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 a 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 very unsatisfactory for a long time. In the last two 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 $1 \le i \le m$. 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 can write k instead of G_i, and if $G_i = G$ for all i we can 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). 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 some cycle 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. Finally, let $\chi(G)$ be the chromatic number of G, and let nG denote n disjoint copies of G.

Section 2 contains the data for the classical two color Ramsey numbers $R(k,l)$ for complete graphs, and section 3 for three much studied two color cases: when the avoided graphs are complete or have the form $K_k - e$, but not both are complete, complete bipartite graphs, and cycles, or cycles versus complete graphs. Section 4 lists other often studied two color cases for general graphs. The multicolor and hypergraph cases are gathered in sections 5 and 6, respectively. Finally, section 7 gives pointers to cumulative data and to the previous surveys.

2. Classical Two Color Ramsey Numbers

2.1. Upper and lower bounds on $R(k, l)$

k \ l	3	4	5	6	7	8	9	10	11	12	13	14	15
3	6	9	14	18	23	28	36	40 43	46 51	52 59	59 69	66 78	73 88
4		18	25	35 41	49 61	56 84	73 115	92 149	97 191	128 238	133 291	141 349	153 417
5			43 49	58 87	80 143	101 216	125 316	143 442	159	185 848	209	235 1461	265
6				102 165	113 298	127 495	169 780	179 1171	253	262 2566	317	 5033	401
7					205 540	216 1031	233 1713	289 2826	405 4553	416 6954	511 10581	 15263	 22116
8						282 1870	317 3583	 6090	 10630	 16944	817 27490	 41525	861 63620
9							565 6588	580 12677	 22325	 39025	 64871	 89203	
10								798 23556		 81200			1265

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

k \ l	4	5	6	7	8	9	10	11	12	13	14	15
3	GG	GG	Kéry	Ka2 GY	GR MZ	Ka2 GR	Ex5 RK2	Ka2 RK2	Ex12 Les	Piw1 RK2	Ex8 RK2	WW Les
4	GG	Ka1 MR4	Ex9 MR5	Ex3 Mac	Ex15 Mac	Ex17 Mac	HaKr Mac	2.3.e Spe3	SLL2 Spe3	2.3.e Spe3	XXR Spe3	XXR Spe3
5		Ex4 MR5	Ex9 HZ1	CET Spe3	HaKr Spe3	Ex17 Mac	Ex17 Mac	Ex17	Ex17 HW+	Ex17	Ex17 HW+	Ex17
6			Ka1 Mac	Ex17 Mac	XXR Mac	XXER Mac	Ex17 Mac	XXR	2.3.e HW+	XXER	 HW+	2.3.h
7				She1 Mac	2.3.e Mac	2.3.g HZ1	2.3.h Mac	XXER HW+	2.3.e HW+	XXR HW+	 HW+	 HW+
8					BR Mac	XXER Ea1	 HZ1	 HW+	 HW+	XXER HW+	 HW+	2.3.h HW+
9						She1 ShZ1	2.3.e Ea1	 HW+	 HW+	 HW+	 HW+	
10							She1 Shi2		 Yang			2.3.h

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.

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].

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

The construction by Mathon [Mat] and Shearer [She1] (see also sections 2.3.i, 5.2.h and 5.2.i), using data obtained by Shearer [She1], gives the following lower bounds for higher diagonal numbers: $R(11,11) \geq 1597$, $R(13,13) \geq 2557$, $R(14,14) \geq 2989$, $R(15,15) \geq 5485$, 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]. The same approach does not improve on an easy bound $R(12,12) \geq 1637$ [XXR], which can be obtained by applying twice 2.3.e. Only some of the higher bounds implied by 2.3.* are shown, and more similar bounds could be easily 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].

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]). Only recently 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 4.16 [HaKr].

The claim that $R(5,5) = 50$ posted on the web [Stone] is in error, and despite being shown so more than once, this incorrect value is being cited by some authors. The bound $R(3,13) \geq 60$ [XZ] 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].

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 $R(4,6) \leq 41$. 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 results by Giraud [Gi3, Gi5, Gi6].

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 marked in Table I [Yang] was obtained by Yang using the method of [HWSYZH] (abbreviated in the table as HW+).

2.2. Lower bounds on $R(k,l)$, higher parameters

The lower bounds marked [XXR], [XXER], 2.3.e and 2.3.h need not to 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.

k \ l	15	16	17	18	19	20	21	22	23
3	73 WW	79 WW	92 WWY1	99 Ex17	106 WWY1	111 Ex17	122 WWY1	125 WWY1	136 WWY1
4	153 XXR	163 Ex17	182 LSS1	187 2.3.e	213 2.3.g	234 Ex17	242 SLZL	282 SL	
5	265 Ex17	289 2.3.h	313 2.3.h	365 2.3.h	393 2.3.h	421 2.3.h	441 2.3.h	485 2.3.h	509 2.3.h
6	401 2.3.h	434 SLLL	548 SLLL	614 SLLL	710 SLLL	878 SLLL		1070 SLLL	
7			711 2.3.g	725 2.3.h	908 SLLL		1214 SLLL		
8	861 2.3.h		929 2.3.h	1045 2.3.g	1236 2.3.g		1617 2.3.h		

Table II. Known nontrivial lower bounds for higher two color Ramsey numbers $R(k,l)$, with references.

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].

Exoo in [Ex15] gives the bounds $R(3,27) \geq 158$ and $R(3,31) \geq 198$. The constructions establishing $R(3,24) \geq 140$, $R(3,25) \geq 143$, $R(3,26) \geq 150$, $R(3,28) \geq 164$, $R(3,29) \geq 174$, $R(3,31) \geq 198$ and $R(3,32) \geq 212$ are presented in [LSWL], [LSWL], [SLL1], [WSLLH], [SLL3], [LSS1] and [LSZL], respectively. In a recent manuscript [WSLX], the following better lower bounds for the latter are claimed: $R(3,24) \geq 143$, $R(3,25) \geq 153$, $R(3,26) \geq 159$,

$R(3,27) \geq 167$, $R(3,28) \geq 172$, $R(3,29) \geq 182$, and $R(3,30) \geq 187$.

Yu [Yu2] constructed a special class of triangle-free cyclic graphs establishing several lower bounds for $R(3,k)$, for $k \geq 61$. Only one of these bounds, $R(3,61) \geq 479$, cannot be easily improved by the inequality $R(3,4k+1) \geq 6R(3,k+1)-5$ from [CCD] (2.3.c) and data from Tables I and II. Finally, for higher parameters we mention two more 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.

In general, one can expect that the lower bounds in Table II are weaker than those in Table I, in the sense that with some work many of them should not be hard to improve, in contrast to the bounds in Table I, especially smaller ones.

2.3. Other 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 $R(3,4k+1) \geq 6R(3,k+1)-5$, for all $k \geq 1$ [CCD].

(d) Constructive results on triangle-free graphs in relation to the case of $R(3,k)$ [BBH1, BBH2, Fra1, Fra2, FrLo, Gri, KM1, Loc, RK3, RK4, Stat, Yu1].

(e) Bounds for the difference between consecutive Ramsey numbers, in particular the bound $R(k,l) \geq R(k,l-1)+2k-3$ for $k,l \geq 3$ [BEFS].

(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].

(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 obtain $R(5,l) \geq 4R(3,l-1)-3$ [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 items 5.2.h and 5.2.i 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].

