, $R(5, k) \geq \Omega(k^{5/3})$ and $R(6, k) \geq \Omega(k^{2})$ [KosPR]. For the same cases classical probabilistic arguments give $\Omega(k/\log k)^{5/2}$, $\Omega(k/\log k)^{3}$ and $\Omega(k/\log k)^{7/2}$, respectively [Spe2]. These were further improved in [Boh, BohK].

(t) Explicit construction of a graph with clique and independence $k$ on $2^{c \log^2 k / \log \log k}$ vertices by Frankl and Wilson [FraWi]. Further constructions by Chung [Chu3] and Grolmusz [Grol1, Grol2]. Explicit constructions like these are usually weaker than known probabilistic results.

(u) In 2010, Conlon [Con1] obtained the best to date upper bound for the diagonal case:

$$R(k + 1, k + 1) \leq \binom{2k}{k} k^{-c \log k / \log \log k}$$

Other asymptotic bounds can be found, for example, in [Chu3, McS, Boh, BohK] (lower bound) and [Tho] (upper bound), and for many other bounds in the general case of $R(k, l)$ consult [Spe2, GRS, GrRô, Chu4, ChGra2, LiRZ1, AlPu, Kriv].
3. Two Colors: $K_n - e$, $K_3$, $K_m, n$

3.1. Dropping one edge from complete graph

This section contains known values and nontrivial bounds for the two color case when the avoided graphs are complete or have the form $K_k - e$, but not both are complete.

![Table III. Two types of Ramsey numbers $R(G, H)$, includes all known nontrivial values.](image)

(a) The exact values in Table III involving $K_3 - e$ are obvious, since one can easily see that $R(K_3 - e, K_k) = R(K_3 - e, K_{k+1} - e) = 2k - 1$, for all $k \geq 2$.

(b) The bound $R(K_3, K_{12} - e) \geq 46$ is given in [MPR]. Wang, Wang and Yan [WWY2] constructed cyclic graphs showing $R(K_3, K_{13} - e) \geq 54$, $R(K_3, K_{14} - e) \geq 59$ and $R(K_3, K_{15} - e) \geq 69$. It is known that $R(K_4, K_{12} - e) \geq 128$ [Shao] using one color of the (4,4,4;127)-coloring defined in [HiIr].

(c) If the quadratic residues Paley graph $Q_p$ of prime order $p = 4t + 1$ contains no $K_k - e$, then $R(K_{k+1} - e, K_{k+1} - e) \geq 2p + 1$. In particular, $R(K_{14} - e, K_{14} - e) \geq 2987$ [LiShen]. See also item 2.3.i.
(d) More bounds (beyond those shown in Table III) can be obtained by using Table I, an obvious generalization of the inequality \( R(k, l) \leq R(k-1, l) + R(k, l-1) \), and by monotonicity of Ramsey numbers, in this case \( R(K_{k-1}, G) \leq R(K_k - e, G) \leq R(K_k, G) \).

(e) All \((K_3, K_k - e)\)-graphs for \( k \leq 6 \) were enumerated in [Ra1], and for \( k = 7 \) in [Fid2].

(f) The critical graphs are unique for: \( R(K_3, K_l - e) \) for \( l = 3 \) [Tr], 6 and 7 [Ra1], \( R(K_4 - e, K_4 - e) \) [FRS2], \( R(K_5 - e, K_5 - e) \) [Ra3] and \( R(K_4 - e, K_7 - e) \) [McR].

(g) The number of \( R(K_3, K_l - e)\)-critical graphs for \( l = 4, 5 \) and 8 is 4, 2 and 9, respectively [MPR], and there are at least 6 such graphs for \( R(K_3, K_9 - e) \) [Ra1].

(h) All the critical graphs for the cases \( R(K_4 - e, K_4) \) [EHM1], \( R(K_4 - e, K_5) \) and \( R(K_5 - e, K_4) \) [DzFi1] are known, and there are 5, 13 and 6 of them, respectively.

(i) Full sets of \((K_3, K_k - e)\)-graphs are available [Fid2] for the following parameters: \((K_3, K_k - e)\) for \( k \leq 7 \), \((K_4, K_k - e)\) for \( k \leq 5 \) and \((K_5, K_k - e)\) for \( k \leq 4 \).

(j) \( R(K_k - e, K_k - e) \leq 4R(K_{k-2}, K_k - e) - 2 \) [LiShen].

For a similar inequality for complete graphs see 2.3.b.

(k) The upper bounds from [ShZ1, ShZ2] are subsumed by a later article [Shi2].

(l) The upper bounds in [HZ2] were obtained by a reasoning generalizing the bounds for classical numbers in [HZ1]. Several other results from section 2.3 apply, though checking in which situation they do may require looking inside the proofs whether they still hold for \( K_n - e \).

<table>
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<th>( K_9 - e )</th>
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<td>FRS1</td>
<td>GH</td>
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<td>Ra1</td>
<td>MPR</td>
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<td>B1</td>
<td>Ex14</td>
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<td>B1</td>
<td>B1</td>
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</table>

References for Table III. B1 abbreviates Boa1.
3.2. Triangle versus other graphs

(a) \( R(3, k) = \Theta(k^2/\log k) \) [Kim].
(b) Explicit construction for \( R(3, 3k + 1) \geq 4R(3, k + 1) - 3 \), for all \( k \geq 2 \) [CleDa], explicit construction for \( R(3, 4k + 1) \geq 6R(3, k + 1) - 5 \), for all \( k \geq 1 \) [ChCD].
(c) Explicit triangle-free graphs with independence \( k \) on \( \Omega(k^{3/2}) \) vertices [Alon2, CPR].
(d) \( R(K_3, K_7 - 2P_2) = R(K_3, K_7 - 3P_2) = 18 \) [SchSch2].
(e) \( R(K_3, K_3 + \bar{K}_m) = R(K_3, K_3 + C_m) = 2m + 5 \) for \( m \geq 212 \) [Zhou1].
(f) \( R(K_3, K_2 + T_n) = 2n + 3 \) for \( n \)-vertex trees \( T_n \), for \( n \geq 4 \) [SonGQ].
(g) \( R(K_3, G) \leq 2e(G) + 1 \) for any connected \( G \) on at least 4 vertices and with at most \( (17n(G) + 1)/15 \) edges, in particular for \( G = P_i \) and \( G = C_i \), for all \( i \geq 4 \) [BEFRS1].
(h) Relations between \( R(3, k) \) and graphs with large \( \chi(G) \) [FüR], further detailed study of the relation between \( R(3, k) \) and the chromatic gap [GySeT].
(i) \( R(K_3, G) \leq 2e(G) + 1 \) for any graph \( G \) without isolated vertices [Sid3, GK].
(j) \( R(K_3, G) \leq n(G) + e(G) \) for all \( G \), a conjecture [Sid2].
(k) \( R(K_3, G) \) for all connected \( G \) up to 9 vertices [BBH1, BBH2], see also section 8.1.
(l) For every positive constant \( c, \Delta, \) and \( n \) large enough, there exists graph \( G \) with \( \Delta(G) \leq \Delta \) for which \( R(K_3, G) > cn \) [Bra3].
(m) For \( R(K_3, K_n) \) see section 2, and for \( R(K_3, K_n - e) \) see section 3.1.
(n) Formulas for \( R(nK_3, mG) \) for all \( G \) of order 4 without isolates [Zeng].
(o) Since \( B_1 = F_1 = C_3 = W_3 = K_3 \), other sections apply. See also [Boh, AKS, BBH1, BBH2, FrLo, Fra1, Fra2, FüR, Gri, GySeT, Loc, KlaM1, LiZa1, RK3, RK4, She2, Spe2, Stat, Yu1].

3.3. Complete bipartite graphs

NOTE: This subsection gathers information on Ramsey numbers where specific bipartite graphs are avoided in edge colorings of \( K_n \) (as everywhere in this survey), in contrast to often studied bipartite Ramsey numbers (not covered in this survey) where the edges of complete bipartite graphs \( K_{n,m} \) are colored.

3.3.1. Numbers

The following Tables IVa and IVb gather information mostly from the surveys by Lortz and Mengersen [LoM3, LoM4]. All cases involving \( K_{1,2} = P_3 \) are solved by a formula for \( R(P_3, G) \), holding for all isolate-free graphs \( G \), derived in [CH2]. All star versus star numbers are given below in the item 3.3.2.a and in section 5.5.
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<td>(\geq 16) *</td>
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</table>

Table IVa. Ramsey numbers \(R(K_{m,n}, K_{p,q})\).
(unpublished results are marked with a *, Sh+ abbreviates ShaXBP)

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<td>21</td>
<td>24</td>
<td>27</td>
<td>(\leq 35)</td>
<td>36-37</td>
<td>40</td>
<td>42</td>
<td>EHM2</td>
</tr>
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</table>

Table IVb. Known Ramsey numbers \(R(K_{2,n}, K_{2,m})\), for \(6 \leq n \leq 11, 2 \leq m \leq 11\).
(unpublished results are marked with a *)
(a) The next few easily computed values of $R(K_{1,n}, K_{2,2})$, extending data in the first row of Table IVa, are 13, 14, 21 and 22 for $n$ equal to 9, 10, 16 and 17, respectively. See function $f(n)$ in 3.3.2.c of the next subsection below.

(b) Formula for $R(K_{1,n}, K_{k_1,k_2}, \ldots, k_m)$ for $m$ large enough, in particular for $t=1, k_1=2$ with $n \leq 5, m \geq 3$ and $n=6, m \geq 11$, for example $R(K_{1,5}, K_{2,2}) = 15$ [Stev].

(c) The values and bounds for higher cases of $R(K_{2,2}, K_{2,n})$ are 20, 22, 22/23, 22/24, 25, 26, 27/28, 28/29, 30 and 32 for $12 \leq n \leq 21$, respectively. More exact values can be found for prime powers $\lceil \sqrt{n} \rceil$ and $\lceil \sqrt{n} \rceil + 1$ [HaMe4].

(d) The known values of $R(K_{2,2}, K_{3,n})$ are 15, 16, 17, 20 and 22 for $6 \leq n \leq 10$ [Lortz], and $R(K_{2,2}, K_{3,11}) = 24$ [Shao]. See Tables IVa and IVb for the smaller cases, and [HaMe4] for upper bounds and values for some prime powers $\lceil \sqrt{n} \rceil$.

(e) $R(K_{2,2}, K_{2,n})$ is equal to 46, 50, 54, 57 and 62 for $12 \leq n \leq 16$, respectively. The first open diagonal case is $65 \leq R(K_{2,17}, K_{2,17}) \leq 66$ [EHM2]. The status of all higher cases for $n < 30$ is listed in [LoM1].

(f) $R(K_{1,4}, K_{4,4}) = R(K_{1,5}, K_{4,4}) = 13$ [ShaXPB]

$R(K_{1,4}, K_{1,2,3}) = R(K_{1,4}, K_{2,2,2}) = 11$ [GuSL]

$R(K_{1,7}, K_{2,3}) = 13$ [Par4, Par6]

$R(K_{1,15}, K_{2,2}) = 20$ [La2]

$R(K_{2,2}, K_{4,4}) = 14$ [HaMe4]

$R(K_{2,2}, K_{4,5}) = 15$ [Shao]

$R(K_{2,2}, K_{4,6}) = 16$ [Shao]

$R(K_{2,2}, K_{5,5}) = R(K_{2,3}, K_{3,5}) = 17$ [Shao]

$R(K_{3,5}, K_{3,5}) \leq 38$ [LoM2]

$R(K_{4,4}, K_{4,4}) \leq 62$ [LoM2]

3.3.2. General results

(a) $R(K_{1,n}, K_{1,m})=n+m-\varepsilon$, where $\varepsilon=1$ if both $n$ and $m$ are even and $\varepsilon=0$ otherwise [Har1]. It is also a special case of multicolor numbers for stars obtained in [BuRo1].

(b) $R(K_{1,3}, K_{m,n}) = m+n+2$ for $m, n \geq 1$ [HaMe3].

(c) $R(K_{1,n}, K_{2,2}) = f(n) \leq n + \sqrt{n} + 1$, with $f(q^2) = q^2 + q + 1$ and $f(q^2+1) = q^2 + q + 2$ for every $q$ which is a prime power [Par3]. Furthermore, $f(n) \geq n + \sqrt{n} - 6n^{11/40}$ [BEFRS54]. For more bounds and values of $f(n)$ see [Par5, Chen, ChenJ, MoCa].

(d) $R(K_{1,n+1}, K_{2,2}) \leq R(K_{1,n}, K_{2,2}) + 2$ [Chen].

(e) $R(K_{2,k+1}, K_{1,v-k+1})$ is either $v+1$ or $v+2$ if there exists a $(v, k, \lambda)$-difference set. This and other related results are presented in [Par4, Par5]. See also [GoCM, GuLi].

(f) Formulas and bounds on $R(K_{2,2}, K_{2,n})$, and bounds on $R(K_{2,2}, K_{m,n})$. In particular, $R(K_{2,2}, K_{2,k}) = n + k \sqrt{n} + c$, for $k=2, 3, 4$ and some prime powers $\lceil \sqrt{n} \rceil$ and $\lceil \sqrt{n} \rceil + 1$, for some $-1 \leq c \leq 3$ [HaMe4].
(g) \( R(K_{2,n}, K_{2,n}) \leq 4n - 2 \) for all \( n \geq 2 \), and the equality holds iff there exists a strongly regular \((4n - 3, 2n - 2, n - 2, n - 1)\)-graph [EHM2].

(h) Conjecture that \( 4n - 3 \leq R(K_{2,n}, K_{2,n}) \leq 4n - 2 \) for all \( n \geq 2 \). Many special cases are solved and several others are discussed in [LoM1].

