

## The Nonabelian Simple Groups $G$ , $|G| < 10^6$ — Maximal Subgroups\*

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**Abstract.** The maximal subgroups of all the simple groups (except  $L(2, q)$ ) of order up to one million are given to within conjugacy. Permutation characters on the cosets of the maximal subgroups are given, as are orbit lengths (whenever practical).

**Introduction.** We present a complete list, to within conjugacy, of the maximal subgroups of each nonabelian simple group  $G$ ,  $|G| > 10^6$ , excepting the family  $L(2, q)$  for which the subgroups are described in the literature [10].

For each  $G$  we calculate its permutation character on the cosets of each maximal subgroup and the corresponding orbits of the representation restricted to that subgroup. Use was made of the GROUP program [2] on a CDC 6400 computer.

**Notation.** Repeated use is made of the character tables for the simple groups  $G$ ,  $|G| < 10^6$ , found in [13]. We refer to the irreducible characters of a group by their degrees and, if necessary, a subscript determined by their order of appearance in these character tables; for example, the irreducible characters of  $M_{22}$  are denoted by 1, 21, 45<sub>1</sub>, 45<sub>2</sub>, 55, 99, 154, 210, 231, 280<sub>1</sub>, 280<sub>2</sub>, 385.

We use the following notation:

$N(K) = N_G(K)$  is the normalizer of  $K$  in  $G$ ;

$C(K) = C_G(K)$  is the centralizer of  $K$  in  $G$ ;

$|H|$  is the order of  $H$ ;

$\chi_i$  denotes the  $i$ th irreducible character of  $G$ ;

$\phi_H$  is a permutation character of  $G$  on the cosets of a subgroup  $H$ ;

2A, 3B, etc., refer to conjugacy classes of  $G$  as listed in the character tables in

[13];

$n$  is the cyclic group of order  $n$ ;

$\Sigma_n$  is the symmetric group of degree  $n$ ;

$A_n$  is the alternating group of degree  $n$ ;

$S_p$  is a Sylow  $p$ -subgroup;

$A.B$  is an extension of  $A$  by  $B$ ;

$A.B.C = A.(B.C)$ ;

$p^n$  is the elementary abelian group of order  $p^n$ ;

$(m, n)^+$  is the even subgroup of index two in  $\Sigma_m \times \Sigma_n$ .

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**The Subgroups and Permutation Characters.** Since more than 100 conjugacy classes of maximal subgroups occur, it is impractical to indicate proofs, but we do give the useful propositions.

**Some Useful Results.** The following are repeatedly used in identifying maximal subgroups:

**PROPOSITION 1 (FINKELSTEIN [6]).** *Any maximal subgroup of a simple group  $G$  is the normalizer in  $G$  of a direct product of isomorphic simple groups. In particular, a maximal subgroup not containing a nonabelian simple group must normalize an elementary abelian group.*

**PROPOSITION 2.** *If  $p^\alpha \mid |G|$  and  $H = N_G(K)$  where  $|K| = p^\beta$ ,  $0 < \beta < \alpha$ , then  $p^{\beta+1} \mid |H|$ .*

*Proof.* Clearly,

$$H = N_G(K) \geq N_{S_p}(K).$$

Since  $K \not\leq S_p$  and  $S_p$  is nilpotent, we have  $K \neq N_{S_p}(K)$ . Thus

$$K \not\leq N_{S_p}(K) \leq N_G(K),$$

so  $p^{\beta+1} \mid |N_G(K)|$ .

The following were used to find the irreducible constituents of  $\phi_H$ .

**PROPOSITION 3.** *A permutation group is primitive if and only if it is equivalent to a representation on the cosets of a maximal subgroup.*

**PROPOSITION 4.**

$$\phi_H(x) = \frac{|H \cap x^G| \cdot |C_G(x)|}{|H|}.$$

In the following  $f_j$  is the degree of an irreducible constituent of  $\phi_H$ ,  $e_j$  its multiplicity,  $n_i$  the length of an orbit of  $H$ ,  $k$  the number of orbits, and  $n = [G : H]$ .