(m) Two color lower bounds can be obtained by using items 5.2.k, 5.2.l and 5.2.m with $r = 2$. Some generalizations of these were obtained in [ZLLS].

In the last six 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.

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

(o) Explicit triangle-free graphs with independence k on $\Omega(k^{3/2})$ vertices [Alon2, CPR].

(p) Other general and asymptotic results on triangle-free graphs in relation to the case of $R(3, k)$ [AKS, Alon2, CCD, CPR, Gri, FrLo, Loc, She2].

(q) In 1947, Erdös gave an amazingly simple probabilistic proof that $R(k, k) \geq c \cdot k 2^{k/2}$ [Erd1]. Spencer [Spe1] improved the constant in the last result. More probabilistic asymptotic lower bounds for other Ramsey numbers were obtained in [Spe1, Spe2, AlPu].

(r) Other asymptotic bounds for $R(k, k)$ can be found, for example, in [Chu3, McS] (lower bound) and [Tho] (upper bound), and for many other bounds in the general case of $R(k, l)$ consult [Spe2, GRS, GrRö, Chu4, ChGra2, LiRZ1, AlPu, Kriv].

(s) 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.

3. Two Colors - Three Most Studied Cases

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.

G \ H	K_3-e	K_4-e	K_5-e	K_6-e	K_7-e	K_8-e	K_9-e	$K_{10}-e$	$K_{11}-e$
K_3-e	3	5	7	9	11	13	15	17	19
K_3	5	7	11	17	21	25	31	37 38	42 47
K_4-e	5	10	13	17	28	29 38	34	41	
K_4	7	11	19	27 36	37 52				
K_5-e	7	13	22	31 39	40 66				
K_5	9	16	30 34	43 67	112				
K_6-e	9	17	31 39	45 70	59 135				
K_6	11	21	37 55	116	205				
K_7-e	11	28	40 66	59 135	251				
K_7	13	28 34	51 88	202					

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

The exact values in Table III involving $K_3 - e$ are trivial, since one can easily see that $R(K_3 - e, K_k) = R(K_3 - e, K_{k+1} - e) = 2k - 1$, for all $k \geq 2$. Other bounds (not 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 $R(K_{k-1}, G) \leq R(K_k - e, G) \leq R(K_k, G)$. The upper bounds from the manuscripts [ShZ1, ShZ2] are subsumed by a later article [Shi2].

All $(K_3, K_l - e)$-graphs for $l \leq 6$ have been enumerated [Ra1]. For the following numbers it was established that the critical graphs are unique: $R(K_3, K_l - e)$ 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]. 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]. All the critical graphs for the cases $R(K_4 - e, K_4)$ [EHM1], $R(K_4 - e, K_5)$ and $R(K_5 - e, K_4)$ [DzFi] are known, and there are 5, 13 and 6 of them, respectively.

G \ H	K_4-e	K_5-e	K_6-e	K_7-e	K_8-e	K_9-e	$K_{10}-e$	$K_{11}-e$
K_3	CH2	Clan	FRS1	GH	Ra1	Ra1	MPR MPR	WWY2 MPR
K_4-e	CH1	FRS2	McR	McR	Ea1 HZ2	Ex14	Ex14	
K_4	CH2	EHM1	Ex11 Ea1	Ex14 HZ2				
K_5-e	FRS2	CEHMS	Ex14 Ea1	Ex14 HZ2				
K_5	BH	Ex8 Ex8	Ea1 HZ2	HZ2				
K_6-e	McR	Ex14 Ea1	Ex14 HZ2	Ex14 HZ2				
K_6	McN	Ex14 Ea1	HYZ	ShZ2				
K_7-e	McR	Ex14 HZ2	Ex14 HZ2	ShZ1				
K_7	Ea1 Ea1	Ex14 ShZ2	HYZ					

References for Table III.

The bound $R(K_3, K_{12} - e) \geq 46$ is given in [MPR]. Wang, Wang and Yan in [WWY2] constructed cyclic graphs showing $R(K_3, K_{13} - e) \geq 54$, $R(K_3, K_{14} - e) \geq 59$ and $R(K_3, K_{15} - e) \geq 69$.

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 $K_n - e$.

3.2. Complete bipartite graphs

NOTE: This subsection gathers information on Ramsey numbers where specific bipartite graphs are avoided in a coloring of K_n (as everywhere in this survey), in contrast to often studied bipartite Ramsey numbers (not covered in this survey) where the initial coloring is of a bipartite graph $K_{n,m}$.

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 by 3.2.a.

p, q / m, n	1, 2	1, 3	1, 4	1, 5	1, 6	2, 2	2, 3	2, 4	2, 5	3, 3	3, 4
2, 2	4 CH2	6 CH2	7 Par3	8 Par3	9 FRS4	6 CH1					
2, 3	5 CH2	7 FRS4	9 Stev	10 FRS4	11 FRS4	8 HaMe4	10 Bu4				
2, 4	6 CH2	8 HaMe3	9 Stev	11 HaMe4	13 LoM4	9 HaMe4	12 ExRe	14 EHM2			
2, 5	7 CH2	9 HaMe3	11 Stev	13 Stev	14 LoM4	11 HaMe4	13 LoM3	16 LoM1	18 EHM2		
3, 3	7 CH2	8 HaMe3	11 LoM4	12 LoM4	13 LoM4	11 Lortz	13 HaMe3	16 LoM4	18 LoM4	18 HaMe3	
3, 4	7 CH2	9 HaMe3	11 LoM4	13 LoM4	14 LoM4	11 Lortz	14 LoM4	≤19 LoM4	≤21 LoM4	≤25 LoM2	≤30 LoM2
3, 5	9 CH2	10 HaMe3				14 HaMe4				≤28 LoM2	≤33 LoM2

Table IVa. Ramsey numbers $R(K_{m,n}, K_{p,q})$,
for published small cases, with references.

m / n	2	3	4	5	6	7	8	9	10	11
6	12 HaMe4	14 LoM3	17 LoM3	20 LoM1	21 EHM2					
7	14 HaMe4	17 LoM3	19 LoM3	21 LoM3	24 LoM1	26 EMH2				
8	15 HaMe4	18 LoM3	20 LoM3	21-23 LoM3	24-25 LoM3	28 LoM1	30 EMH2			
9	16 HaMe4	19 LoM3	22 LoM3	22-25 LoM3	24-27 LoM3	28-29 LoM3	32 LoM1	33 EHM2		
10	17 HaMe4	21 LoM3	24 LoM3	27 LoM3	27-29 LoM3	28-31 LoM3	32-33 LoM3	36 LoM1	38 EHM2	
11	18 HaMe4						≤35 LoM3	36-37 LoM3	40 LoM1	42 EHM2

Table IVb. Known Ramsey numbers $R(K_{2,n}, K_{2,m})$,
for $6 \le n \le 11$, $2 \le m \le 11$, with references.

$R(K_{2,3}, K_{1,7}) = 13$ [Par4]
$R(K_{2,2}, K_{1,15}) = 20$ [La2]
$R(K_{2,2}, K_{4,4}) = 14$ [HaMe4]
$R(K_{3,5}, K_{3,5}) \leq 38$ [LoM2]
$R(K_{4,4}, K_{4,4}) \leq 62$ [LoM2]
$R(K_{1,4}, K_{1,2,3}) = 11$ [GuSL]
$R(K_{1,4}, K_{2,2,2}) = 11$ [GuSL]

- 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 3.2.c below.
- 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 30 for $12 \leq n \leq 21$, respectively, and for $R(K_{2,2}, K_{3,n})$ are 15, 16, 17, 20 and 22 for $6 \leq n \leq 10$, respectively [HaMe4]. See Tables IVa and IVb for the smaller cases.
- $R(K_{2,n}, K_{2,n})$ 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].