(i) \( R(K_{2,n-1}, K_{2,n}) \leq 4n - 4 \) for all \( n \geq 3 \), with the equality if there exists a symmetric Hadamard matrix of order \( 4n - 4 \). There are only 4 cases in which the equality does not hold for \( 3 \leq n \leq 58 \), namely 30, 40, 44 and 48 [LoM1].

(j) \( R(K_{2,n-s}, K_{2,n}) \leq 4n - 2s - 3 \) for \( s \geq 2 \) and \( n \geq s + 2 \), with the equality in many cases involving Hadamard matrices or strongly regular graphs. Asymptotics of \( R(K_{2,n}, K_{2,m}) \) for \( m \gg n \) [LoM3].

(k) Some algebraic lower and upper bounds on \( R(K_{s,n}, K_{t,m}) \) for various combinations of \( n \), \( m \) and \( 1 \leq t, s \leq 3 \) [BaiLi, BaLX]. A general lower bound \( R(K_{m,n}) \geq 2^m (n - n^{0.525}) \) for large \( n \) [Dong].

(l) Upper bounds for \( R(K_{2,2}, K_{m,n}) \) for \( m, n \geq 2 \), with several cases identified for which the equality holds. Special focus on the cases for \( m = 2 \) [HaMe4].

(m) Bounds for the numbers of the form \( R(K_{k,n}, K_{k,m}) \), specially for fixed \( k \) and close to the diagonal cases. Asymptotics of \( R(K_{3,n}, K_{3,m}) \) for \( m \gg n \) [LoM2].

(n) \( R(nK_{1,3}, mK_{1,3}) = 4n + m - 1 \) for \( n \geq m \geq 1 \), \( n \geq 2 \) [BES].

(o) Asymptotics for \( K_{2,m} \) versus \( K_n \) [CLRZ]. Upper bound asymptotics for \( K_{k,m} \) versus \( K_n \) [LiZa1] and for some bipartite graphs \( K_n \) [JiSa].

(p) Special two-color cases apply in the study of asymptotics for multicolor Ramsey numbers for complete bipartite graphs [ChGra1].
4. Two Colors: Numbers Involving Cycles

4.1. Cycles, cycles versus paths and stars

The paper *Ramsey Numbers Involving Cycles* [Ra4] is based on the revision #12 of this survey. It collects and comments on the results involving cycles versus any graphs, in two or more colors. It contains some more details than this survey, but only until 2009.

**Cycles**

\[ R(C_3, C_3) = 6 \quad [GG, Bush] \]

\[ R(C_4, C_4) = 6 \quad [CH1] \]

\[ R(C_3, C_n) = 2n - 1 \text{ for } n \geq 4, \ R(C_4, C_n) = n + 1 \text{ for } n \geq 6, \]

\[ R(C_5, C_n) = 2n - 1 \text{ for } n \geq 5, \text{ and } R(C_6, C_6) = 8 \quad [ChS] \]

Result obtained independently in [Ros1] and [FS1], a new simpler proof in [KáRos]:

\[ R(C_m, C_n) = \begin{cases} 
2n - 1 & \text{for } 3 \leq m \leq n, \text{ } m \text{ odd, } (m, n) \neq (3, 3), \\
n - 1 + m/2 & \text{for } 4 \leq m \leq n, \text{ } m \text{ and } n \text{ even, } (m, n) \neq (4, 4), \\
\max \{ n - 1 + m/2, 2m - 1 \} & \text{for } 4 \leq m < n, \text{ } m \text{ even and } n \text{ odd.}
\end{cases} \]

\[ R(mC_3, nC_3) = 3n + 2m \text{ for } n \geq m \geq 1, \text{ } n \geq 2 \quad [BES] \]

\[ R(mC_4, nC_4) = 2n + 4m - 1 \text{ for } m \geq n \geq 1, \text{ } (m, n) \neq (1, 1) \quad [LiWa1] \]

Formulas for \( R(mC_4, nC_5) \) [LiWa2]

Formulas and bounds for \( R(nC_m, nC_m) \) [Den, Biel1]

Unions of cycles, formulas and bounds for various cases including diagonal, different lengths, different multiplicities [MiSa, Den], and their relation to 2-local Ramsey numbers [Biel1].

**Cycles versus paths**

Result obtained by Faudree, Lawrence, Parsons and Schelp in 1974 [FLPS]:

\[ R(C_m, P_n) = \begin{cases} 
2n - 1 & \text{for } 3 \leq m \leq n, \text{ } m \text{ odd,} \\
n - 1 + m/2 & \text{for } 4 \leq m \leq n, \text{ } m \text{ even,} \\
\max \{ m - 1 + \lfloor n/2 \rfloor, 2n - 1 \} & \text{for } 2 \leq n \leq m, \text{ } m \text{ odd,} \\
m - 1 + \lfloor n/2 \rfloor & \text{for } 2 \leq n \leq m, \text{ } m \text{ even.}
\end{cases} \]

For all \( n \) and \( m \) it holds that \( R(P_m, P_n) \leq R(C_m, P_n) \leq R(C_m, C_n) \). Each of the two inequalities can become an equality, and, as derived in [FLPS], all four possible combinations of \( < \) and \( = \) hold for an infinite number of pairs \( (m, n) \). For example, if both \( m \) and \( n \) are even, and at least one of them is greater than 4, then \( R(P_m, P_n) = R(C_m, P_n) = R(C_m, C_n) \). For related generalizations see [BEFRS2].
Cycles versus stars

Only partial results for \( C_m \) versus stars are known. Lawrence [La1] settled the cases for odd \( m \) and for long cycles (see also [Clark, Par6]). The case for short even cycles is open, it is related in particular to bipartite graphs. Partial results for \( C_4 = K_{2,2} \) are pointed to in subsections 3.3.1 and 3.3.2.

\[
R(C_m, K_{1,n}) = \begin{cases} 
2n + 1 & \text{for odd } m \leq 2n + 1, \\
m & \text{for } m \geq 2n.
\end{cases}
\]

4.2. Cycles versus complete graphs

Since 1976, it was conjectured that \( R(C_n, K_m) = (n-1)(m-1) + 1 \) for all \( n \geq m \geq 3 \), except \( n=m=3 \) [FS4, EFRS2]. The parts of this conjecture were proved as follows: for \( n \geq m^2-2 \) [BoEr], for \( n > 3 = m \) [ChaS], for \( n \geq 4 = m \) [YHZ1], for \( n \geq 5 = m \) [BJYHRZ], for \( n \geq 6 = m \) [Schi1], for \( n \geq m \geq 7 \) with \( n \geq m(m-2) \) [Schi1], for \( n \geq 7 = m \) [ChenCZ1], and for \( n \geq 4m+2, m \geq 3 \) [Nik]. Open conjectured cases are marked in Table V by "conj."

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<th>( K_3 )</th>
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<th>( C_6 )</th>
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<th>( C_n ) for ( n \geq m )</th>
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</table>

Table V. Known Ramsey numbers \( R(C_n, K_m) \).
(Ch+ abbreviates ChenCZ1, for comments on joint credits see 4.2.b)
(a) The first column in Table V gives data from the first row in Table I.

(b) Joint credit [He2/JR4] in Table V refers to two cases in which Hendry [He2] announced the values without presenting the proofs, which later were given in [JR4]. The special cases of $R(C_6, K_5) = 21$ [JR2] and $R(C_7, K_5) = 25$ were solved independently in [YHZ2] and [BJYHRZ]. The double pointer [JaBa/ChenCZ1] refers to two independent papers, similarly as [JaAl1/ZZ3], except that in the latter case [ZZ3] refers to an unpublished manuscript. For joint credits marked in Table V with "-", the first reference is for the lower bound and the second for the upper bound.

(c) Erdo\'{s} et al. [EFRS2] asked what is the minimum value of $R(C_n, K_m)$ for fixed $m$, and they suggested that it might be possible that $R(C_n, K_m)$ first decreases monotonically, then attains a unique minimum, then increases monotonically with $n$.

(d) There exist constants $c_1, c_2 > 0$ such that $c_1 (m/\log m)^{3/2} \leq R(C_4, K_m) \leq c_2 (m/\log m)^2$. The lower bound was obtained by Spencer [Spe2] using the probabilistic method. The upper bound is in a paper by Caro, Li, Rousseau and Zhang [CRLZ], who in turn give the credit to an unpublished work by Szemerédi from 1980.

(e) Erdős, in 1981, in the Ramsey problems section of the paper [Erd2] formulated a challenge by asking for a proof of $R(C_4, K_m) < m^{2-\varepsilon}$, for some $\varepsilon > 0$. No such proof is known to date.

(f) Lower bound asymptotics [Spe2, FS4, AlRo].

(g) Upper bound asymptotics [BoEr, FS4, EFRS2, CLRZ, Sud1, LiZa2, AlRö, DoLL2].
4.3. Cycles versus wheels

Note: In this survey the wheel graph $W_n = K_1 + C_{n-1}$ has $n$ vertices, while some authors use the definition $W_n = K_1 + C_n$ with $n + 1$ vertices. For the cases involving $W_3 = C_3$ versus $C_m$ see sections 3.2 and 4.2.

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Table VI. Ramsey numbers $R(W_n, C_m)$, for $n \leq 9$, $m \leq 8$.
(results from unpublished manuscript are marked with a *)

(a) $R(C_3, W_n) = 2n - 1$ for $n \geq 6$ [BE3]. All critical graphs have been enumerated. The critical graphs are unique for $n = 3, 5$, and for no other $n$ [RaJi].

(b) $R(C_4, W_n) = 13, 14, 16, 17$ for $n = 10, 11, 12, 13$, respectively [Tse1].

(c) $R(C_4, W_n) \leq n + \lceil (n - 1)/3 \rceil$ for $n \geq 7$ [SuBUB].

(d) $R(W_n, C_m) = 3m - 2$ for even $n \geq 4$ with $m \geq n - 1$, $m \neq 3$, was conjectured by Surahmat et al. [SuBT1, SuBT2, Sur]. Parts of this conjecture were proved in [SuBT1, ZhaCC1, Shi5], and the proof was completed in [ChenCN].

(e) Conjecture that $R(W_n, C_m) = 2m - 1$ for odd $n \geq 3$ and all $m \geq 5$ with $m > n$ [Sur].

(f) It was proved for $2m \geq 5n - 7$ [SuBT1], and further for $2m \geq 3n - 1$ [ChenCMN].

See also [Shi5].

(f) Observe apparently four distinct situations with respect to parity of $m$ and $n$. 
(g) Cycles are Ramsey unsaturated for some wheels [AliSur], see also comments on [BaLS] in subsection 5.16.

(h) Study of cycles versus generalized wheels $W_{k,n}$ [Sur, SuBTB, Shi5].

### 4.4. Cycles versus books

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Table VII. Ramsey numbers $R(B_n, C_m)$ for $n, m \leq 11$.

(� et. abbreviations: Fall/FRS, Cal/CRSPS, Sal1/ShaXBP, Sal2/ShaXB)

(a) For the cases of $B_1 = K_3$ versus $C_m$ see section 4.2.

The exact values for the cases $(3,7), (4,8), (4,9), (5,10), (5,11)$ were obtained independently in [Sal1, Sal2]/[ShaXBP, ShaXB] using computer algorithms.

(b) $R(C_4, B_{12}) = 21$ [Tse1], $R(C_4, B_{13}) = 22$, $R(C_4, B_{14}) = 24$ [Tse2].

$R(C_4, B_8) = 17$ [Tse2] (it was reported incorrectly in [FRS6] to be 16).

(c) $q^2 + q + 2 \leq R(C_4, B_{q^2+q+1}) \leq q^2 + q + 4$ for prime power $q$ [FRS6]. $B_n$ is a subgraph of $B_{n+1}$, hence likely $R(C_4, B_n) = n + O(\sqrt{n})$ (compare to $R(C_4, K_{2,n})$ in section 3.3).
(d) \( R(B_n, C_m) = 2n + 3 \) for odd \( m \geq 5 \) with \( n \geq 4m - 13 \) [FRS8].

(e) \( R(B_n, C_m) = 2m - 1 \) for \( n \geq 1, m \geq 2n + 2 \) [FRS8]. The range of \( m \) was extended to \( m \geq 2n - 1 \geq 7 \) in [ShaXB], and to \( m > (6n + 7)/4 \) in [Shi5].

(f) \( R(B_n, C_n) \geq 3n - 2 \) and \( R(B_{n-1}, C_n) \geq 3n - 4 \) for \( n \geq 3 \) [ShaXB].

(g) More theorems on \( R(B_n, C_m) \) in [FRS6, FRS8, NiRo4, Zhou1]

(h) Cycles versus some generalized books [Shi5].

4.5. Cycles versus other graphs

(a) \( C_4 \) versus stars [Par3, Par4, Par5, BEFRS4, Chen, ChenJ, GoMC, MoCa]. For several exact results see \( K_{2,2} \) in Tables IVa and IVb, and for general results see items 3.3.1.a, 3.3.2.c and 3.3.2.d.