**PROPOSITION 5 (FRAME [19]).** *The expression of*

$$q = n^{k-2} \prod_i n_i \Big/ \prod_j f_j e_j^2$$

*is a rational integer. If, in addition, all irreducible constituents of  $\phi_H$  are rational, then  $q$  is a square.*

**PROPOSITION 6 (SEE [19]).** *If all  $e_j = 1$  and  $l$  of the numbers  $f_j$  are divisible by some  $p^\alpha$ , then at least  $l$  of the numbers  $nn_i$  are divisible by  $p^\alpha$ .*

**The Alternating Groups.** We do an analysis of the maximal subgroups of the alternating groups.

(i) *Intransitive subgroups.* By  $(k, l)^+$  where  $k + l = n$  we mean  $A_n \cap (\Sigma_k \times \Sigma_l)$ , whose transitive constituents have lengths  $k$  and  $l$ . (Notice that a subgroup of  $A_n$  having  $> 2$  transitive constituents cannot be maximal.) Now  $(k, l)^+$  is maximal whenever  $k \neq l$ ; this may be proved by induction on  $n$ . It is easy to see that  $(k, l)^+ \cong (A_k \times A_l).2$ .

(ii) *Imprimitive subgroups.* The group  $H = (k, k, \dots, k)^+$ ,  $k > 1$ , is not maximal since we may always adjoin an element to  $H$  giving rise to a group  $M$  for

which  $H \not\leq M \not\leq A_n$  and  $M$  is maximal imprimitive. The order of  $M$  is  $\frac{1}{2}b!(k!)^n$ , where  $b$  is the number of transitive constituents of  $H$ . This may be shown by an elementary counting argument. The subgroup  $M$  is maximal except when  $k = 2$ —again this is shown by induction. When  $k = 2$ ,  $A_8$  contains an example of  $M$  not maximal:  $(2, 2, 2, 2)^+$  is a group of order 192 which is contained in  $2^3.L(3, 2)$ .

(iii) *Primitive subgroups.* Sims' list [17] gives the primitive groups of degree up to 20 to within isomorphism. Those of degree  $n$  which are maximal subgroups of  $A_n$  are determined by examining orders or by arguments using Propositions 1 and 2 and/or the character table for  $A_n$ .

The number of conjugacy classes of each type of maximal subgroup is determined in the following manner:

(i) *Intransitive.*  $(k, l)^+$ ,  $k \neq l$ . Each of these groups is the stabilizer of a point in the (transitive) action of  $A_n$  on the  $k$ -tuples of  $\{1, \dots, n\}$ . Thus, there is one class each of the intransitive maximal subgroups.

(ii) *Imprimitive.* The action of  $A_n$  on the  $k$ -tuples of  $\{1, \dots, n\}$  is imprimitive, and the maximal imprimitive group containing  $(k, k, \dots, k)^+$  is the stabilizer of a point in the action of  $A_n$  on a resulting block system. Again, we have only one class of each maximal subgroup.

(iii) *Primitive.* The number of classes of the primitive maximal subgroups was arrived at using structure constants for the classes of involutions in [13] and, in some cases, characterizations of the simple groups as minimal  $(2, m, n)$  groups in [20].

We note that the four-dimensional linear groups including  $L(4, 2) \cong A_8$  have recently been treated by Mwene [16], who classifies the maximal subgroups up to isomorphism.

Finally, the authors would like to learn of any inaccuracies found in the tables.

Order	Index	Description	Permutation Character	Orbit Lengths
$A_5$ ( $60 = 2^2.3.5$ )				
6	10	$\Sigma_3 = (3, 2)^+$ , intransitive	1+4+5	1, 3, 6
10	6	dihedral, primitive	1+5	1, 5
12	5	$A_4 = (4, 1)^+$ , intransitive	1+4	1, 4
$L(3, 2)$ ( $168 = 2^3.3.7$ )				
21	8	7.3	1+7	1, 7
24	7	$\Sigma_4$	1+6	1, 6
24	7	$\Sigma_4$	1+6	1, 6