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, $f(n) \geq n + \sqrt{n} - 6n^{11/40}$ [BEFRS5]. For more bounds and values of $f(n)$ see [Par5, Chen, ChenJ].

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

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

(f) $R(K_{2,n}, K_{2,n}) \leq 4n - 2$ for all $n \geq 2$, and the equality holds iff a strongly regular $(4n-3, 2n-2, n-2, n-1)$-graph exists [EHM2].

(g) 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].

(h) $R(K_{2,n-1}, K_{2,n}) \leq 4n - 4$ 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].

(i) $R(K_{2,n-s}, K_{2,n}) \leq 4n - 2s - 3$ 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].

(j) 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].

(k) 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].

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

(m) Asymptotics for $K_{2,m}$ versus K_n [CLRZ].

(n) Upper bound asymptotics for $K_{k,m}$ versus K_n [LiZa1].

(o) Special two-color case applies in the study of asymptotics for multicolor Ramsey numbers for complete bipartite graphs [ChGra1].

3.3. Cycles, Cycles versus Complete Graphs

Cycles

$R(C_3, C_3) = 6$ [GG]
$R(C_4, C_4) = 6$ [CH1]

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

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

$R(nC_3, mC_3) = 3n + 2m$ for $n \geq m \geq 1$, $n \geq 2$ [BES]
$R(nC_4, mC_4) = 2n + 4m - 1$ for $m \geq n \geq 1$, $(n, m) \neq (1,1)$ [LiWa1]
Formulas for $R(nC_4, mC_5)$ [LiWa2]
Unions of cycles, formulas and bounds for various cases [MiSa, Den]

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 $n > 3 = m$ [FS1], 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 $n \geq 7 = m$ [ChenZ1], and for $n \geq 4m + 2$, $m \geq 3$ [Nik]. Open conjectured cases are marked in Table V by "conj."

	C_3	C_4	C_5	C_6	C_7	C_8	...	C_n for $n \geq m$
K_3	6 GG	7 CS	9 CS	11 FS1	13 FS1	15 FS1	...	$2n-1$ FS1
K_4	9 GG	10 CH2	13 He2/JR4	16 JR2	19 YHZ1	22 YHZ1	...	$3n-2$ YHZ1
K_5	14 GG	14 Clan	17 He2/JR4	21 JR2	25 YHZ2	29 BJYHRZ	...	$4n-3$ BJYHRZ
K_6	18 Kéry	18 Ex2/RoJa1	21 JR5	26 Schi1	31 Schi1	36 Schi1	...	$5n-4$ Schi1
K_7	23 Ka2/GY	22 RT/JR1	25 Schi2	31* CheCZN	37* CheCZN	43* ChenZ1	...	$6n-5$* ChenZ1
K_8	28 GR/MZ	26 RT			43* ChenZ2	50* ZZ3	...	$7n-6$ conj.
K_9	36 Ka2/GR	≥ 30 RT					...	$8n-7$ conj.
K_{10}	40 - 43 Ex5/RK2	≥ 34 RT					...	$9n-8$ conj.

Table V. Known Ramsey numbers $R(C_n, K_m)$,
results from unpublished manuscripts are marked with a *.

(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]. For other joint credits in Table V, the first reference is for the lower bound and the second for the upper bound. The special cases of $R(C_6, K_5) = 21$ [JR2] and $R(C_7, K_5) = 25$ were also solved independently in [YHZ2] and [BJYHRZ].

(c) Lower bound asymptotics [Spe2, FS4, AlRö].

(d) Upper bound asymptotics [BoEr, FS4, EFRS2, CLRZ, Sud1, LiZa2, AlRö].

(e) For the numbers of cycles versus graphs other than complete see section 4.6.

4. 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, 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 7, or be a special case of a general result listed in this section. Note that $B_1 = F_1 = C_3 = W_3 = K_3$, $B_2 = K_4 - e$, $P_3 = K_3 - e$, $W_4 = K_4$ and $C_4 = K_{2,2}$ imply other identities not mentioned explicitly.

4.1. Paths

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

Stripes mP_2 [CL1, CL2, Lor]

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

4.2. 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.

$R(W_3, W_5) = 11$ [Clan]
$R(W_3, W_n) = 2n - 1$ for all $n \ge 6$ [BE3]
All critical colorings for $R(W_3, W_n)$ for all $n \ge 3$ [RaJi]
$R(W_4, W_5) = 17$ [He3]
$R(W_5, W_5) = 15$ [HaMe2, He2]

$R(W_4, W_6) = 19$, $R(W_5, W_6) = 17$ and $R(W_6, W_6) = 17$,
and all critical colorings (2, 1 and 2) for these numbers [FM].

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

4.3. Books

$R(B_1, B_n) = 2n + 3$ for all $n > 1$ [RS1]
$R(B_3, B_3) = 14$ [RS1, HaMe2], and $R(B_2, B_4) = 13$ [Rou]

$R(B_2, B_5) = 16$, $R(B_3, B_5) = 17$, $R(B_5, B_5) = 21$,
$R(B_4, B_4) = 18$, $R(B_4, B_6) = 22$, $R(B_6, B_6) = 26$ [RS1]
$254 \le R(B_{37}, B_{88}) \le 255$ [Par6]

$R(B_n, B_m) = 2n + 3$ for all $n \ge cm$ for some $c < 10^6$ [NiRo1, NiRo2]

$R(B_n, B_n) = (4 + o(1))n$ [RS1, NiRS]

In general, $R(B_n, B_n) = 4n + 2$ for $4n + 1$ a prime power, and several other general equalities and bounds for $R(B_n, B_m)$ [RS1, FRS7, Par6, NiRS, LiRZ2].

4.4. Trees and forests

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

(a) $R(T_n, T_n) \le 4n+1$ [EG].

(b) $R(T_n, T_n) \ge \lfloor (4n-1)/3 \rfloor$ [BE2], see also 4.16.

(c) Conjecture that $R(T_n, T_n) \le 2n-2$, note that this is almost the same as asking if $R(T_n, T_n) \le R(K_{1,n-1}, K_{1,n-1})$ [BE2], see also [Bu7, FSS1, ChGra2]. Discussion of the conjecture that $R(T_n, T_m) \le n+m-2$ holds for all trees [FSS1].

(d) If $\Delta(T_n) = n-2$, $\Delta(T_m) = m-2$ then the exact values of $R(T_n, T_m)$ are known, and they are between $n+m-5$ and $n+m-3$ depending on n and m. In particular, for $n=2k+1$ $R(T_{2k+1}, T_{2k+1}) = 2n-5$ [GuoV].

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

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

(g) Comment in [BaLS] about a recent result of the authors of [AKS], which implies that $R(T_n, T_n) \le 2n-2$ holds for sufficiently large n.

(h) $R(T_m, K_{1,n}) \le m+n-1$, with equality for $(m-1) \mid (n-1)$ [Bu1].

(i) $R(T_m, K_{1,n}) = m+n-1$ for sufficiently large n for almost all trees T_m [Bu1]. Many cases where identified when $R(T_m, K_{1,n}) = m+n-2$ [Coc, ZZ1], see also [Bu1].

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

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

(l) Paths versus trees [FSS1], see also other parts of this survey involving special graphs, in particular sections 4.5 and 4.7.