(b) \( C_4 \) versus unions of stars [HaABS, Has]

(c) \( C_4 \) versus trees [EFRS4, Bu7, BEFRS4, Chen]

(d) \( C_4 \) versus all graphs on six vertices [JR3]

(e) \( C_4 \) versus various types of complete bipartite graphs, see section 3.3

(f) \( R(C_4, G) \leq 2q + 1 \) for any isolate-free graph \( G \) with \( q \) edges [RoJa2]

(g) \( R(C_4, G) \leq p + q - 1 \) for any connected graph \( G \) on \( p \) vertices and \( q \) edges [RoJa2]

(h) \( R(C_5, K_6 - e) = 17 \) [JR4]

(i) \( R(C_5, K_4 - e) = 9 \) [CRSPS]

(j) \( C_5 \) versus all graphs on six vertices [JR4]

(k) \( R(C_6, K_5 - e) = 17 \) [JR2]

(l) \( C_6 \) versus all graphs on five vertices [JR2]

(m) \( R(C_{2m+1}, G) = 2n - 1 \) for sufficiently large sparse graphs \( G \) on \( n \) vertices, in particular \( R(C_{2m+1}, T_n) = 2n - 1 \) for all \( n > 1512m + 756 \), for \( n \)-vertex trees \( T_n \) [BEFRS2].

(n) \( R(C_n, G) \leq 2q + \lfloor n/2 \rfloor - 1 \), for \( 3 \leq n \leq 5 \), for any isolate-free graph \( G \) with \( q > 3 \) edges. It is conjectured that it also holds for other \( n \) [RoJa2].

(o) Cycles versus trees [BEFRS2, FSS1]

(p) Monotone paths and cycles [Lef]

(q) Cycles versus \( K_n, m \) and multipartite complete graphs [BoEr]

(r) Cycles versus generalized books and wheels [Shi5, Sur, SuBTB], and versus other special graphs of the form \( K_n + G \) with small \( n \leq 3 \) and sparse \( G \) [Shi5].
5. General Graph Numbers in Two Colors

This section includes data with respect to general graph results. We tried to include all nontrivial values and identities regarding exact results (or references to them), but only those out of general bounds and other results which, in our opinion, may have a direct connection to the evaluation of specific numbers. If some small value cannot be found below, it may be covered by the cumulative data gathered in section 8, or be a special case of a general result listed in this section. Note that $P_2 = K_2$, $B_1 = F_1 = C_3 = W_3 = K_3$, $B_2 = K_4 - e$, $P_3 = K_3 - e$, $W_4 = K_4$ and $C_4 = K_{2,2}$ imply other identities not mentioned explicitly.

5.1. Paths

\[ R(P_m, P_n) = n + \lfloor m/2 \rfloor - 1 \] for all $n \geq m \geq 2$ [GeGy]

Stripes $mP_2$ [CocL1, CocL2, Lor]

Disjoint unions of paths (also called linear forests) [BuRo2, FS2]

5.2. Wheels

Note: In this survey the wheel graph $W_n = K_1 + C_{n-1}$ has $n$ vertices, while some authors use the definition $W_n = K_1 + C_n$ with $n + 1$ vertices.

![Table VIII. Ramsey numbers $R(W_m, W_n)$, for $m \leq n \leq 7$.](image)

(a) $R(W_3, W_n) = 2n - 1$ for all $n \geq 6$ [BE3]

All critical colorings for $R(W_3, W_n)$ for all $n \geq 3$ [RaJi]

(b) The value $R(W_5, W_5) = 15$ was given in the Hendry’s table [He2] without a proof. Later the proof was published in [HaMe2].

(c) All critical colorings (2, 1 and 2) for $R(W_n, W_6)$ for $n = 4, 5, 6$ [FM]

(d) $R(W_6, W_6) = 17$, $R(4,4) = 18$ and $\chi(W_6) = 4$ give a counterexample $G = W_6$ to the Erdős conjecture (see [GRS]) that $R(G, G) \geq R(K_{\chi(G)}, K_{\chi(G)})$. 

- 22 -
5.3. Books

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Table IX. Ramsey numbers \( R(B_m, B_n) \), for \( m, n \leq 7 \).

(Sh+ abbreviates ShaXBP)

(a) \( 254 \leq R(B_{37}, B_{88}) \leq 255 \) [Par6]

(b) Unpublished result \( R(B_2, B_3) = 17 \) [Rou] was later confirmed in [BLR].

(c) There are 4 Ramsey-critical graphs for \( R(B_2, B_3) \), unique graph for \( R(B_3, B_4) \) [ShaXBP], 3 for \( R(B_2, B_6) \) and 65 for \( R(B_2, B_7) \) [BLR].

(d) \( R(B_1, B_n) = 2n + 3 \) for all \( n > 1 \) [RS1]

(e) \( R(B_n, B_m) = 2n + 3 \) for all \( n \geq cm \) for some \( c < 10^6 \) [NiRo2, NiRo3]

(f) \( R(B_n, B_m) = (4 + o(1))n \) [RS1, NiRS]

(g) In general, \( R(B_n, B_n) = 4n + 2 \) for \( 4n + 1 \) a prime power. Several other specific values (like \( R(B_{62}, B_{65}) = 256 \)) and general equalities and bounds for \( R(B_n, B_m) \) can be found in [RS1, FRS7, Par6, NiRS, LiRZ2].

5.4. Trees and forests

In this subsection \( T_n \) and \( F_n \) denote \( n \)-vertex tree and forest, respectively.

(a) \( R(T_n, T_n) \leq 4n + 1 \) [EG]

(b) \( R(T_n, T_n) \geq [(4n - 1)/3] \) [BE2], see also section 5.15

(c) Conjecture that \( R(T_n, T_n) \leq 2n - 2 \), note that this is almost the same as asking if \( R(T_n, T_n) \leq R(K_{1,n-1}, K_{1,n-1}) \) [BE2], see also [Bu7, FSS1, ChGra2]. Discussion of the conjecture that \( R(T_m, T_n) \leq n + m - 2 \) holds for all trees [FSS1].
(d) If $\Delta(T_m) = m - 2$ and $\Delta(T_n) = n - 2$ then the exact values of $R(T_m, T_n)$ are known, and they are between $n + m - 5$ and $n + m - 3$ depending on $n$ and $m$. In particular, for $n = 2k + 1$ we have $R(T_{2k+1}, T_{2k+1}) = 2n - 5$ [GuSL].

(e) Examples of families $T_m$ and $T_n$ (including $P_n$) for which $R(T_m, T_n) = n + m - c$, $c = 3, 4, 5$ [SunZ], extending the results in [GuSL].

(f) View tree $T$ as a bipartite graph with parts $t_1$ and $t_2$, $t_2 \geq t_1$. Define $b(T) = \max\{2t_1 + t_2 - 1, 2t_2 - 1\}$. Then the bound $R(T, T) \geq b(T)$ holds always, $R(T, T) = b(T)$ holds for many classes of trees [EFRS3, GeGy], and asymptotically [HaLT], but cases for nonequality have been found [GHK].

(g) Comments in [BaLS] about some conjectures on Ramsey saturation of non-star trees, which would imply that $R(T_n, T_n) \leq 2n - 2$ holds for sufficiently large $n$.

(h) $R(T_m, K_{1,n}) \leq m + n - 1$, with equality for $(m-1) | (n-1)$ [BuL].

(i) $R(T_m, K_{1,n}) = m + n - 1$ for sufficiently large $n$ for almost all trees $T_m$ [BuL]. Many cases were identified for which $R(T_m, K_{1,n}) = m + n - 2$ [Coc, ZZ1], see also [BuL].

(j) $R(T_m, K_{1,n}) \leq m + n$ if $T_n$ is not a star and $(m-1) \nmid (n-1)$, some classes of trees and stars for which the equality holds [GuSL].

(k) $R(F_n, F_n) > n + \log_2 n - O(\log \log n)$ [BE2], forests are tight for this bound [CsKo].

(l) Forests, linear forests (unions of paths) [BuRo2, FS3, CsKo].

(m) Paths versus trees [FSS1], see also other parts of this survey involving special graphs, in particular sections 5.5, 5.6, 5.10, 5.12 and 5.15.

5.5. Stars, stars versus other graphs

$R(K_{1,n}, K_{1,m}) = n + m - \varepsilon$, where $\varepsilon = 1$ for even $n$ and $m$, and $\varepsilon = 0$ otherwise [Har1]. This is also a special case of multicolor numbers for stars 6.6.e obtained in [BuRo1].

$R(K_{1,n}, K_m) = n (m - 1) + 1$ by Chvátal’s theorem [Chv].

Stars versus $C_4$ [Par3, Par4, Par5, BEFRS4, Chen, ChenJ, GoMC, MoCa]
Stars versus $K_{2,n}$ [Par4, GoMC]
Stars versus $K_{n,m}$ [Stev, Par3]
Stars versus complete bipartite graphs [Par4, Stev]
See also section 3.3

$R(K_{1,4}, B_4) = 11$ [RS2]

$R(K_{1,4}, K_{1,2,3}) = R(K_{1,4}, K_{2,2,2}) = 11$ [GuSL]

$nK_{1,m}$ versus $W_5$ [BaHA]
Stars versus $W_5$ and $W_6$ [SuBa1]
Stars versus $W_9$ [Zhang2, ZhaCZ1]
Stars versus wheels [HaBA1, ChenZZ2, Kor]
Stars versus paths [Par2, BEFRS2]
Stars versus cycles [La1, Clark], see also [Par6] and section 4.1
Stars versus books [CRSPS, RS2]
Stars versus trees [Bu1, Cheng, Coc, GuoV, SunZ, ZZ1]
Stars versus stripes $mP_2$ [CocL1, CocL2, Lor]
Stars versus $K_n - tK_2$ [Hua1, Hua2]
Stars versus $2K_2$ [MeO]
Union of two stars [Gros2]
Unions of stars versus $C_4$ and $W_5$ [HaABS, Has]
Unions of stars versus wheels [BaHA, HaBA2, SuBAU1]

5.6. Paths versus other graphs
Note: for cycles versus $P_n$ see section 4.1.

$P_3$ versus all isolate-free graphs [CH2]
Paths versus stars [Par2, BEFRS2]
Paths versus trees [FS4, FSS1, SunZ]
Paths versus books [RS2]
Paths versus $K_n$ [Par1]
Paths versus $2K_n$ [SuAM]
Paths versus $K_{n,m}$ [Häg]
Paths versus $W_5$ and $W_6$ [SuBa1]
Paths versus $W_7$ and $W_8$ [Bas]
Paths versus wheels [BaSu, ChenZZ1, SaBr3, Zhang1]
Paths versus beaded wheels [AliBT2]
Paths versus fans [SaBr2]
Paths versus $K_1 + P_m$ [SaBr1, SaBr4]
Paths and cycles versus trees [FSS1]

Unions of paths [BuRo2]
Paths and unions of paths versus Jahangir graphs [AliBas, AliBT1, AliSur]
Paths and unions of paths versus $K_{2m} - mK_2$ [AliBB]
Sparse graphs versus paths and cycles [BEFRS2]
Graphs with long tails [Bu2, BG]
Monotone paths and cycles [Lef]

5.7. Fans, fans versus other graphs

\[ R(F_1, F_n) = R(K_3, F_n) = 4n + 1 \text{ for } n \geq 2, \text{ and bounds for } R(F_m, F_n) \text{ [LR2, GGS]} \]
\[ R(F_2, F_n) = 4n + 1 \text{ for } n \geq 2 \text{ and } R(F_m, F_n) \leq 4n + 2m \text{ for } n \geq m \geq 2 \text{ [LinLi]} \]
\[ R(K_4, F_n) = 6n + 1 \text{ for } n \geq 3 \text{ [SuBB3]} \]

Fans versus paths, formulas for a number of cases including $R(P_6, F_n)$ [SaBr2].
Missing case $R(P_6, F_4) = 12$ solved in [Shao].

Fans versus cycles [Shi5]
Fans versus $K_n$ [LR2]
Lower bounds on $R(F_2, K_n)$ from cyclic graphs for $n \leq 9$ [Shao]
5.8. Wheels versus other graphs

Notes: In this survey the wheel graph $W_n = K_1 + C_{n-1}$ has $n$ vertices, while some authors use the definition $W_n = K_1 + C_n$ with $n+1$ vertices.

For cycles versus $W_n$ see section 4.3.

$R(W_5, K_5 - e) = 17$ [He2][YH]
$R(W_5, K_5) = 27$ [He2][RST]
$R(W_5, K_6) \geq 33$, $R(W_5, K_7) \geq 43$ [Shao]

$W_5$ and $W_6$ versus stars and paths [SuBa1]
$W_5$ versus $nK_{1,m}$ [BaHA]
$W_5$ versus unions of stars [Has]
$W_5$ and $W_6$ versus trees [BSNM]

$W_7$ and $W_8$ versus paths [Bas]
$W_7$ versus trees $T_n$ with $\Delta(T_n) \geq n-3$, other special trees $T$, and for $n \leq 8$ [ChenZZ3, ChenZZ5, ChenZZ6]
$W_7$ and $W_8$ versus trees [ChenZZ4, ChenZZ5]
$W_9$ versus stars [Zhang2, ZhaCZ1, ZhaCC2]
$W_9$ versus trees of high degree [ZhaCZ2]

Wheels versus stars [HaBA1, ChenZZ2, Kor]
Wheels $W_n$, for even $n$, versus star-like trees [SuBB1]
Wheels versus paths [BaSu, ChenZZ1, SaBr3, Zhang1]
Wheels versus books [Zhou3]
Wheels versus unions of stars [BaHA, HaBA2, SuBAU1]
Wheels versus linear forests (disjoint unions of paths) [SuBa2]
Generalized wheels versus cycles [Shi5]
Upper bound asymptotics for $R(W_n, K_m)$ [Song5, SonBL]

5.9. Books versus other graphs

Note: for cycles versus $B_n$ see section 4.4.

$R(B_3, K_4) = 14$ [He3]
$R(B_3, K_5) = 20$ [He2][BaRT]
$R(B_4, K_{1,4}) = 11$ [RS2]

Cyclic lower bounds for $R(B_m, K_n)$ for $m \leq 7$, $n \leq 9$
and for $R(B_3, K_n - e)$ for $n \leq 7$ [Shao]

Books versus paths [RS2]
Books versus stars [CRSPS, RS2]
Books versus trees [EFRS7]
Books versus $K_n$ [LR1, Sud2]
Books versus wheels [Zhou3]
Books versus $K_2 + C_n$ [Zhou3]
Books and $(K_1 + tree)$ versus $K_n$ [LR1]
Generalized books $K_3 + qK_1$ versus cycles [Shi5]
Generalized books $K_r + qK_1$ versus $K_n$ [NiRo1, NiRo4]

5.10. Trees and forests versus other graphs

In this subsection $T_n$ and $F_n$ denote $n$-vertex tree and forest, respectively.

$$R(T_n, K_m) = (n-1)(m-1) + 1$$ [Chv]

$$R(T_n, C_{2m+1}) = 2n - 1 \text{ for all } n > 1512m + 756$$ [BEFRS2]

$$R(T_n, B_m) = 2n - 1 \text{ for all } n \geq 3m - 3$$ [EFRS7]

$$R(F_{nk}, K_m) = (n-1)(m-2) + nk$$ for all forests $F_{nk}$ consisting of $k$ trees with $n$ vertices each, also exact formula for all other cases of forests versus $K_m$ [Stahl]

Exact results for almost all small $(n(G) \leq 5)$ connected graphs $G$ versus all trees [FRS4]

Trees versus $C_4$ [EFRS4, Bu7, BEFRSS5, Chen]
Trees versus paths [FS4, FSS1]
Trees versus cycles [FSS1, EFRS6]
Trees versus stars [Bu1, Cheng, Coc, GuoV, ZZ1]
Trees versus books [EFRS7]
Trees versus $W_5$ and $W_6$ [BSNM]
Trees versus $W_7$ and $W_8$ [ChenZZ4, ChenZZ5]

Trees $T_n$ with $\Delta(T_n) \geq n - 3$, other special trees $T$,
and for $n \leq 8$ versus $W_7$ [ChenZZ3, ChenZZ5, ChenZZ6]
Trees $T_n$ with $\Delta(T_n) \geq n - 4$ versus $W_9$ [ZhaCZ2]

Star-like trees versus odd wheels [SuBB1, ChenZZ3]
Trees versus $K_n + \overline{K}_m$ [RS2, FSR]
Trees versus bipartite graphs [BEFRS4, EFRS6]
Trees versus almost complete graphs [GoJa2]
Trees versus multipartite complete graphs [EFRS8, BEFRSGJ]

Linear forests versus $3K_3$ and $2K_4$ [SuBAU2]
Linear forests versus wheels [SuBa2]
Forests versus almost complete graphs [CGP]
Forests versus complete graphs [BE1, Stahl, BaHA]

Study of graphs $G$ for which all or almost all trees are $G$-good [BF, BEFRSGJ],
see also section 5.15 and 5.16, item [Bu2], for the definition and more pointers.
See also various parts of this survey for special trees and section 5.4.

5.11. Cases for $n(G), n(H) \leq 5$

Clancy [Clan], in 1977, presented a table of $R(G,H)$ for all isolate-free graphs $G$ with $n(G) = 4$ and $H$ with $n(H) = 4$, except 5 entries. All five of the open entries have been solved as follows:
An interesting case in [Clan] is
\[ R(K_4, K_5 - P_3) = R(K_4, K_4 + e) = R(4, 4) = 18. \]

Hendry [He2], in 1989, presented a table of \( R(G, H) \) for all graphs \( G \) and \( H \) on 5 vertices without isolates, except 7 entries. Five of the open entries have been solved:

- \( R(K_5, K_4 + e) = R(4, 5) = 25 \) \([Ka1][MR4]\)
- \( R(K_5, K_5 - P_3) = 25 \) \([Ka1][Boza2, CalSR]\)
- \( R(K_5, B_3) = 20 \) \([He2][BaRT]\)
- \( R(K_5, W_5) = 27 \) \([He2][RST]\)
- \( R(W_5, K_5 - e) = 17 \) \([He2][YH]\)

The still open cases for \( K_5 \) versus \( K_5 - e \) and \( K_5 \) are:

\[ 30 \leq R(K_5, K_5 - e) \leq 34 \] \([Ex6][Ex8]\)
\[ 43 \leq R(K_5, K_5) \leq 49 \] \([Ex4][MR5]\)

All critical colorings for the case \( R(C_5 + e, K_5) = 17 \) were found in [He5].

### 5.12. Mixed cases

- \( 26 \leq R(K_{2,2,2}, K_{2,2,2}), \ K_{2,2,2} \) is an octahedron \([Ex8]\)
- Unicyclic graphs [Gros1, Köh, KrRod]
- \( K_{2,m} \) and \( C_{2m} \) versus \( K_n \) \([CLRZ]\)
- \( K_{2,n} \) versus any graph \([RoJa2]\)
- Union of two stars [Gros2]
- Double stars* [GHK, BahS]
- Graphs with bridge versus \( K_n \) \([Li1]\)
- Multipartite complete graphs [BFRS, FRS3, Stev]
- Multipartite complete graphs versus sparse graphs [EFRS4]
- Multipartite complete graphs versus trees [EFRS8, BEFRSGJ]
- Graphs with long tails [Bu2, BG]
- Brooms+ [EFRS3]

* double star is a union of two stars with their centers joined by an edge
+ broom is a star with a path attached to its center
5.13. Multiple copies of graphs, disconnected graphs
(a) $2K_2$ versus all isolate-free graphs [CH2]
(b) $nK_2$ versus $mK_2$, in particular $R(nK_2, nK_2) = 3n - 1$ for $n \geq 1$ [CocL1, CocL2, Lor]
(c) $nK_3$ versus $mK_3$, in particular $R(nK_3, nK_3) = 5n$ for $n \geq 2$ [BES], see also section 4.1
(d) $nK_3$ versus $mK_4$ [LorMu]
(e) $nK_{1,m}$ versus $W_5$ [BaHA]
(f) $R(nK_4, nK_4) = 7n + 4$ for large $n$ [Bu8]
(g) Stripes $mP_2$ [CocL1, CocL2, Lor]
(h) $R(G, H)$ for all disconnected isolate-free graphs $H$ on at most 6 vertices versus all $G$ on at most 5 vertices, except 3 cases [LoM5]. Missing cases were completed in [KroMe].
(i) $R(F, G \cup H) \leq \max\{R(F, G) + n(H), R(F, G)\}$ [Par6]
(j) $R(mG, nH) \leq (m - 1)n(G) + (n - 1)n(H) + R(G, H)$ [BES]
Formulas for $R(nK_3, mG)$ for all isolate-free graphs $G$ on 4 vertices [Zeng]
Variety of results for numbers $R(nG, mH)$ [Bu1, BES, HaBA2, SuBAU1]
(k) Disjoint unions of paths (linear forests) [BuRo2, FS2]
Linear forests versus $3K_3 \cup 2K_4$ [SuBAU2]
(l) Forests versus $K_n$ [Stahl, BaHA] and $W_n$ [BaHA]. Generalizations to forests versus other graphs $G$ in terms of $\chi(G)$ and the chromatic surplus of $G$ [Biel4], and for linear forests versus $2K_n$ [SuAM].
(m) Disconnected graphs versus other graphs [BE1, GoJa1]
(n) See section 4.1 for cases involving unions of cycles
(o) See also [Bu9, BE1, LorMu, MiSa, Den, Biel1, Biel2]

5.14. General results for special graphs

[BEFS] $R(K_{m,n}^p, K_q^t) = R(K_m^p, K_n^t)$ for $m, n \geq 3$, $m + n \geq 8$, $p \leq m/(n - 1)$ and $q \leq n/(m - 1)$, where $K'_t$ is a $K_t$ with additional vertex connected to it by $t$ edges. Some applications can be found in [BLR].
[RoJa2] $R(K_{2,k}, G) \leq kq + 1$, for $k \geq 2$, for isolate-free graphs $G$ with $q \geq 2$ edges.
[FM] $R(W_6, W_6) = 17$ and $\chi(W_6) = 4$. This gives a counterexample $G = W_6$ to the Erdős conjecture (see [GRS]) $R(G, G) \geq R(K_{\chi(G)}, K_{\chi(G)})$, since $R(4,4) = 18$.
[BE1] $R(G + K_1, H) \leq R(K_1, R(G, H), H)$.
[LiShen] $R(\overline{K}_2 + G, \overline{K}_2 + G) \leq 4R(\overline{K}_2 + G) - 2$.
[LiLD] Study of $R(G + K_1, nH + K_1)$.
[NiRo1] $R(K_{p+1}, B_q^r) = p(q + r - 1) + 1$ for generalized books $B_q^r = K_r + qK_1$, for all sufficiently large $q$.
5.15. General results for sparse graphs

[Chv] \( R(K_n, T_m) = (n-1)(m-1) + 1 \) for any tree \( T_m \) on \( m \) vertices.

[BE3] Graphs yielding \( R(K_n, G) = (n-1)(n(G)-1) + 1 \), called Ramsey \( n \)-good, and related results (see also [EFRS5]). An extensive survey and further study of \( n \)-goodness appeared in [NiRo4].

[BFRS2] \( R(C_{2m+1}, G) = 2n - 1 \) for sufficiently large sparse graphs \( G \) on \( n \) vertices, little more complicated formulas for \( P_{2m+1} \) instead of \( C_{2m+1} \).

[CRST] \( R(G, G) \leq c_d n(G) \) for all \( G \), where constant \( c_d \) depends only on the maximum degree \( d \) in \( G \). The constant was improved in [GRR1, FoxSu1]. Tight lower and upper bounds for bipartite \( G \) [GRR2, Con2]. Further improvements of the constant \( c_d \) in general were obtained in [ConFS5], and for graphs with bounded bandwidth in [AllBS].

[BE1] Study of \( L \)-sets, which are sets of pairs of graphs whose Ramsey numbers are linear in the number of vertices. Conjecture that Ramsey numbers grow linearly for \( d \)-degenerate graphs (graph is \( d \)-degenerate if all its subgraphs have minimum degree at most \( d \)). Progress towards this conjecture was obtained by several authors, including [KoRö1, KoRö2, KoSu, FoxSu1, FoxSu2].

[ChenS] \( R(G, G) \leq c_d n \) for all \( d \)-arrangeable graphs \( G \) on \( n \) vertices, in particular with the same constant for all planar graphs. The constant \( c_d \) was improved in [Eaton]. An extension to graphs not containing a subdivision of \( K_d \) [RöTh].

[AllBS] Conjecture that \( R(G, G) \leq 12n(G) \) for all planar \( G \), for large \( n \).

[Shi3] Ramsey numbers grow linearly for degenerate graphs versus some sparser graphs, arrangeable graphs, crowns, graphs with bounded maximum degree, planar graphs, and graphs without any topological minor of a fixed clique.
5.16. General results

[CH2] \( R(G,H) \geq (\chi(G)-1)(c(H)-1)+1 \), where \( \chi(G) \) is the chromatic number of \( G \), and \( c(H) \) is the size of the largest connected component of \( H \).

[CH3] \( R(G,G) > (s2^{2\chi(G)-1}e(G))^{1/\chi(G)} \), where \( s \) is the number of automorphisms of \( G \). Hence \( R(K_{n,n},K_{n,n}) > 2^n \), see also item 6.7.i.

[BE2] \( R(G,G) \geq \lceil (4n(G)-1)/3 \rceil \) for any connected \( G \), and \( R(G,G) \geq 2n - 1 \) for any connected nonbipartite \( G \). These bounds can be achieved for all \( n \geq 4 \).

[Bu2] Graphs \( H \) yielding \( R(G,H) = (\chi(G)-1)(n(H)-1)+s(G) \), where \( s(G) \) is a chromatic surplus of \( G \), defined as the minimum number of vertices in some color class under all vertex colorings in \( \chi(G) \) colors (such \( H \)'s are called \( G \)-good). This idea, initiated in [Bu2], is a basis of a number of exact results for \( R(G,H) \) for large and sparse graphs \( H \) [BG, BEFRS2, BEFRS3, Bu5, FS, EFRS4, FRS3, BEFRS3J, BF, LR4, Biel2, SuBAU3, Song6, AllBS]. Surveys of this area appeared in [FRS5, NiRo4].

[BaLS] Graph \( G \) is Ramsey saturated if \( R(G+e, G+e) > R(G, G) \) for every edge \( e \) in \( G \). This paper contains several theorems involving cycles, cycles with chords and trees on Ramsey saturated and unsaturated graphs, and also seven conjectures including one stating that almost all graphs are Ramsey unsaturated. Some classes of graphs were proved to be Ramsey unsaturated [Ho]. Special cases involving cycles and Jahangir graphs were studied in [AliSur].

[Für] Relations between \( R(3,k) \) and graphs with large \( \chi(G) \). Further detailed study of the relation between \( R(3,k) \) and the chromatic gap [GySeT].

[Bra3] \( R(G,H)>h(G,d)n(H) \) for all nonbipartite \( G \) and almost every \( d \)-regular \( H \), for some \( h \) unbounded in \( d \).
[DoLL1] Lower asymptotics of $R(G,H)$ depending on the average degree of $G$ and the size of $H$. This continues the study initiated in [EFRS5], later much enhanced for both lower and upper bounds in [Sud3].

[LiZa1] Lower bound asymptotics of $R(G,H)$ for large dense $H$.

[AIKS] Discussion of a conjecture by Erdős that there exists a constant $c$ such that $R(G,G) \leq 2^{e(G)}$ for all isolate-free graphs $G$. Proof for bipartite graphs and progress in other cases. In 2011, Sudakov [Sud4] completed the proof of this conjecture.