4.5. 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 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, BEFRS5, Chen, ChenJ, GoMC]
Stars versus $K_{2,n}$ [Par4, GoMC]
Stars versus $K_{n,m}$ [Stev, Par3]
Stars versus complete bipartite graphs [Par4, Stev]
See also section 3.2

$R(K_{1,4}, B_4) = 11$ [RS2]
$R(K_{1,4}, K_{1,2,3}) = R(K_{1,4}, K_{2,2,2}) = 11$ [GuSL]

Stars versus W_5 and W_6 [SuBa1]
Stars versus wheels [HaBA, ChenZZ2, Kor]
Stars versus paths [Par2, BEFRS2]
Stars versus cycles [La1, Clark, see Par6]
Stars versus books [CRSPS, RS2]
Stars versus trees [Bu1, Coc, GuoV, ZZ1]
Stars versus stripes mP_2 [CL1, CL2, Lor]
Stars versus $K_n - tK_2$ [Hua1, Hua2]
Stars versus $2K_2$ [MO]
Union of two stars [Gros2]
Unions of stars versus wheels [BaHA]

4.6. Fans, fans versus other graphs

Fans $F_n = K_1 + nK_2$ versus paths [SaBr1]
Fans versus K_m [LR2]
$R(F_n, K_4) = 6n+1$ for $n \geq 3$ [SuBB3]
$R(F_1, F_n) = R(K_3, F_n) = 4n+1$ for $n \geq 2$, and bounds for $R(F_m, F_n)$ [GGS]

4.7. Paths versus other graphs

P_3 versus all isolate-free graphs [CH2]
Paths versus stars [Par2, BEFRS2]
Paths versus trees [FS4, FSS1]
Paths versus books [RS2]
Paths versus cycles [FLPS, BEFRS2]
Paths versus K_n [Par1]
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, Zhang]
Paths versus fans [SaBr1]
Paths versus $K_1 + P_m$ [SaBr2]
Paths and cycles versus trees [FSS1]
Sparse graphs versus paths and cycles [BEFRS2]
Graphs with long tails [Bu2, BG]
Unions of paths [BuRo2]

4.8. Triangle versus other graphs

$R(3,k) = \Theta(k^2/\log k)$ [Kim]
Explicit construction for $R(3,4k+1) \geq 6R(3,k+1)-5$, for all $k \geq 1$ [CCD]
Explicit triangle-free graphs with independence k on $\Omega(k^{3/2})$ vertices [Alon2, CPR]

$R(K_3, K_7 - 2P_2) = R(K_3, K_7 - 3P_2) = 18$ [SchSch2]
$R(K_3, K_3 + \overline{K}_m) = R(K_3, K_3 + C_m) = 2m + 5$ for $m \geq 212$ [Zhou1]
$R(K_3, K_2 + T_n) = 2n + 3$ for n-vertex trees T_n, for $n \geq 4$ [SoGQ]

$R(K_3, G) = 2n(G) - 1$ 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]

$R(K_3, G) \leq 2e(G) + 1$ for any graph G without isolated vertices [Sid3, GK]
$R(K_3, G) \leq n(G) + e(G)$ for all G, a conjecture [Sid2]
$R(K_3, G)$ for all connected G up to 9 vertices [BBH1, BBH2], see also section 7.1
$R(K_3, K_n)$, see section 2
$R(K_3, K_n - e)$, see section 3.1

Formulas for $R(nK_3, mG)$ for all G of order 4 without isolates [Zeng]

Since $B_1 = F_1 = C_3 = W_3 = K_3$, other sections apply

See also [AKS, BBH1, BBH2, FrLo, Fra1, Fra2, Gri, Loc, KM1, LiZa1, RK3, RK4, She2, Spe2, Stat, Yu1]

4.9. Cycles versus other graphs

C_4 versus stars [Par3, Par4, Par5, BEFRS5, Chen, ChenJ, GoMC]
C_4 versus trees [EFRS4, Bu7, BEFRS5, Chen]
C_4 versus all graphs on six vertices [JR3]
C_4 versus various types of complete bipartite graphs, see section 3.2

$R(C_4, B_n) = 7, 9, 11, 12, 13$ and 16, for $2 \leq n \leq 7$, respectively [FRS6]
$R(C_4, B_n) = 17, 18, 19, 20$ and 21, for $8 \leq n \leq 12$, respectively [Tse1]
$R(C_4, B_{13}) = 22$ and $R(C_4, B_{14}) = 24$ [Tse2]
$R(C_4, W_n) = 10, 9, 10, 9, 11, 12, 13, 14, 16$ and 17, for $4 \leq n \leq 13$, respectively [Tse1]
$R(C_4, W_n) \leq n + \lceil (n-1)/3 \rceil$ for $n \geq 7$ [SuBUB]
$R(C_4, G) \leq 2q + 1$ for any isolate-free graph G with q edges [RoJa2]
$R(C_4, G) \leq p + q - 1$ for any connected graph G on p vertices and q edges [RoJa2]

$R(C_5, W_6) = 13$ [ChvS]
$R(C_5, K_6 - e) = 17$ [JR4]
$R(C_5, B_1) = R(C_5, B_2) = 9$ [CRSPS]
$R(C_5, B_3) = 10$, and in general $R(C_5, B_n) = 2n + 3$ for $n \geq 4$ [FRS8]
C_5 versus all graphs on six vertices [JR4]
$R(C_6, K_5 - e) = 17$ [JR2]
C_6 versus all graphs on five vertices [JR2]

$R(C_{2m+1}, G) = 2n - 1$ 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]

$R(C_n, G) \leq 2q + \lfloor n/2 \rfloor - 1$, 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].

Cycles versus paths [FLPS, BEFRS2]
Cycles versus stars [La1, Clark, see Par6]
Cycles versus trees [BEFRS2, FSS1]
Cycles versus books [FRS6, FRS8, Zhou1]
Cycles versus $K_{n,m}$ [BoEr]

$R(C_5, W_6) = 13$ [ChvS]
$R(C_n, W_5) = 2n - 1$ and $R(C_n, W_6) = 3n - 2$ for $n \geq 5$ [SuBB2]
Odd cycles versus wheels [Zhou2]
Cycles versus W_m for odd m [SuBT]

4.10. Wheels versus other graphs

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.

$R(W_5, K_5 - e) = 17$ [He2][YH]
$R(W_5, K_5) = 27$ [He2][RST]
W_5 and W_6 versus stars and paths [SuBa1]
Wheels versus stars [HaBA, ChenZZ2, Kor]
W_5 and W_6 versus trees [BSNM]
$R(W_6, C_5) = 13$ [ChvS]
$R(W_5, C_n) = 2n - 1$ and $R(W_6, C_n) = 3n - 2$ for $n \geq 5$ [SuBB2]
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]
Wheels versus paths [BaSu, ChenZZ1, Zhang]
Wheels W_n, for even n, versus star-like trees [SuBB1]
$R(W_n, C_4) \leq n + \lceil (n-1)/3 \rceil$ for $n \geq 7$ [SuBUB]
Wheels versus C_4 [Tse1]
Wheels W_n, for odd n, versus cycles [SuBT]
Wheels versus odd cycles [Zhou2]
Wheels versus books [Zhou3]
Wheels versus linear forests (disjoint unions of paths) [SuBa2]
Wheels versus unions of stars [BaHA]
Upper bound asymptotics for $R(W_n, K_m)$ [Song5]