[Kriv] Lower bound on $R(G,K_n)$ depending on the density of subgraphs of $G$. This construction for $G = K_m$ produces a bound similar to the best known probabilistic lower bound by Spencer [Spe2]. Further lower and upper bounds on $R(G,K_n)$ in terms of $n$ and $e(G)$ can be found in [Sud3].

[Con3] Upper bounds on $R(G,K_n)$ for dense graphs $G$.

[BE1] Relations between the cases of $G$ or $G + K_1$ versus $H$ or $H + K_1$.

[HaKr] Study of cyclic graphs yielding lower bounds for Ramsey numbers. Exact formulas for paths and cycles, and values for small complete graphs and for graphs with up to five vertices.

[Par3] Relations between some Ramsey graphs and block designs. See also [Par4].

[Li2] Relations between the Shannon capacity of noisy communication channels and graph Ramsey numbers. See also section 6 in [Ros2].

[Bu6] Given integer $m$ and graphs $G$ and $H$, determining whether $R(G,H) \leq m$ holds is NP-hard. Further complexity results related to Ramsey theory were presented in [Bu10].

[Scha] Ramsey arrowing is $\Pi_2^P$-complete, a rare natural example of a problem higher than NP in the polynomial hierarchy of computational complexity theory.

[-] Special cases of multicolor results listed in section 6.

[-] See also surveys listed in section 8.
6. Multicolor Ramsey Numbers

The only known value of a multicolor classical Ramsey number:

\[ R_3(3) = R(3,3,3) = R(3,3;2) = 17 \quad \text{[GG]} \]

2 critical colorings (on 16 vertices) \quad \text{[KaSt, LayMa]}
2 colorings on 15 vertices \quad \text{[Hein]}
115 colorings on 14 vertices \quad \text{[PR1]}

6.1. Bounds for classical numbers

General upper bound, implicit in [GG]:

\[ R(k_1, \ldots, k_r) \leq 2 - r + \sum_{i=1}^{r} R(k_1, \ldots, k_{i-1}, k_i - 1, k_{i+1}, \ldots, k_r) \quad \text{(a)} \]

Inequality in (a) is strict if the right hand side is even, and at least one of the terms in the summation is even. It is suspected that this upper bound is never tight for \( r \geq 3 \) and \( k_i \geq 3 \), except for \( r = k_1 = k_2 = k_3 = 3 \). However, only two cases are known to improve over (a), namely \( R_4(3) \leq 62 \) [FKR] and \( R(3,3,4) \leq 31 \) [PR1, PR2], for which (a) produces the bounds of 66 and 34, respectively.

Diagonal Cases

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<th>6</th>
<th>7</th>
<th>8</th>
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</table>

Table X. Known nontrivial lower bounds for diagonal multicolor Ramsey numbers \( R_r(m) \), with references.

The best published bounds corresponding to the entries in Table X marked as personal communications [Ex17] and [Xu] are \( 415 \leq R_3(5) \), \( 2721 \leq R_4(5) \) and \( 26082 \leq R_5(5) \) [XXER].
The most studied and intriguing open case is

[Chu1] \( 51 \leq R_4(3) = R(3,3,3,3) \leq 62 \) [FKR]

The construction for \( 51 \leq R_4(3) \) as described in [Chu1] is correct, but be warned of a typo found by Christopher Frederick in 2003 (there is a triangle (31,7,28) in color 1 in the displayed matrix). The inequality 6.1.a implies \( R_4(3) \leq 66 \), Folkman [Fol] in 1974 improved this bound to 65, and Sánchez-Flores [San] in 1995 proved \( R_4(3) \leq 64 \).

The upper bounds in \( 162 \leq R_5(3) \leq 307, 538 \leq R_6(3) \leq 1838, 1682 \leq R_7(3) \leq 12861, 128 \leq R_3(4) \leq 236 \) and \( 634 \leq R_4(4) \leq 6474 \) are implied by 6.1.a (we repeat lower bounds from Table X just to see easily the ranges). All the latter and other upper bounds obtainable from known smaller bounds and 6.1.a can be computed with the help of a LISP program written by Kerber and Rowat [KerRo].

**Off-Diagonal Cases**

Three colors:

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<td>Reb3</td>
<td>Ex16</td>
<td>Ex17</td>
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</table>

Table XI. Known nontrivial lower bounds for 3-color Ramsey numbers of the form \( R(3,k,m) \), with references.

In addition, the bounds \( 303 \leq R(3,6,6) \), \( 609 \leq R(3,7,7) \) and \( 1689 \leq R(3,9,9) \) were derived in [XXER] (used there for building other lower bounds for some diagonal cases).

The other most studied, and perhaps the only open case of a classical multicolor Ramsey number, for which we can anticipate exact evaluation in the not-too-distance future is

[Ka2] \( 30 \leq R(3,3,4) \leq 31 \) [PR1, PR2]

In [PR1] it is conjectured that \( R(3,3,4) = 30 \), and the results in [PR2] eliminate some cases which could give \( R(3,3,4) = 31 \). The upper bounds in \( 45 \leq R(3,3,5) \leq 57, 55 \leq R(3,4,4) \leq 79, \) and \( 89 \leq R(3,4,5) \leq 160 \) are implied by 6.1.a (we repeat lower bounds from the Table XI to show explicitly the current ranges).
Lower bounds for higher numbers can be obtained by using general constructive results from section 6.2 below. For example, the bounds $261 \leq R(3,3,15)$ and $247 \leq R(3,3,3,7)$ were not published explicitly but are implied by 6.2.f and 6.2.g, respectively.

### 6.2. General results for complete graphs

(a) $R(k_1, \ldots, k_r) \leq 2 - r + \sum_{i=1}^{r} R(k_1, \ldots, k_{i-1}, k_i - 1, k_{i+1}, \ldots, k_r)$ [GG]  
(b) $R_r(3) \geq 3R_{r-1}(3) + R_{r-3}(3) - 3$ [Chu1]  
(c) $R_r(m) \geq c_m(2m - 3)^r$, and some slight improvements of this bound for small values of $m$ were described in [AbbH, Gi1, Gi2, Song2]. For $m = 3$, the best known lower bound is $R_r(3) \geq (3.199 \ldots)^r$ [XXER].  
(d) $R_r(3) \leq r!(e - e^{-1} + 3)/2 \approx 2.67r!$ [Wan], which improves the classical $3r!$ [GRS].  
(e) The limit $L = \lim_{r \to \infty} R_r(3)^{1/r}$ exists, though it can be infinite [ChGri].  
   It is known that $3.199 < L$, as implied by (c) above. For more related results, mostly on the asymptotics of $R_r(3)$, see [AbbH, Fre, Chu2, GRS, GrRö].  
(f) $R(3,k,l) \geq 4R(k,l-1) - 3$, and in general for $r \geq 2$ and $k_i \geq 2$,  
   $R(3,k_1,\ldots,k_r) \geq 4R(k_1-1,k_2,\ldots,k_r) - 3$ for $k_1 \geq 5$, and  
   $R(k_1,2k_2-1,k_3,\ldots,k_r) \geq 4R(k_1-1,k_2,\ldots,k_r) - 3$ for $k_1 \geq 5$ [XX2, XXER].  
(g) $R(3,3,3,k_1,\ldots,k_r) \geq 3R(3,3,k_1,\ldots,k_r) + R(k_1,\ldots,k_r) - 3$ [Rob2]  
(h) For $r+1$ colors, avoiding $K_3$ in the first $r$ colors and avoiding $K_m$ in the last color,  
   $R(3,\ldots,3,m) \leq r!m^{r+1}$ [Sár].  
(i) $R(k_1,\ldots,k_r) \geq S(k_1,\ldots,k_r) + 2$, where $S(k_1,\ldots,k_r)$ is the generalized Schur number [AbbH, Gi1, Gi2]. In particular, the special case $k_1=\ldots=k_r=3$ has been widely studied [Fre, FreSw, Ex10, Rob3].  
(j) $R(k_1,\ldots,k_r) \geq L(k_1,\ldots,k_r) + 1$, where $L(k_1,\ldots,k_r)$ is the maximal order of any cyclic $(k_1,\ldots,k_r)$-coloring, which can be considered a special case of Schur partitions defining (symmetric) Schur numbers. Many lower bounds for Ramsey numbers were established.
by cyclic colorings. The following recurrence can be used to derive lower bounds for higher parameters. For \(k_i \geq 3\) [Gi2],
\[
L(k_1, \ldots, k_r, k_{r+1}) \geq (2k_{r+1} - 3)L(k_1, \ldots, k_r) - k_{r+1} + 2.
\]

(k) \(R_r(m) \geq p + 1\) and \(R_r(m+1) \geq r(p + 1) + 1\) if there exists a \(K_m\)-free cyclotomic \(r\)-class association scheme of order \(p\) [Mat].

(l) If the quadratic residues Paley graph \(Q_p\) of prime order \(p = 4t + 1\) contains no \(K_k\), then \(R(s, k + 1, k + 1) \geq 4ps - 6p + 3\) [XXER].

(m) \(R_r(pq + 1) > (R_r(p + 1) - 1)(R_r(q + 1) - 1)\) [Abb1]

(n) \(R_r(pq + 1) > R_r(p + 1)(R_r(q + 1) - 1)\) for \(p \geq q\) [XXER]

(o) \(R(p_1q_1 + 1, \ldots, p_rq_r + 1) > (R(p_1 + 1, \ldots, p_r + 1) - 1)(R(q_1 + 1, \ldots, q_r + 1) - 1)\) [Song3]

(p) \(R_{r+1}(m) > (R_r(m) - 1)(R_s(m) - 1)\) [Song2]

(q) \(R(k_1, k_2, \ldots, k_r) > (R(k_1, \ldots, k_i) - 1)(R(k_{i+1}, \ldots, k_r) - 1)\) in [Song1], see [XXER].

(r) \(R(k_1, k_2, \ldots, k_r) > (k_1 + 1)(R(k_2 - k_1 + 1, k_3, \ldots, k_r) - 1)\) [Rob4]

(s) Further lower bound constructions, though with more complicated assumptions, were presented in [XX2, XXER].

(t) Grolmusz [Grol1] generalized the classical constructive lower bound by Frankl and Wilson [FraWi] (item 2.3.t) to more colors and to hypergraphs [Grol3] (item 7.3.i).

(u) Exact asymptotics of a very special but important case is known, namely \(R(3, 3, n) = \Theta(n^3 \text{poly-log } n)\) [AlRö]. For general upper bounds and more asymptotics see in particular [Chu4, ChGra2, ChGri, GRS, GrRö].

All lower bounds in (b) through (t) above are constructive. (g) generalizes (b), (o) generalizes both (m) and (q), and (q) generalizes (p). (n) is stronger than (m). Finally, we note that the construction in (o) with \(q_1 = \ldots = q_i = 1 = p_{i+1} = \ldots = p_r\) is the same as (q).

6.3. Cycles

The paper \textit{Ramsey Numbers Involving Cycles} [Ra4] is based on the revision #12 of this survey. It collects and comments on the results involving cycles versus any graphs, in two or more colors. It contains some more details than this survey, but only until 2009.

6.3.1. Three colors

(a) One long cycle.

The first larger paper in this area by Erdős, Faudree, Rousseau and Schelp [EFRS1] appeared in 1976. It gives several formulas and bounds for \(R(C_m, C_n, C_k)\) and \(R(C_m, C_n, C_k)\) for large \(m\). For three colors [EFRS1] includes:
\[
R(C_m, C_{2p+1}, C_{2q+1}) = 4m - 3 \quad \text{for } p \geq 2, q \geq 1,
\]
\[
R(C_m, C_{2p}, C_{2q+1}) = 2(m + p) - 3 \quad \text{and}
\]
\[
R(C_m, C_{2p}, C_{2q}) = m + p + q - 2 \quad \text{for } p, q \geq 1 \text{ and large } m.
\]
Table XII. Ramsey numbers $R(C_m, C_n, C_k)$ for $m, n, k \leq 7$ and $m = n = k = 8$.

(Sun1+ abbreviates SunYWLX, Sun2+ abbreviates SunYLZ2, the work in [SunYWLX] and [SunYLZ2] is independent from [Tse3])

(b) Triple even cycles.

$R_3(C_{2m}) \geq 4m$ for all $m \geq 2$ \cite{DzNS}, see also 6.3.2.c/d/e.

In 2005, Dzido \cite{Dzi1} conjectured that $R_3(C_{2m}) = 4m$ for all $m \geq 3$. It is known that $R(C_n, C_n, C_n) = (2 + o(1))n$ for even $n$ \cite{FiLu1, GyRSS}. Next, the diagonal case was improved to exactly $2n$ for large $n$ \cite{BenSk}. The first open case is for $R_3(C_{10})$, known to be at least 20. A more general result holds for slightly off-diagonal cases \cite{FiLu1}:

$$R_3(C_{2q}) \geq 4q \text{ for } q \geq 2 \text{ \cite{DzNS}}$$

$$R_3(C_{2q+1}) = 8q + 1 \text{ for large } q \text{ \cite{KoSS}}$$

$$R_3(C_{2q}) = 4q \text{ for large } q \text{ \cite{BenSk}}$$
\[
R(C_2[\alpha_1 n], C_2[\alpha_2 n], C_2[\alpha_3 n]) = \\
(\alpha_1 + \alpha_2 + \alpha_3 + \max\{\alpha_1, \alpha_2, \alpha_3\} + o(1)) n, \text{ for all } \alpha_1, \alpha_2, \alpha_3 > 0.
\]

(c) Triple odd cycles.

\[R_3(C_{2m+1}) = 8m + 1\] for all sufficiently large \(m\), or equivalently
\[R(C_n, C_n, C_n) = 4n - 3\] for all sufficiently large odd \(n\) [KoSS].

\[R(C_n, C_n, C_n) \leq (4 + o(1)) n\], with equality for odd \(n\) [Luc]. In 1981, it was conjectured by Bondy and Erdős, see [Erd2], that \(R(C_n, C_n, C_n) \leq 4n - 3\) for \(n \geq 4\). If true, then for all odd \(n \geq 5\) we have \(R(C_n, C_n, C_n) = 4n - 3\). The first open case is for \(R_3(C_9)\), known to be at least 33.

(d) \(R(C_3, C_3, C_k) = 5k - 4\) for \(k \geq 5\) [SunYWLX], and \(R(C_4, C_4, C_k) = k + 2\) for \(k \geq 11\) [SunYLZ2]. All exceptions to these formulas for small \(k\) are listed in Table XII.

(e) Asymptotics for triples of cycles of mixed parity similar in form to (b) [FiLu2].

(f) Almost all of the off-diagonal cases in Table XII required the use of computers.

### 6.3.2. More colors

For results on \(R_k(C_3) = R_k(K_3)\) see sections 6.1, 6.2.

\[
R_4(C_4) = 18 \quad \text{[Ex2] [SunYLZ1]}
\]
\[
18 \leq R_4(C_6) \quad \text{[SunYLS]}
\]
\[
27 \leq R_5(C_4) \leq 29 \quad \text{[LaWo1]}
\]
\[
R_5(C_6) = 26 \quad \text{[SunYLS] [SunYW]}
\]
\[
24 \leq R(C_3, C_4, C_4, C_4) \leq 27 \quad \text{[DyDz] [XuR2]}
\]
\[
30 \leq R(C_3, C_3, C_4, C_4) \leq 36 \quad \text{[DyDz] [XuR2]}
\]
\[
49 \leq R(C_3, C_3, C_3, C_4) \quad 6.7.e
\]

(a) Formulas for \(R(C_m, C_n, C_k, C_l)\) for large \(m\) [EFRS1].

(b) \(R_k(C_4) \leq k^2 + k + 1\) for all \(k \geq 1\), \(R_k(C_4) \geq k^2 - k + 2\) for all \(k - 1\) which is a prime power [Ir, Chu2, ChGra1], and \(R_k(C_4) \geq k^2 + 2\) for odd prime power \(k\) [LaWo1]. The latter was extended to any prime power \(k\) in [Ling, LaMu].

Bounds in (c) through (g) below cover different situations and each is best in some respect.

(c) \(R_k(C_{2m}) \geq (k + 1)m\) for odd \(k\) and \(m \geq 2\), and
\(R_k(C_{2m}) \geq (k + 1)m - 1\) for even \(k\) and \(m \geq 2\) [DzNS].

(d) \(R_k(C_{2m}) \geq 2(k - 1)(m - 1) + 2\) [SunYXL].

(e) \(R_k(C_{2m}) \geq k^2 + 2m - k\) for \(2m \geq k + 1\) and prime power \(k\) [SunYLS].
(f) \( R_k(C_{2m}) = \Theta(k^{m/(m-1)}) \) for fixed \( m = 2, 3 \) and 5 [LiLih].

(g) \( R_k(C_{2m}) \leq 201km \) for \( k \leq 10^m/201m \) [EG].

(h) \( R_k(C_{2m}) \leq 2km + o(m) \) for all fixed \( k \geq 2 \) [LucSS].

(i) \( R_k(C_5) < \sqrt{18k^k}/10 \) [Li4].

(j) \( 2^{km} < R_k(C_{2m+1}) \leq (k+2)!(2m+1) \) [BoEr].

Better upper bound \( R_k(C_{2m+1}) < 2(k+2)!m \) was obtained in [EG].

Much better upper bound \( R_k(C_{2m+1}) \leq (c^kk!)^{1/m} \), for some positive constant \( c \),
if all Ramsey-critical graphs for \( C_{2m+1} \) are not far from regular, was obtained in [Li4].

(k) Conjecture that \( R_k(C_{2m+1}) = 2^{km} + 1 \) for all \( m \geq 2 \), was credited by several authors to
Bondy and Erdős [BoEr], though only lower bound not the conjecture is in this paper.

(l) \( R(C_n, C_{l_1}, \ldots, C_{l_s}) = 2^k(n-1) + 1 \) for all \( l_i \)'s odd with \( l_i > 2^i \), and every sufficiently
large \( n \), in particular we have \( R_k(C_n) = 2^{k-1}(n-1) + 1 \) for large odd \( n \) [AllBS].

(m) \( R_k(C_{2m+1}) \leq k2^{km} + o(m) \) for all fixed \( k \geq 4 \) [LucSS].

(n) Asymptotic bounds for \( R_k(C_n) \) [Bu1, GRS, ChGra2, Li4, LiLih, ŁucSS].

(o) Survey of multicolor cycle cases [Li3].

### 6.3.3. Cycles versus other graphs

\begin{align*}
20 & \leq R(C_4, C_4, K_4) \leq 22 \quad \text{[DyDz] [XSR1]} \\
27 & \leq R(C_3, C_4, K_4) \leq 32 \quad \text{[DyDz] [XSR1]} \\
52 & \leq R(C_4, K_4, K_4) \leq 72 \quad \text{[XSR1]} \\
34 & \leq R(C_4, C_4, K_4, K_4) \leq 50 \quad \text{[DyDz] [XSR1]} \\
43 & \leq R(C_3, C_4, C_4, K_4) \leq 76 \quad \text{[DyDz] [XSR1]} \\
87 & \leq R(C_4, C_4, C_4, K_4, K_4) \leq 179 \quad \text{[XSR1]} \\
R(K_{1,3}, C_4, K_4) & = 16 \quad \text{[KlaM2]} \\
R(C_4, C_4, K_4 - e) & = 16 \quad \text{[DyDz]} \\
R(C_4, C_4, C_4, T) & = 16 \quad \text{for } T = P_4 \text{ and } T = K_{1,3} \quad \text{[ExRe]}
\end{align*}

(a) Study of \( R(C_n, K_{t_1}, \ldots, K_{t_k}) \) and \( R(C_n, K_{t_1}, s_1, \ldots, K_{t_k}, s_k) \) for large \( n \) [EFRS1].

(b) \( R(C_n, K_{t_1}, \ldots, K_{t_k}) = (n-1)(r-1) \) for \( n \geq 4r+2 \), where \( r = R(K_{t_1}, \ldots, K_{t_k}) \) [OmRa2].

(c) Study of asymptotics for \( R(C_m, \ldots, C_m, K_n) \), in particular for any fixed number of colors
\( k \geq 4 \) we have \( R(C_4, C_4, \ldots, C_4, K_n) = \Theta(n^2/\log^2 n) \) [AlRö].

(d) Study of asymptotics for \( R(C_{2m}, C_{2m}, K_n) \) for fixed \( m \) [AlRö, ShiuLL], in particular
\( R(C_4, C_4, K_n) = \Theta(n^2 \text{poly-log } n) \) [AlRö].

(e) Monotone paths and cycles [Lef].

(f) For combinations of \( C_3 \) and \( K_n \) see sections 2.2, 3.2, 4.2, 6.1 and 6.2.
6.4. Paths, paths versus other graphs

In 2007, Gyárfás, Ruszinkó, Sárközy and Szemerédi [GyRSS] established that for all sufficiently large $n$ we have

$$R(P_n, P_n, P_n) = 2n - 2 + n \mod 2.$$  

6.4.1. Three color path and path-cycle cases

(a) $R(P_m, P_n, P_k) = m + \lceil n/2 \rceil + \lceil k/2 \rceil - 2$ for $m \geq 6(n + k)^2$ [FS2], the equality holds asymptotically for $m \geq n \geq k$ with an extra term $o(m)$ [FiLu1], extensions of the range of $m, n, k$ for which (a) holds were obtained in [Biel3].

(b) $R_3(P_3) = 5$ [Ea1], $R_3(P_4) = 6$ [Ir].

$R(P_m, P_n, P_k) = 5$ for other $m - n - k$ combinations with $3 \leq m, n, k \leq 4$ [AKM], $R_3(P_5) = 9$ [YR1], $R_3(P_6) = 10$ [YR1], and $R_3(P_7) = 13$ [YY].

(c) $R(P_4, P_4, P_{2n}) = 2n + 2$ for $n \geq 2$,

$R(P_5, P_5, P_5) = R(P_5, P_5, P_6) = 9,$

$R(P_5, P_5, P_n) = n + 2$ for $n \geq 7,$

$R(P_5, P_6, P_n) = R(P_4, P_6, P_n) = n + 3$ for $n \geq 6$,

$R(P_6, P_6, P_{2n}) = R(P_4, P_8, P_{2n}) = 2n + 4$ for $n \geq 14$ [OmRa1].

(d) $R(P_m, P_n, C_k) = 2n + 2 \lceil m/2 \rceil - 3$ for large $n$ and odd $m \geq 3$ [DzFi2], improvements on the range of $m, n, k$ [Biel3, Fid1].

(e) $R(P_3, P_3, C_m) = 5, 6, 6$, for $m = 3, 4$ [AKM], $5$,

$R(P_3, P_3, C_m) = m$ for $m \geq 6$ [Dzi2].

$R(P_3, P_4, C_m) = 7$ for $m = 3, 4$ [AKM] and 5,

$R(P_3, P_4, C_m) = m + 1$ for $m \geq 6$ [Dzi2].

$R(P_4, P_4, C_m) = 9, 7, 9$ for $m = 3, 4$ [AKM] and 5 [Dzi2],

$R(P_4, P_4, C_m) = m + 2$ for $m \geq 6$ [DzKP].

(f) $R(P_3, P_5, C_m) = 9, 7, 9, 7, 9$ for $m = 3, 4, 5, 6, 7$ [Dzi2, DzFi2],

$R(P_3, P_5, C_m) = m + 1$ for $m \geq 8$ [DzKP].

A table of $R(P_3, P_k, C_m)$ for all $3 \leq k \leq 8$ and $3 \leq m \leq 9$ [DzFi2].

(g) $R(P_4, P_5, C_m) = 11, 7, 11, 11$, and $m + 2$ for $m = 3, 4, 5, 7$ and $m \geq 23$,

$R(P_4, P_6, C_m) = 13, 8, 13, 13$, and $m + 3$ for $m = 3, 4, 5, 7$ and $m \geq 18$ [ShaXSP].

(h) $R(P_3, P_n, C_4) = n + 1$ for $n \geq 6$ [DzFi2],

$R(P_3, P_n, C_6) = n + 2$ for $n \geq 6$,

$R(P_3, P_n, C_8) = n + 3$ for $n \geq 7$ [Fid1],

$R(P_3, P_n, C_k) = 2n - 1$, and

$R(P_4, P_n, C_k) = 2n + 1$ for odd $k \geq 3$ and $n \geq k$ [DzFi2].
(i) \( R(P_3, P_6, C_m) = m + 2 \) for \( m \geq 23 \),  
\( R(P_6, P_6, C_m) = R(P_4, P_8, C_m) = m + 4 \) for \( m \geq 27 \),  
\( R(P_6, P_7, C_m) = m + 4 \) for \( m \geq 57 \),  
\( R(P_4, P_n, C_4) = R(P_5, P_n, C_4) = n + 2 \) for \( n \geq 5 \) [OmRa1].

(j) \( R(P_3, C_3, C_3) = 11 \) [BE3], \( R(P_3, C_4, C_4) = 8 \) [AKM], \( R(P_3, C_6, C_6) = 9 \) [Dzi2].  
\( R(P_3, C_m, C_m) = R(C_m, C_m) = 2m - 1 \) for odd \( m \geq 5 \) [DzKP] (for \( m = 5, 7 \) [Dzi2]),

(k) \( R(P_3, C_n, C_m) = R(C_n, C_m) \) for \( n \geq 7 \) and odd \( m, 5 \leq m \leq n \), and  
some values and bounds on \( R(P_3, C_n, C_m) \) in other cases [Fid1].

(l) \( R(P_3, C_3, C_4) = 8 \) [AKM], \( R(P_3, C_3, C_5) = 9 \), \( R(P_3, C_3, C_6) = 11 \),  
\( R(P_3, C_3, C_7) = 13 \), \( R(P_3, C_4, C_5) = 8 \), \( R(P_3, C_4, C_6) = 8 \),  
\( R(P_3, C_4, C_7) = 8 \), \( R(P_3, C_5, C_6) = 11 \), \( R(P_3, C_5, C_7) = 13 \) and  
\( R(P_3, C_6, C_7) = 11 \) [Dzi2].

(m) Formulas for \( R(pP_3, qP_3, rP_3) \) and \( R(pP_4, qP_4, rP_4) \) [Scob].

(n) \( R(P_3, K_4-e, K_4-e) = 11 \) [Ex7]. All colorings (which can be any color neighborhood  
for the open case \( R_3(K_4-e) \), see section 6.5) were found in [Piw2].

6.4.2. More colors

(a) \( R_k(P_3) = k + 1 + (k \mod 2) \), \( R_k(2P_2) = k + 3 \) for all \( k \geq 1 \) [Ir].