4.11. Books versus other graphs

$R(B_4, K_{1,4}) = 11$ [RS2]
$R(B_3, K_4) = 14$ [He3]
$R(B_3, K_5) = 20$ [He2][BaRT]
Books versus paths [RS2]
Books versus stars [CRSPS, RS2]
Books versus trees [EFRS7]
Books versus cycles [FRS6, FRS8, Zhou1, Tse1, Tse2]
Books versus K_n [LR1, Sud2]
Books versus wheels [Zhou3]
Books versus $K_2 + C_n$ [Zhou3]
Books and $(K_1 + \mathit{tree})$ versus K_n [LR1]
Generalized books $K_r + qK_1$ versus K_n [NiRo3]

4.12. 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]
$R(T_n, C_{2m+1}) = 2n-1$ for all $n > 1512m + 756$ [BEFRS2]
$R(T_n, B_m) = 2n-1$ 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 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, 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]

Star-like trees versus odd wheels [SuBB1, ChenZZ3]
$nK_{1,m}$ versus wheels [BaHA]
Trees versus $K_n + \overline{K}_m$ [RS2, FSR]
Trees versus bipartite graphs [BEFRS5, EFRS6]
Trees versus almost complete graphs [GoJa2]
Trees versus multipartite complete graphs [EFRS8, BEFRSGJ]
Linear forests versus wheels [SuBa2]
Forests versus almost complete graphs [CGP]

Study of graphs G for which all or almost all trees are G-good [BF, BEFRSGJ], see also section 4.16, item [Bu2], for the definition and more pointers.

See also various parts of this survey for special trees, sparse graphs and section 4.4.

4.13. Mixed special cases:

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. Four of the open entries have been solved,

$R(4,5) = 25$	[Ka1][MR4]
$R(W_5, K_5 - e) = 17$	[He2][YH]
$R(B_3, K_5) = 20$	[He2][BaRT]
$R(W_5, K_5) = 27$	[He2][RST]

The still open cases are for K_5 versus K_5 (section 2.1), $K_5 - e$ (section 3), and $K_5 - P_3$.

$25 \le R(K_5 - P_3, K_5) \le 28$ [He2]
$R(C_5 + e, K_5) = 17$ [He5]
$26 \le R(K_{2,2,2}, K_{2,2,2})$, $K_{2,2,2}$ is an octahedron [Ex8]

4.14. Mixed general cases

Unicyclic graphs [Gros1, Köh, KrRod]
$K_{2,m}$ and C_{2m} versus K_n [CLRZ]
$K_{2,n}$ versus any graph [RoJa2]
$2K_2$ versus all isolate-free graphs [CH2]
nK_2 versus mK_2, in particular $R(nK_2, nK_2) = 3n - 1$ for $n \ge 1$ [CL1, CL2, Lor]
nK_3 versus mK_3, in particular $R(nK_3, nK_3) = 5n$ for $n \ge 2$ [BES], see also section 3.3
nK_3 versus mK_4 [LorMu]
$R(nK_4, nK_4) = 7n + 4$ for large n [Bu8]
Variety of results for numbers $R(nG, mH)$ [Bu1, BES]

Union of two stars [Gros2]
Double stars* [GHK]
Graphs with bridge versus K_n [Li]
Multipartite complete graphs [BEFRS3, FRS3, Stev]
Multipartite complete graphs versus sparse graphs [EFRS4]
Multipartite complete graphs versus trees [EFRS8, BEFRSGJ]
Disconnected graphs versus any graph [GoJa1]
Graphs with long tails [Bu2, BG]
Brooms+ [EFRS3]

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* 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

4.15. General results for sparse graphs

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

[BEFRS2] $R(C_{2m+1}, G) = 2n-1$ for sufficiently large sparse graphs G on n vertices, little more complicated formulas for P_{2m+1} instead of C_{2m+1}.

[CRST] $R(G,G) \le c_d n(G)$ for all G, where constant c_d depends only on the maximum degree d in G. The constant was improved in [GRR1]. Tight lower and upper bounds for bipartite G [GRR2].

[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].

[ChenS] $R(G,G) \le c_d n$ 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].

[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.

[EFRS9] Study of graphs G, called *Ramsey size linear,* for which there exists a constant c_G such that for all H with no isolates $R(G,H) \le c_G e(H)$. An overview and further results were given in [BaSS].

[LRS] $R(G,G) < 6n$ for all n-vertex graphs G, in which no two vertices of degree at least 3 are adjacent. This improves the result $R(G,G) \le 12n$ in [Alon1].

[Gros1] Conjecture that $R(G,G) = 2n(G)-1$ if G is unicyclic of odd girth. Further support for the conjecture was given in [Köh, KrRod].

[-] See also earlier subsections 4.* for various specific sparse graphs.

4.16. Other general two color results

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

[CH3] $R(G,G) > (s\, 2^{e(G)-1)})^{1/n(G)}$, where s is the number of automorphisms of G. Hence $R(K_{n,n}, K_{n,n}) > 2^n$.

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

[BE3] Graphs yielding $R(K_n, G) = (n-1)(n(G)-1)+1$ and related results (see also [EFRS5]).

[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, BEFRS4, Bu5, FS, EFRS4, FRS3, BEFSRGJ, BF, LR4]. A survey of this area appeared in [FRS5].

[BaLS] Graph G is Ramsey saturated if $R(G+e, G+e) > R(G,G)$ for every edge e in $\overline{G}$. Several theorems involving cycles, cycles with chords and trees on Ramsey saturated and unsaturated graphs. Seven conjectures including one stating that almost all graphs are Ramsey unsaturated.

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

[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.

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

[AlKS] Discussion of a conjecture by Erdös that there exists a constant c such that $R(G,G) \le 2^{c\sqrt{e(G)}}$. Proof for bipartite graphs G and progress towards the conjecture in other cases.

[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].

[Shi1] $R(Q_n, Q_n) \le 2^{(3+\sqrt{5})n/2 + o(n)}$, for the n-dimensional cube Q_n with 2^n vertices. This bound can also be derived from a theorem in [KoRö1].

[RoJa2] $R(K_{2,k}, G) \le kq + 1$, for $k \ge 2$, for isolate-free graphs G with $q \ge 2$ edges.

[FM] $R(W_6, W_6) = 17$ and $\chi(W_6) = 4$. This gives a counterexample $G = W_6$ to the Erdös conjecture (see [GRS]) $R(G,G) \ge R(K_{\chi(G)}, K_{\chi(G)})$, since $R(4,4) = 18$.

[NiRo3] $R(K_{p+1}, B_q^r) = p(q + r - 1) + 1$ for generalized books $B_q^r = K_r + qK_1$, for all sufficiently large q.

[LR3] Bounds on $R(H + \overline{K}_n, K_n)$ for general H. Also, for fixed k and m, as $n \to \infty$, $R(K_k + \overline{K}_m, K_n) \le (m + o(1))\, n^k / (\log n)^{k-1}$ [LiRZ1].

[LiTZ] Asymptotics of $R(H + \overline{K}_n, K_n)$. In particular, the order of magnitude of $R(K_{m,n}, K_n)$ is $n^{m+1}/(\log n)^m$.

[LiRZ2] Let G'' be a graph obtained from G by deleting two vertices. Then $R(G,H) \le A + B + 2 + 2\sqrt{(A^2 + AB + B^2)/3}$, where $A = R(G'', H)$ and $B = R(G, H'')$.

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

[Zeng] Formulas for $R(nK_3, mG)$ for all isolate-free graphs G on 4 vertices.