(b) \( R_k(P_4) = 2k + c_k \) for all \( k \) and some \( 0 \leq c_k \leq 2 \). If \( k \) is not divisible by 3 then  
\( c_k = 3 - k \mod 3 \) [Ir]. Wallis [Wall] showed \( R_6(P_4) = 13 \), which already implied  
\( R_{3t}(P_4) = 6t + 1 \), for all \( t \geq 2 \). Independently, the case \( R_k(P_4) \) for \( k \neq 3m \) was completed  
by Lindström in [Lind], and later Bierbrauer proved \( R_{3m}(P_4) = 2 \cdot 3m + 1 \) for all  
\( m > 1 \). \( R_3(P_4) = 6 \) [Ir].

(c) Formula for \( R(P_{n_1}, \ldots, P_{n_k}) \) for large \( n_1 \) [FS2], and some extensions [Biel3].  
Conjectures about \( R(P_{n_1}, \ldots, P_{n_k}) \) when all or all but one of \( n_i \)'s are even [OmRa1].

(d) Formulas for \( R(P_{n_1}, \ldots, P_{n_k}, C_m) \) for some cases, for large \( m \) [OmRa1].

(e) Formula for \( R(n_1P_2, \ldots, n_kP_2) \), in particular \( R(nP_2, nP_2, nP_2) = 4n - 2 \) [CocL1].

(f) Cockayne and Lorimer [CocL1] found the exact formula for \( R(n_1P_2, \ldots, n_kP_2) \), and later  
Lorimer [Lor] extended it to a more general case of \( R(K_m, n_1P_2, \ldots, n_kP_2) \). More general  
cases of the latter, with multiple copies of the complete graph, stars and forests,  
were studied in [Stahl, LorSe, LorSo, GyRSS].

(g) Multicolor cases for one large path or cycle involving small paths, cycles, complete and  
complete bipartite graphs [EFRS1].

(h) See section 8.2, especially [AKM], for a number of cases for triples of small graphs.
6.5. Special cases

\[
R_3(K_3 + e) = R_3(K_3) \quad [= 17] \quad \text{[YR3, AKM], where } K_3 + e = K_4 - P_3
\]

\[
R(K_3 + e, K_3 + e, K_4 - e) = 17 \quad \text{[ShWR]}
\]

If \( R_4(K_3) = 51 \) then \( R_4(K_3 + e) = 52 \), and if \( R_4(K_3) > 51 \) then \( R_4(K_3 + e) = R_4(K_3) \) \[ShWR\]

\[
28 \leq R_3(K_4 - e) \leq 30 \quad \text{[Ex7] [Pilw2]}
\]

\[
R(P_3, K_4 - e, K_4 - e) = 11 \quad \text{[Ex7], all colorings [Pilw2]}
\]

\[
21 \leq R(K_3, K_4 - e, K_4 - e) \leq 27 \quad \text{[ShWR]}
\]

\[
33 \leq R(K_4, K_4 - e, K_4 - e) \leq 60 \quad \text{[ShWR]}
\]

\[
R(C_4, P_4, K_4 - e) = 11 \quad \text{[DyDz], correcting an error in [AKM]}
\]

\[
R(C_4, C_4, K_4 - e) = 16 \quad \text{[DyDz]}
\]

\[
19 \leq R(C_4, K_4 - e, K_4 - e) \leq 22 \quad \text{[DyDz]}
\]

6.6. General results for special graphs

(a) Formulas for \( R_k(G) \), where \( G \) is one of the graphs \( P_3, 2K_2 \) and \( K_{1,3} \) for all \( k \), and for \( P_4 \) if \( k \) is not divisible by 3 [Ir]. For some details see section 6.4.2.b.

(b) \( tk^2 + 1 \leq R_k(K_{2,t+1}) \leq tk^2 + k + 2 \), where the upper bound is general, and the lower bound holds when both \( t \) and \( k \) are prime powers [ChGra1, LaMu].

(c) \((m-1)(k+1)/2 < R_k(T_m) \leq 2km +1 \) for any tree \( T_m \) with \( m \) edges [EG], see also [GRS]. The lower bound can be improved for special large \( k \) [EG, GRS]. The upper bound was improved to \( R_k(T_m) < (m-1)(k + \sqrt{k(k-1)} + 2 \) in [GyTu].

(d) \( k(\sqrt{m} - 1)/2 < R_k(F_m) < 4km \) for any forest \( F_m \) with \( m \) edges [EG], see [GRS]. See also pointers in items (l) and (m) below.

(e) \( R(S_1, \ldots , S_k) = n + \epsilon, \text{ where } S_i \text{'s are arbitrary stars, } n = n(S_1) + \ldots + n(S_k) - 2k, \text{ and we set } \epsilon = 1 \text{ if } n \text{ is even and some } n(S_i) \text{ is odd, and } \epsilon = 2 \text{ otherwise [BuRo1]. See also [GauST, Par6].}

(f) Formula for \( R(S_1, \ldots, S_k, K_n) \), where \( S_i \text{'s are arbitrary stars [Jac]. It was generalized to a formula for } R(S_1, \ldots, S_k, K_{k_1}, \ldots, K_{k_r}) \text{ expressed in terms of } R(k_1, \ldots, k_r) \text{ and star orders [BoCGR]. A much shorter proof of the latter was presented in [OmRa2].}

(g) Formula for \( R(S_1, \ldots, S_k, nK_2) \), where \( S_i \text{'s are arbitrary stars [CocL2].}

(h) Formula for \( R(S_1, \ldots, S_k, T) \), where \( S_i \text{'s are stars and } T \text{ is a tree [ZZ1].}

(i) Formulas for \( R(S_1, \ldots, S_k) \), where each \( S_i \text{'s is a star or } m_i K_2 \) [ZZ2, EG], formula for the case \( R(S, mK_2, nK_2) \) [GySá2].

(j) Bounds on \( R_k(G) \) for unicyclic graphs \( G \) of odd girth. Some exact values for special graphs \( G \), for \( k = 3 \) and \( k = 4 \) [KrRo].
(k) $R_k(K_{3,3}) = (1 + o(1)) k^3$ \ [AlRóS].

(l) Bounds on $R_k(K_s,t)$, in particular for $K_{2,2} = C_4$ and $K_{2,t}$ \ [ChGra1, AFM]. Asymptotics of $R_k(K_s,t)$ for fixed $k$ and $s$ \ [DoLi, LiTZ]. Upper bounds on $R_k(K_s,t)$ \ [SunLi].

(m) Bounds on $R_k(G)$ for trees, forests, stars and cycles \ [Bu1].

(n) Bounds for trees $R_k(T)$ and forests $R_k(F)$ \ [EG, GRS, BB, GyTu, Bra1, Bra2, SwPr].

(o) Study of the case $R(K_m, n_1 P_2, \ldots, n_k P_2)$ \ [Lor]. More general cases, with multiple copies of the complete graph, stars and forests, were investigated in \ [Stahl, LorSe, LorSo, GyRSS]. See also section 6.4.

(p) See section 8.2, especially \ [AKM], for a number of cases for other small graphs, similar to those listed in sections 6.3 and 6.4.

6.7. General results

(a) Szemerédi’s Regularity Lemma \ [Szem] states that the vertices of every large graph can be partitioned into similar size parts so that the edges between these parts behave almost randomly. This lemma in various forms has been used extensively to prove the upper bounds, including \ [BenSk, GyRSS, GySS1, HaèP1+, HaèP2+, KoSS].

(b) $R(m_1 G_1, \ldots, m_k G_k) \leq R(G_1, \ldots, G_k) + \sum_{i=1}^k n(G_i)(m_i - 1)$, exercise 8.3.28 in \ [West].

(c) If $G$ is connected and $R(K_k, G) = (k - 1)(n(G) - 1) + 1$, in particular if $G$ is any $n$-vertex tree, then $R(K_{k_1}, \ldots, K_{k_r}, G) = (R(k_1, \ldots, k_r) - 1)(n - 1) + 1$ \ [BE3]. A generalization for connected $G_1, \ldots, G_n$ in place of $G$ appeared in \ [Jac].

(d) If $F, G, H$ are connected graphs then $R(F, G, H) \geq (R(F, G) - 1)(\chi(H) - 1) + \min\{ R(F, G), s(H) \}$, where $s(G)$ is the chromatic surplus of $G$ (see item \ [Bu2] in section 5.16). This leads to several formulas and bounds for $F$ and $G$ being stars and/or trees when $H = K_n$ \ [ShiuLL].

(e) $R(K_{k_1}, \ldots, K_{k_r}, G_1, \ldots, G_s) \geq (R(k_1, \ldots, k_r) - 1)(R(G_1, \ldots, G_s) - 1) + 1$ for arbitrary graphs $G_1, \ldots, G_s$ \ [Bev]. This generalizes 6.2.o.

(f) Constructive bound $R(G_1, \ldots, G_{t+1}) \geq t^n + 1$ for decompositions of $K_t$ \ [LaWo1, LaWo2].

(g) $R(G_1, \ldots, G_k) \leq 32\Delta k^\Delta n$, where $n \geq n(G_i)$ and $\Delta \geq \Delta(G_i)$ for all $1 \leq i \leq k$ \ [FoxSu1].

(h) $R(G_1, \ldots, G_k) \leq k^{2k^\Delta} q^\Delta n$, where $q \geq \chi(G_i)$ for all $1 \leq i \leq k$ \ [FoxSu1].

(i) $R_k(G) > (sk e(G') - 1)^{1/n(G)}$, where $s$ is the number of automorphisms of $G$ \ [CH3]. Other general bounds for $R_k(G)$ \ [CH3, Par6].

(j) Study of $R(G_1, \ldots, G_k, G)$ for large sparse $G$ \ [EFRS1, Bu3].

(k) Study of asymptotics for $R(C_n, \ldots, C_n, K_m)$ \ [AlRó]. See also sections 6.3.3.b/c.

(l) See surveys listed in section 8.
7. Hypergraph Numbers

7.1. Values and bounds for numbers

The only known value of a classical Ramsey number for hypergraphs:

\[ R(4,4;3) = 13 \]

more than 200000 critical colorings \[\text{[MR1]}\]

The computer evaluation of \( R(4,4;3) \) in 1991 consisted of an improvement of the upper bound from 15 to 13. This result followed an extensive theoretical study of this number by several authors [Gi4, Isb1, Sid1].

(a) \( 33 \leq R(4,5;3) \) \[\text{[Ex13]}\]
\( 38 \leq R(4,6;3) \) \[\text{[HuSo+]}\]
\( 65 \leq R(5,5;3) \) \[\text{[Ea1]}\]
\( 56 \leq R(4,4,4;3) \) \[\text{[Ex8]}\]
\( 34 \leq R(5,5;4) \) \[\text{[Ex11]}\]

(b) \( R(K_4-t,K_4-t;3) = 7 \) \[\text{[Ea2]}\]
\( R(K_4-t,K_4;3) = 8 \) \[\text{[Sob, Ex1, MR1]}\]
\( 14 \leq R(K_4-t,K_5;3) \) \[\text{[Ex1]}\]
\( 13 \leq R(K_4-t,K_4-t,K_4-t;3) \leq 16 \) \[\text{[Ex1]} [Ea3]\]

(c) The first bound on \( R(4,5;3) \geq 24 \) was obtained by Isbell [Isb2]. Shastri [Shas] gave a weak bound \( R(5,5;4) \geq 19 \) (now 34 in [Ex11]), nevertheless his lemmas, the stepping-up lemmas by Erdős and Hajnal (see [GRS, GrRó], also 7.4.a below), and others in [Ka3, Abb2, GRS, GrRó, HuSo, SonYL] can be used to derive better lower bounds for higher numbers.

(d) Several lower bound constructions for 3-uniform hypergraphs were presented in [HuSo]. Study of lower bounds on \( R(p,q;4) \) can be found in [Song3] and [SonYL, Song4] (the latter two papers are almost the same in contents). Most of the concrete lower bounds in these papers can be easily improved by using the same techniques, but starting with better constructions for small parameters as listed above.

(e) \( R(p,q;4) \geq 2R(p-1,q;4) - 1 \) for \( p, q \geq 4 \), and
\( R(p,q;4) \geq (p-1)R(p-1,q;4) - p + 2 \) for \( p \geq 5, q \geq 7 \) \[\text{[SonYL]}\].

Lower bound asymptotics for \( R(p,q;4) \) \[\text{[SonLi]}\].
7.2. Cycles and paths

**Definitions.** A *loose* 3-uniform \((r = 3)\) cycle \(C_n\) on \([n]\) is the set of triples \(\{123, 345, 567, \ldots, (n - 1)n1\}\). Note that \(n\) must be even. In 3-uniform *tight* cycles and *tight* paths consecutive edges share two points. A 3-uniform *Berge* cycle is formed by \(n\) distinct vertices, such that all consecutive pairs \((t = 2)\) of vertices are in an edge of the cycle, and all of the cycle edges are distinct. Berge cycles are not determined uniquely. These definitions can be generalized to \(t\)-tight cycles and \(r\)-uniform hypergraphs.

(a) Tetrahedron, or four triples on the set of four points, can be seen as a tight 3-uniform cycle \(C_4\). The corresponding Ramsey number is \(R(4, 4; 3) = 13\) [MR1].

(b) For loose cycles, \(R(C_3, C_3; 3) = 7\), \(R(C_4, C_4; 3) = 9\), and in general for \(r\)-uniform case \(R(C_3, C_3; r) = 3r - 2\) and \(R(C_4, C_4; r) = 4r - 3\), for \(r \geq 3\). Results and discussion of several related cases involving paths were presented in [GyRa].

(c) For 3-uniform Berge cycles and two colors, \(R(C_n, C_n; 3) = n\) for \(n \geq 5\) [GyLS].

(d) For loose cycles, \(R(C_{4k}, C_{4k}; 3) > 5k - 2\) and \(R(C_{4k+2}, C_{4k+2}; 3) > 5k + 1\), and asymptotically these lower bounds are tight [HaLP1]. Generalizations to \(r\)-uniform hypergraphs and graphs other than cycles appeared in [GySS1].

(e) For loose cycles, \(R(C_3, C_3, C_3; 3) = 8\), and in general for \(k \geq 4\) colors Gyárfás and Raeisi established the bounds \(k + 5 \leq R_k(C_3; 3) \leq 3k\) [GyRa].

(f) For tight cycles, \(R(C_{3k}, C_{3k}; 3) \approx 4k\) and \(R(C_{3k+i}, C_{3k+i}; 3) \approx 6k\) for \(i = 1\) or 2, and for tight paths \(R(P_k, P_k; 3) \approx 4k/3\) [HaLP2]. Some related results are discussed in [PoRRS].

(g) For 3-uniform Berge cycles, \(R_3(C_n; 3) = (1 + o(1))5n/4\) [GySá].

(h) Gyárfás, Sárközy and Szemerédi proved that, for sufficiently large \(n\), every 2-coloring of the edges of the complete 4-uniform hypergraph \(K_n\) contains a monochromatic 3-tight Berge cycle \(C_n\) [GySS2]. Special multicolor cases for \(r\)-uniform hypergraphs were studied in [GyLS].

7.3. General results for 3-uniform hypergraphs

(a) \(2^{cn^2} \ll R(n, n; 3) < 2^n\) is credited to Erdős, Hajnal and Rado (see [ChGra2] p. 30).

(b) For some \(a, b\) the numbers \(R(m, a, b; 3)\) are at least exponential in \(m\) [AbbS].

(c) Improved lower and upper asymptotics for \(R(s, n; 3)\) for fixed \(s\) and large \(n\), proof of related Erdős and Hajnal conjecture on the growth of \(R(4, n; 3)\), and the lower bound \(2^{n\ln n} < R(n, n, n; 3)\) [ConFS2].

(d) \(R(G, G; 3) \leq c \cdot n(H)\) for some constant \(c\) depending only on the maximum degree of a 3-uniform hypergraph \(H\) [CooFKO, NaORS]. Similar results were proved for \(r\)-uniform hypergraphs in [KüCFO, Ishi, CooFKO2, ConFS1], see also item 7.4.f.
(e) Upper bounds on $R_k(H; 3)$ for complete multipartite 3-uniform hypergraphs $H$, a 4-color case, and some other general and special cases [ConFS1, ConFS2, ConFS3].

7.4. General results

(a) If $R(n, n; r) > m$ then $R(2n + r - 4, 2n + r - 4; r + 1) > 2^m$, for $n > r \geq 3$ (see [GRS] p. 106). This is the so-called stepping-up lemma, usually credited to Erdős and Hajnal. An improvement of the stepping-up lemma implying better lower bounds for a few types of hypergraph Ramsey numbers were obtained by Conlon, Fox and Sudakov [ConFS4].

(b) Lower bounds on $R_k(n; r)$ are discussed in [AbbW, DLR].

(c) General lower bounds for large number of colors were given in an early paper by Hirschfeld [Hir], and some of them were later improved in [AbbL].

(d) Lower and upper asymptotics of $R(s, n; k)$ for fixed $s$ [ConFS2].

(e) Exact results for large 2-loose cycles (generalizing 7.2.d above) and 2- and 3-color cases for all $r$-uniform diamond matchings [GySS1].

(f) $R(H, H; r) \leq c \cdot n(H)^{1+\epsilon}$, for some constant $c = c(\Delta, r, \epsilon)$ depending only on the maximum degree of $H$, $r$ and $\epsilon > 0$ [KoRö3]. The proofs of the linear bound $c \cdot n(H)$ were obtained independently in [KüCFO] and [Ishi], the latter including the multicolor case, and then without regularity lemma in [ConFS1]. More discussion of lower and upper bounds for various cases can be found in [ConFS1, ConFS2, ConFS3, CooFKO2].

(g) Let $T_r$ be an $r$-uniform hypergraph with $r$ edges containing a fixed $(r - 1)$-vertex set $S$ and the $(r + 1)$-st edge intersecting all former edges in one vertex outside $S$. Then $R(T_r, K_t; r) = O(t^{r+1}/\log t)$ [KosMV].

(h) Let $H^r(s, t)$ be the complete $r$-partite $r$-uniform hypergraph with $r - 2$ parts of size 1, one part of size $s$, and one part of size $t$ (for example, for $r = 2$ it is the same as $K_s$, $t$). For the multicolor numbers, Lazebnik and Mubayi [LaMu] proved that

$$tk^2 - k + 1 \leq R_k(H^r(2, t+1); r) \leq tk^2 + k + r,$$

where the lower bound holds when both $t$ and $k$ are prime powers. For the general case of $H^r(s, t)$, more bounds are presented in [LaMu].

(i) Grolmusz [Grol1] generalized the classical constructive lower bound by Frankl and Wilson [FraWi] (section 2.3.t) to more colors and to hypergraphs [Grol3].

(j) Lower and upper asymptotics, and other theoretical results on hypergraph numbers are gathered in [GrRö, GRS, ConFS1, ConFS2, ConFS3].
8. Cumulative Data and Surveys

8.1. Cumulative data for two colors

[CH1] \(R(G,G)\) for all graphs \(G\) without isolates on at most 4 vertices.

[CH2] \(R(G,H)\) for all graphs \(G\) and \(H\) without isolates on at most 4 vertices.

[Clan] \(R(G,H)\) for all graphs \(G\) on at most 4 vertices and \(H\) on 5 vertices, except five entries (now all solved, see section 5.11). All critical colorings for the isolate-free graphs \(G\) and \(H\) studied in [Clan] were found in [He4].

[Bu4] \(R(G,G)\) for all graphs \(G\) without isolates and with at most 6 edges.

[He1] \(R(G,G)\) for all graphs \(G\) without isolates and with at most 7 edges.

[HaMe2] \(R(G,G)\) for all graphs \(G\) on 5 vertices and with 7 or 8 edges.

[He2] \(R(G,H)\) for all graphs \(G\) and \(H\) on 5 vertices without isolates, except 7 entries (2 still open, see 5.11 and the paragraph at the end of this section).

[LoM5] \(R(G,H)\) for all disconnected isolate-free graphs \(H\) on at most 6 vertices versus all \(G\) on at most 5 vertices, except 3 cases. Missing cases were completed in [KroMe].

[HoMe] \(R(G,H)\) for \(G=K_{1,3}+e\) and \(G=K_{4}-e\) versus all connected graphs \(H\) on 6 vertices, except \(R(K_{4}-e,K_{6})=21\). The result \(R(K_{4}-e,K_{6})=21\) was claimed by McNamara [McN, unpublished].

[FRS4] \(R(G,T)\) for all connected graphs \(G\) with \(n(G)\leq5\), and almost all trees \(T\).

[FRS1] \(R(K_{3},G)\) for all connected graphs \(G\) on 6 vertices.

[Jin] \(R(K_{3},G)\) for all connected graphs \(G\) on 7 vertices. Some errors in [Jin] were found [SchSch1].

[Zeng] Formulas for \(R(nK_{3},mG)\) for all \(G\) of order 4 without isolates.

[Brin] \(R(K_{3},G)\) for all connected graphs \(G\) on at most 8 vertices. The numbers for \(K_{3}\) versus sets of graphs with fixed number of edges, on at most 8 vertices, were presented in [KlaM1].

[BBH1] \(R(K_{3},G)\) for all connected graphs \(G\) on 9 vertices. See also [BBH2].

[JR3] \(R(C_{4},G)\) for all graphs \(G\) on at most 6 vertices.

[JR4] \(R(C_{5},G)\) for all graphs \(G\) on at most 6 vertices.

[JR2] \(R(C_{6},G)\) for all graphs \(G\) on at most 5 vertices.

[LoM3] \(R(K_{2,n},K_{2,m})\) for all \(2\leq n, m\leq10\) except 8 cases, for which lower and upper bounds are given. Further data for other complete bipartite graphs are gathered in section 3.3 and [LoMe4].

[HaKr] All best lower bounds up to 102 from cyclic graphs. Formulas for best cyclic lower bounds for paths and cycles, and values for small complete graphs and for graphs with up to five vertices.
Chvátal and Harary [CH1, CH2] formulated several simple but very useful observations how to discover values of some numbers. All five missing entries in the tables of Clancy [Clan] have been solved (section 5.11). Out of 7 open cases in [He2] 5 have been solved, including
\[ R(4, 5) = R(G_{19}, G_{23}) = 25 \] and other cases listed in section 5.11. The still open 2 cases are for \( K_5 \) versus \( K_5 \) (section 2.1) and \( K_5 \) versus \( K_5 - e \) (section 3.1).

8.2. Cumulative data for three colors

- \([YR3]\) \( R_3(G) \) for all graphs \( G \) with at most 4 edges and no isolates.
- \([YR1]\) \( R_3(G) \) for all graphs \( G \) with 5 edges and no isolates, except \( K_4 - e \).
  The case of \( R_3(K_4 - e) \) remains open (see section 6.5).
- \([YY]\) \( R_3(G) \) for all graphs \( G \) with 6 edges and no isolates, except 10 cases.
- \([AKM]\) \( R(F, G, H) \) for most triples of isolate-free graphs with at most 4 vertices.
  Some of the missing cases completed in [KlaM2].
- \([DzFi2]\) \( R(P_3, P_k, C_m) \) for all \( 3 \leq k \leq 8 \) and \( 3 \leq m \leq 9 \).

8.3. Surveys

- \([Bu1]\) A general survey of results in Ramsey graph theory by S. A. Burr (1974)
- \([Par6]\) A general survey of results in Ramsey graph theory by T. D. Parsons (1978)
- \([BuRo3]\) Survey of results and new problems on multiplicities and Ramsey multiplicities
  by S. A. Burr and V. Rosta (1980)
- \([Har2]\) Summary of progress by Frank Harary (1981)
- \([ChGri]\) A general survey of bounds and values by F. R. K. Chung and C. M. Grinstead (1983)
- \([JGT]\) Special volume of the Journal of Graph Theory (1983)
- \([Bu7]\) What can we hope to accomplish in generalized Ramsey Theory? (1987)
- \([FRS5]\) Survey by Faudree, Rousseau and Schelp of graph goodness results, i.e. conditions for the formula
  \( R(G, H) = (\chi(G) - 1)(n(H) - 1) + s(G) \) (1991)
Among 114 open problems and conjectures of Paul Erdős, presented and commented by F. R. K. Chung, 31 are concerned directly with Ramsey numbers. 216 references are given (1997). An extended version of this work was prepared jointly with R. L. Graham [ChGra2]. (1998)

An extensive chapter on Ramsey theory in a widely used student textbook and researcher’s guide of graph theory (2001)


Ramsey Theory. Yesterday, Today and Tomorrow, a special volume in the series Progress in Mathematics. A survey of Ramsey numbers involving cycles by the author is included in this volume [Ra4]. (2011)

The surveys by S. A. Burr [Bu1] and T. D. Parsons [Par6] contain extensive chapters on general exact results in graph Ramsey theory. F. Harary presented the state of the theory in 1981 in [Har2], where he also gathered many references including seven to other early surveys of this area. More than two decades ago, Chung and Grinstead in their survey paper [ChGri] gave less data than in this work, but included a broad discussion of different methods used in Ramsey computations in the classical case. S. A. Burr, one of the most experienced researchers in Ramsey graph theory, formulated in [Bu7] seven conjectures on Ramsey numbers for sufficiently large and sparse graphs, and reviewed the evidence for them found in the literature. Three of them have been refuted in [Bra3].

For newer extensive presentations see [GRS, GrRö, FRS5, Neš, Chu4, ChGra2], though these focus on asymptotic theory not on the numbers themselves. A very welcome addition is the 2004 compilation of applications of Ramsey theory by V. Rosta [Ros2]. This survey could not be complete without recommending special volumes of the Journal of Graph Theory [JGT, 1983] and Combinatorics, Probability and Computing [CoPC, 2003], which, besides a number of research papers, include historical notes and present to us Frank P. Ramsey (1903-1930) as a person. Finally, read a colorful book by A. Soifer [Soi1, 2009] on history and results in Ramsey theory, followed by a collection of essays and technical papers based on presentations from the 2009 Ramsey theory workshop at DIMACS [Soi2, 2011].

The historical perspective and, in particular, the timeline of progress on prior best bounds, can be obtained by checking all the previous versions of this survey since 1994 at http://www.cs.rit.edu/~spr/EJC/eline.html.
9. Concluding Remarks

This compilation does not include information on numerous variations of Ramsey numbers, nor related topics, like size Ramsey numbers, zero-sum Ramsey numbers, irredun-dant Ramsey numbers, induced Ramsey numbers, local Ramsey numbers, connected Ramsey numbers, chromatic Ramsey numbers, avoiding sets of graphs in some colors, coloring graphs other than complete, or the so called Ramsey multiplicities. Interested readers can find such information in the surveys listed in section 8 here.

Ramsey@Home [RaHo] is a distributed computing project at the University of Wisconsin-Oshkosh designed to find new lower bounds for various Ramsey numbers. Join and help! Readers may be interested in knowing that the US patent 6965854 B2 issued on November 15, 2005 claims a method of using Ramsey numbers in "Methods, Systems and Computer Program Products for Screening Simulated Traffic for Randomness". Check the original document at http://www.uspto.gov/patft if you wish to find out whether your usage of Ramsey numbers is covered by this patent.

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The author apologizes for any omissions or other errors in reporting results belonging to the scope of this work. Suggestions for any kind of corrections or additions will be greatly appreciated and considered for inclusion in the next revision of this survey.