[BES] Study of Ramsey numbers for multiple copies of graphs.
See also [Bu1, Bu8, Bu9, BE1, LorMu, MiSa, Den].

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

[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 Π_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 5.

[-] See also surveys listed in section 7.

5. Multicolor Graph Numbers

The only known value of a multicolor classical Ramsey number:

$R_3(3) = R(3,3,3) = R(3,3,3;2) = 17$	[GG]
2 critical colorings (on 16 vertices)	[KaSt, LayMa]
2 colorings on 15 vertices	[Hein]
115 colorings on 14 vertices	[PR1]

General upper bound, implicit in [GG]:

$$R(k_1, \ldots, k_r) \le 2 - r + \sum_{i=1}^{r} R(k_1, \ldots, k_{i-1}, k_i - 1, k_{i+1}, \ldots, k_r) \qquad \text{(a)}$$

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 $r \ge 3$ and $k_i \ge 3$, except for $r = k_1 = k_2 = k_3 = 3$. However, only two cases are known to improve over (a), namely $R_4(3) \le 62$ [FKR] and $R(3,3,4) \le 31$ [PR1, PR2], for which (a) produces only the bounds of 66 and 34, respectively.

5.1. Bounds for multicolor classical numbers

Diagonal Cases

r \ m	3	4	5	6	7	8	9
3	17 GG	128 HiIr	417 Ex17	1070 Mat	3214 Xu	5384 XX2	13761 XXER
4	51 Chu1	634 XXER	3049 Xu	15202 XXER	62017 XXER		
5	162 Ex10	3416 XXER	26912 Xu				
6	538 FreSw						
7	1682 FreSw						

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

The best published bounds corresponding to the entries in Table VI marked by personal communication [Xu] are: $3211 \le R_3(7)$ [Mat], $2721 \le R_4(5)$ [XXER] and $26082 \le R_5(5)$ [XXER].

The most studied and intriguing open case is

$$\text{[Chu1]} \quad 51 \leq R_4(3) = R(3,3,3,3) \leq 62 \quad \text{[FKR]}$$

The inequality 5.a implies $R_4(3) \leq 66$, Folkman [Fo] in 1974 improved this bound to 65, and Sánchez-Flores [San] in 1995 proved $R_4(3) \leq 64$. The upper bounds in $162 \leq R_5(3) \leq 307$, $538 \leq R_6(3) \leq 1838$, $1682 \leq R_7(3) \leq 12861$, and $128 \leq R(4,4,4) \leq 236$ are implied by 5.(a) (we repeat lower bounds from Table VI just to see easily the ranges).

Off-Diagonal Cases

Three colors:

k \ m	4	5	6	7	8	9	10	11	12	13	14
3	30 Ka2	45 Ex2	60 Rob3	81 Ex16	101 Ex17	117 Ex17	141 5.2.c	157 5.2.c	182 LSS2	212 LSS2	233 5.2.c
4	55 KLR	81 Ex17	107 Ex17	143 Ex17	193 5.2.c						
5	81 Ex17	129 Ex17	169 5.2.c								

Table VII. 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

$$\text{[Ka2]} \quad 30 \leq R(3,3,4) \leq 31 \quad \text{[PR1, PR2]}$$

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 $81 \leq R(3,4,5) \leq 160$ are implied by 5.(a) (we repeat lower bounds from the Table VII to show explicitly the current ranges).

Four colors:

$93 \leq R(3,3,3,4) \leq 153$	[Ex16, XXER], 5.(a)
$162 \leq R(3,3,3,5)$	[XXER]
$171 \leq R(3,3,4,4)$	[Ex16, XXER]
$561 \leq R(3,3,3,11)$	[XX2, XXER]

Lower bounds for higher numbers can be obtained by using general constructive results from section 5.2 below. For example, the bounds $261 \le R(3,3,15)$ and $247 \le R(3,3,3,7)$ were not published explicitly but are implied by 5.2.c and 5.2.d, respectively.

5.2. General multicolor results for complete graphs

(b) $R_r(3) \ge 3R_{r-1}(3) + R_{r-3}(3) - 3$ [Chu1]

(c) $R(3,k,l) \ge 4R(k,l-1) - 3$, and in general for $r \ge 2$ and $k_i \ge 2$
$R(3,k_1,\dots,k_r) \ge 4R(k_1-1,k_2,\dots,k_r) - 3$ for $k_1 \ge 5$, and
$R(k_1,2k_2-1,k_3,\dots,k_r) \ge 4R(k_1-1,k_2,\dots,k_r) - 3$ for $k_1 \ge 5$ [XX2, XXER]

(d) $R(3,3,3,k_1,\dots,k_r) \ge 3R(3,3,k_1,\dots,k_r) + R(k_1,\dots,k_r) - 3$ [Rob2]

(e) Bounds for $R_k(3)$ [AbbH, Fre, Chu2, ChGri, GrRö, Wan, XXER]

(f) $R(k_1,\dots,k_r) \ge S(k_1,\dots,k_r) + 2$, where $S(k_1,\dots,k_r)$ is the generalized Schur number [AbbH, Gi1, Gi2]. In particular, the special case $k_1 = \dots = k_r = 3$ has been widely studied [Fre, FreSw, Ex10, Rob3].

(g) $R(k_1,\dots,k_r) \ge L(k_1,\dots,k_r) + 1$, where $L(k_1,\dots,k_r)$ is the maximal order of any cyclic $(k_1,\dots,k_r)$-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 $k_i \ge 3$

$L(k_1,\dots,k_r,k_{r+1}) \ge (2k_{r+1}-3)L(k_1,\dots,k_r) - k_{r+1} + 2$ [Gi2]

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

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

(j) $R_r(m) \ge c_m(2m-3)^r$, and some slight improvements of this bound for small values of m [AbbH, Gi1, Gi2, Song2].

(k) $R_r(pq+1) > (R_r(p+1)-1)(R_r(q+1)-1)$ [Abb1]

(l) $R_r(pq+1) > R_r(p+1)(R_r(q+1)-1)$ for $p \ge q$ [XXER]

(m) $R(p_1q_1+1,\dots,p_rq_r+1) > (R(p_1+1,\dots,p_r+1)-1)(R(q_1+1,\dots,q_r+1)-1)$ [Song3]

(n) $R_{r+s}(m) > (R_r(m)-1)(R_s(m)-1)$ [Song2]

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

(p) $R(k_1,k_2,\dots,k_r) > (k_1+1)(R(k_2-k_1+1,k_3,\dots,k_r) - 1)$ [Rob4]

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

(r) Grolmusz [Grol1] generalized the classical constructive lower bound by Frankl and Wilson [FraWi] (section 2.3.r) to more colors and to hypergraphs [Grol3] (section 6).

All lower bounds in (b) through (r) above are constructive. (d) generalizes (b), (m) generalizes both (k) and (o), and (o) generalizes (n). (l) is stronger than (k). Finally observe that the construction (m) with $q_1 = ... = q_i = 1 = p_{i+1} = ... = p_r$ is the same as (o).

5.3. Special multicolor cases

Cycles

$R_3(C_3) = 17$	[GG, see also page 25]
$R_3(C_4) = 11$	[BS, see also Clap]
$R_3(C_5) = 17$	[YR1]
$R_3(C_6) = 12$	[YR2]
$R_3(C_7) = 25$	[FSS2]
$R_3(C_{2m}) \geq 4m$ for all $m \geq 2$	[DzNS]
$R_3(C_{2m+1}) = 8m + 1$ for all sufficiently large m	[KoSS]

For more results on $R_3(C_n)$ see section 5.4.
For more results on $R_k(C_3)$ see sections 5.1 and 5.2.

$18 \leq R_4(C_4) \leq 19$	[Ex2] [Eng]
$27 \leq R_5(C_4) \leq 29$	[LaWo1]
$R(C_3, C_3, C_4) = 17$	[ExRe]
$R(C_3, C_4, C_4) = 12$	[Schu]
$R(C_3, C_4, C_5) = 13$	[Rao][Tse3]
$R(C_3, C_4, C_6) = 13$	[Tse3]
$R(C_3, C_4, C_7) \geq 15$	[Tse3]
$R(C_3, C_3, C_5) \geq 21$	[Tse3]
$R(C_3, C_5, C_5) \geq 17$	[Tse3]

$R(C_4, C_4, C_5) = 12$	[Tse3]
$R(C_4, C_4, C_6) = 12$	[Tse3]
$R(C_4, C_4, C_7) = 12$	[Tse3]
$R(C_4, C_5, C_5) = 13$	[Tse3]
$R(C_4, C_5, C_6) = 13$	[Tse3]
$R(C_4, C_5, C_7) \geq 15$	[Tse3]
$R(C_4, C_6, C_6) = 11$	[Tse3]
$R(C_4, C_6, C_7) = 13$	[Tse3]
$R(C_3, C_3, C_4, C_4) \geq 27$	[Eng]

Xu in an unpublished note obtained $R(C_3, C_3, C_4, C_4) \geq 28$ [Xu]

Mixed cases

$R(P_3, P_4, C_3) = 7$	[AKM]
$R(P_3, P_4, C_4) = 7$	[AKM]
$R(P_3, P_4, C_5) = 7$	[Dzi]
$R(P_4, P_4, C_3) = 9$	[AKM]
$R(P_4, P_4, C_4) = 7$	[AKM]
$R(P_4, P_4, C_5) = 9$	[Dzi]
$R(P_4, P_4, C_6) = 8$	[Dzi], see also 5.4.k
$R(P_3, C_3, C_3) = 11$	[BE3]
$R(P_3, C_3, C_4) = 8$	[AKM]
$R(P_3, C_3, C_5) = 9$	[Dzi]
$R(P_3, C_3, C_6) = 11$	[Dzi]
$R(P_3, C_4, C_4) = 8$	[AKM]
$R(P_3, C_4, C_5) = 8$	[Dzi]
$R(P_3, C_4, C_6) = 8$	[Dzi]
$R(P_3, C_5, C_5) = 9$	[Dzi], see also 5.4.i
$R(P_3, C_5, C_6) = 11$	[Dzi]
$R(P_3, C_6, C_6) = 9$	[Dzi]
$R(K_4 - e, K_4 - e, P_3) = 11$	[Ex7]
$R(K_{1,3}, C_4, K_4) = 16$	[KM2]
$R(C_4, C_4, C_4, T) = 16$ for $T = P_4$ and $T = K_{1,3}$	[ExRe]
$28 \leq R_3(K_4 - e) \leq 30$	[Ex7] [Piw2]
$86 \leq R(K_4, K_4, C_4, C_4)$	[Bev], 5.2.o+

All colorings for $(K_4 - e, K_4 - e, P_3)$ were found in [Piw2].

5.4. General multicolor results for cycles and paths

(a) $R(C_n, C_n, C_n) \le (4+o(1))n$, with equality for odd n [Łuc]. It was conjectured by Bondy and Erdös, see [Erd2], that $R(C_n, C_n, C_n) \le 4n-3$ for $n \ge 4$. If true, then for all odd $n \ge 5$ we have $R(C_n, C_n, C_n) = 4n-3$.

(b) $R(C_n, C_n, C_n) = 4n-3$ for all sufficiently large odd n [KoSS].

(c) $R(C_n, C_n, C_n) = (2+o(1))n$ for even n [FiŁu].

(d) Formulas for $R(C_n, C_m, C_k)$ and $R(C_n, C_m, C_k, C_l)$ for large n [EFRS1].

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

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

(g) $2^k m < R_k(C_{2m+1}) < 2(k+2)!m$ [EG], see [GRS].

(h) Asymptotic bounds for $R_k(C_n)$ [Bu1, GRS, ChGra2].

(i) $R(P_3, C_n, C_n) = R(C_n, C_n) = 2n-1$ for odd $n \ge 5$ [DzKP].

(j) $R(P_3, P_4, C_n) = n+1$ for $n \ge 6$ [Dzi].

(k) $R(P_4, P_4, C_n) = n+2$ for $n \ge 6$, and
$R(P_3, P_5, C_n) = n+1$ for $n \ge 8$ [DzKP].

(l) $R(P_n, P_n, P_n) = 2n-1$ for odd n, for all sufficiently large n, and
$R(P_n, P_n, P_n) = 2n-2$ for even n, for all sufficiently large n [GyRSS].

(m) Formulas for $R(P_{n_1}, \ldots, P_{n_k})$ for several special cases [FS2].

(n) Formulas for $R_k(P_3)$ for all k, and for $R_k(P_4)$ if k is not divisible by 3 [Ir]. Wallis [Wall] showed $R_6(P_4) = 13$, which already implied $R_{3t}(P_4) = 6t+1$, for all $t \ge 2$. Independently, the case $R_k(P_4)$ for $k \ne 3^m$ was completed by Lindström in [Lind], and later Bierbrauer proved $R_{3^m}(P_4) = 2 \cdot 3^m + 1$ for all $m \ge 1$.

(o) Formulas for $R(n_1 P_2, \ldots, n_k P_2)$, in particular $R(nP_2, nP_2, nP_2) = 4n-2$ [CL1].

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

(q) Monotone paths and cycles [Lef].

(r) Study of asymptotics for $R(C_m, \ldots, C_m, K_n)$ [AlRö].

(s) Study of asymptotics for $R(C_{2m}, C_{2m}, K_n)$ for fixed m [ShiuLL, AlRö].

(t) See section 7.2, especially [AKM], for a number of cases for other small graphs, similar to those listed in section 5.3.

5.5. Other general multicolor results

(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].

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

(c) $(m-1)\lfloor (k+1)/2 \rfloor < R_k(T_m) < 2km+1$ for any tree T_m with m edges [EG], see [GRS]. The upper bound was improved to $R_k(T_m) < (m-1)(k+\sqrt{k(k-1)})+2$ in [GyTu].

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

(e) Formula for $R(S_1, \ldots, S_k)$, where S_i's are arbitrary stars [BuRo1].

(f) Formula for $R(S_1, \ldots, S_k, K_n)$, where S_i's are arbitrary stars [Jac].

(g) Formula for $R(S_1, \ldots, S_k, nP_2)$, where S_i's are arbitrary stars [CL2].

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

(i) Formula for $R(S_1, \ldots, S_k)$, where each S_i's is a star or $m_i K_2$ [ZZ2, EG].

(j) Cockayne and Lorimer [CL1] 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 $R(K_m, n_1P_2, \ldots, n_kP_2)$. Still more general cases of the latter, with multiple copies of the complete graph, stars and forests, were studied in [Stahl, LorSe, LorSo, GyRSS].

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

(l) If F, G, H are connected graphs then $R(F, G, H) \ge (R(F, G)-1)(\chi(H)-1) + \min\{R(F, G), s(H)\}$, where $s(G)$ is the chromatic surplus of G (see item [Bu2] in section 4.16). This leads to several formulas and bounds for F and G being stars and/or trees when $H = K_n$ [ShiuLL].

(m) $R(K_{k_1}, \ldots, K_{k_r}, G_1, \ldots, G_s) \ge (R(k_1, \ldots, k_r)-1)(R(G_1, \ldots, G_s)-1)+1$ for arbitrary graphs $G_1, \ldots, G_s$ [Bev]. This generalizes 5.2.o.

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

(o) Bounds on $R_k(G)$ for unicyclic graphs G of odd girth. Some exact values for special graphs G, for $k=3$ and $k=4$ [KrRod].

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

(q) Bounds on $R_k(K_{s,t})$, in particular for $K_{2,2} = C_4$ and $K_{2,t}$ [ChGra1, AFM].

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

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

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

(u) Study of asymptotics for $R(C_n, \ldots, C_n, K_m)$ [AlRö].

(v) Asymptotics of $R_k(K_{s,t})$ for fixed k and s [LiTZ].

(w) See also surveys listed in section 7.

6. Hypergraph Numbers

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

$R(4,4;3) = 13$	
more than 200000 critical colorings	[MR1]

Other hypergraph cases:

$33 \le R(4,5;3)$	[Ex13]
$63 \le R(5,5;3)$	[Ea1]
$56 \le R(4,4,4;3)$	[Ex8]
$34 \le R(5,5;4)$	[Ex11]
$R(K_4-t, K_4-t;3) = 7$	[Ea2]
$R(K_4-t, K_4;3) = 8$	[Sob, Ex1, MR1]
$14 \le R(K_4-t, K_5;3)$	[Ex1]
$13 \le R(K_4-t, K_4-t, K_4-t;3) \le 17$	[Ex1] [Ea1]

The computer evaluation of $R(4,4;3)$ in [MR1] consisted of an improvement of the upper bound from 15 to 13, which followed an extensive theoretical study of this number in [Gi4, Is1, Sid1]. The first bound on $R(4,5;3) \ge 24$ was obtained by Isbell [Is2]. Shastri in [Sha] shows a weak bound $R(5,5;4) \ge 19$ (now 34 in [Ex11]), nevertheless his lemmas, the Stepping-Up Lemmas by Erdös and Hajnal (see [GRS, GrRö]), and others in [Ka3, Abb2, GRS, GrRö, HuSo] could be used to derive better lower bounds for higher numbers.

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 [SYL, Song4] (the latter two papers are almost the same in contents). Most lower bounds in these papers can be easily improved by using the same techniques, but starting with better constructions for small parameters listed above.

General hypergraph results:

(a) $2^{cn^2} < R(n,n;3) < 2^{2^n}$, Erdös, Hajnal and Rado (see [ChGra2] p. 30).

(b) $R(H,H;r) \le c \cdot n(H)^{1+\varepsilon}$, for some constant $c = c(\Delta, r, \varepsilon)$ depending only on the maximum degree of H, r and $\varepsilon > 0$ [KoRö3].

(c) A *loose* 3-uniform cycle C_n on $[n]$ is the set of triples $\{123, 345, 567, \ldots, (n-1)n1\}$ (note that n must be even). For such loose cycles we have $R(C_{4k}, C_{4k}; 3) > 5k-2$ and $R(C_{4k+2}, C_{4k+2}; 3) > 5k+1$, and asymptotically these lower bounds are tight [HaŁP+].

(d) 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

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

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].

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

(f) Lower bounds on $R_m(k;s)$ are discussed in [DLR, AbbW]. In [AbbS], it is shown that for some values of a,b the numbers $R(m,a,b;3)$ are at least exponential in m.

(g) 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].

(h) Lower and upper asymptotics, and other theoretical results on hypergraph numbers are gathered in [GrRö, GRS].

7. Cumulative Data and Surveys

7.1. 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).

[He4] All critical colorings for $R(G,H)$, for isolate-free graphs G and H as in [Clan] above.

[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 (3 still open, see the paragraph at the end of this section).

[HoMe] $R(G,H)$ for $G=K_{1,3}+e$ and $G=K_4-e$ versus all connected graphs H on 6 vertices, except $R(K_4-e,K_6)$. The result $R(K_4-e,K_6)=21$ was claimed by McNamara [McN, unpublished].

[FRS4] $R(G,T)$ for all connected graphs G on at most 5 vertices and all (except some cases) 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 by [SchSch1].

[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 [KM1].

[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 $2 \le n,m \le 10$ except 8 cases, for which lower and upper bounds are given. Further data for other complete bipartite graphs in [LoMe4] and in section 4.22 of this survey.

[HaKr] All best lower bounds up to 102 from cyclic graphs. Formulas for best cyclic lower bounds for paths and cycles, 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. Out of 7 open cases in [He2] 4 have been solved, namely $R(4,5) = R(G_{19},G_{23}) = 25$ and the items 2, 3 and 4 in section 4.13. The still open 3 cases are for K_5 versus the graphs K_5 (section 2.1), K_5-e (section 3.1), and K_5-P_3 (section 4.13).

7.2. 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 5.3).

[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 [KM2].

7.3. 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)
[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)
[Rob1]	A review of Ramsey graph theory for newcomers by F. S. Roberts (1984)
[Bu7]	What can we hope to accomplish in generalized Ramsey Theory ? (1987)
[GrRö]	Survey of asymptotic problems by R. L. Graham and V. Rödl (1987)
[GRS]	An excellent book by R. L. Graham, B. L. Rothschild and J. H. Spencer, second edition (1990)
[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)
[Neš]	A chapter in *Handbook of Combinatorics* by J. Nešetřil (1996)
[Caro]	Survey of zero-sum Ramsey theory by Y. Caro (1996)
[Chu4]	Among 114 open problems and conjectures of Paul Erdös, 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)
[GrNe]	Ramsey Theory and Paul Erdös (2002)
[CoPC]	Special issue of *Combinatorics, Probability and Computing* (2003)
[Ros2]	Dynamic survey of Ramsey theory applications by V. Rosta (2004)

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. The newest very welcome addition is a 2004 compilation of applications of Ramsey theory by Rosta [Ros2]. Finally, this compilation could not pretend to be complete without mentioning special volumes of the *Journal of Graph Theory* [JGT, 1983] and *Combinatorics, Probability and Computing* [CoPC, 2003], dedicated entirely to Ramsey theory. Besides a number of research papers, they include historical notes and present to us Frank P. Ramsey (1903-1930) as a person.

8. 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, irredundant 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 reader can find such information in the surveys listed in section 7 here.

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.

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.

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References

We mark the papers containing results obtained with the help of computer algorithms with stars. We identify two categories of such papers: marked with * involving some use of computers, where the results are easily verifiable with some computations, and those marked with **, where cpu intensive algorithms have to be implemented to replicate or verify the results. The first category contains mostly constructions done by algorithms, while the second mostly nonexistence results or claims of complete enumerations of special classes of graphs.

The references are ordered alphabetically by the last name of the first author, for the same first author by the last name of the second author, etc. We preferred that all work by the same author be in consecutive positions. Unfortunately, this causes that some of the abbreviations are not in alphabetical order, for example [BaRT] is earlier on the list than [BaLS]. We also wish to explain a possible confusion with respect to the order of parts and spelling of Chinese names. We put them without any abbreviations, with the last name written first as is customary in original. This is often distinct from citations in other sources. One can obtain all variations of writing any specific name by consulting authors database of *Mathematical Reviews* at http://www.ams.org/mathscinet/search.

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