Order	Index	Description	Permutation Character	Orbit Lengths
$A_6$ ( $360 = 2^3 \cdot 3^2 \cdot 5$ )				
24	15	$\Sigma_4 = (4, 2)^+$ , intransitive	$1+5_1+9$	1, 6, 8
24	15	$\Sigma_4$ , imprimitive	$1+5_2+9$	1, 6, 8
36	10	$(A_3 \times A_3).2.2$	$1+9$	1, 9
60	6	$A_5 = (5, 1)^+$ , intransitive	$1+5_1$	1, 5
60	6	$A_5$ , transitive	$1+5_2$	1, 5
$A_7$ ( $2520 = 2^3 \cdot 3^2 \cdot 5 \cdot 7$ )				
72	35	$(4, 3)^+$ , intransitive	$1+6+14_1+14_2$	1, 4, 12, 18
120	21	$\Sigma_5 = (5, 2)^+$ , intransitive	$1+6+14_2$	1, 10, 10
168	15	$L(3, 2)$ , primitive	$1+14_1$	1, 14
360	7	$A_6 = (6, 1)^+$ , intransitive	$1+6$	1, 6
$L(3, 3)$ ( $5616 = 2^4 \cdot 3^3 \cdot 13$ )				
24	234	$\Sigma_4 = N(2^2)$	$1+2.12+16_1+16_2$ $+16_3+16_4+2 \times 26_1$ $+2.27+39$	1, 3, $4^2$ , 6, $12^8$ , $24^5$
39	144	$13.3 = N(13)$	$1+13+16_1+16_2+16_3$ $+16_4+27+39$	1, $13^5$ , $39^2$
432	13	Hessian.2	$1+12$	1, 12
432	13	Hessian.2	$1+12$	1, 12
$U(3, 3)$ ( $6048 = 2^5 \cdot 3^3 \cdot 7$ )				
96	63	$C(2A)$	$1+14+21_1+27$	1, 6, 24, 32
96	63	$N(2^2)$	$1+7_2+7_3+21+27$	1, 6, $16^2$ , 24
168	36	$L(3, 2)$	$1+7_2+7_3+21_1$	1, 7, 7, 21
216	28	Hessian	$1+27$	1, 27
$M_{11}$ ( $7920 = 2^4 \cdot 3^2 \cdot 5 \cdot 11$ )				
48	165	$M_8, \Sigma_3 = C(2A)$	$1+10_1+11+2.44+55$	1, 8, 12, $24^4$ , 48
120	66	$\Sigma_5 = N(A_5)$	$1+10_1+11+44$	1, 15, 20, 30
144	55	$M_9.2 = N(3^2)$	$1+10_1+44$	1, 18, 36
660	12	$L(2, 11)$	$1+11$	1, 11
720	11	$M_{10}$	$1+10_1$	1, 10

Order	Index	Description	Permutation Character	Orbit Lengths
$A_8 (20, 160 = 2^6.3^2.5.7)$				
360	56	$(5, 3)^+$ , intransitive	1+7+20+28	1, 10, 15, 30
576	35	$(A_4 \times A_4).2.2$ , imprimitive	1+14+20	1, 16, 18
720	28	$\Sigma_6 = (6, 2)^+$ , intransitive	1+7+20	1, 12, 15
1344	15	$2^3 L(3, 2)$ , primitive	1+14	1, 14
1344	15	$2^3 L(3, 2)$ , primitive	1+14	1, 14
2520	8	$A_7 = (7, 1)^+$ , intransitive	1+7	1, 7
$L(3, 4) (20, 160 = 2^6.3^2.5.7)$				
72	280	$N(S_3)$	1+20+45 <sub>1</sub> +45 <sub>2</sub> +35 <sub>1</sub> +35 <sub>2</sub> +35 <sub>3</sub> +64	1, 9, 18 <sup>3</sup> , 72 <sup>3</sup>
168	120	$L(3, 2)$	1+20+35 <sub>1</sub> +64	1, 21, 42, 56
168	120	$L(3, 2)$	1+20+35 <sub>2</sub> +64	1, 21, 42, 56
168	120	$L(3, 2)$	1+20+35 <sub>3</sub> +64	1, 21, 42, 56
360	56	$A_6$	1+20+35 <sub>1</sub>	1, 10, 45
360	56	$A_6$	1+20+35 <sub>2</sub>	1, 10, 45
360	56	$A_6$	1+20+35 <sub>3</sub>	1, 10, 45
960	21	$4^2.PGL(2, 4)$	1+20	1, 20
960	21	$4^2.PGL(2, 4)$	1+20	1, 20
$U(4, 2) (25, 920 = 2^6.3^4.5)$				
576	45	$C(2A)$	1+20+24	1, 12, 32
648	40	$C(3A)$	1+15 <sub>1</sub> +24	1, 12, 27
648	40	$N(3^2)$	1+15 <sub>1</sub> +24	1, 12, 27
720	36	$\Sigma_6$	1+15 <sub>2</sub> +20	1, 15, 20
960	27		1+6+20	1, 10, 16
$Sz(8) (29, 120 = 2^6.5.7.13)$				
20	1456	$N(5)$	1+2.35 <sub>1</sub> +2.35 <sub>2</sub> +2.35 <sub>3</sub> +4.65 <sub>1</sub> +4.65 <sub>2</sub> +4.65 <sub>3</sub> +3.64+3.91	
52	560	$N(13)$	1+35 <sub>1</sub> +35 <sub>2</sub> +35 <sub>2</sub> +64+2.65 <sub>1</sub> +2.65 <sub>2</sub> +2.65 <sub>3</sub>	1, 13, 26 <sup>9</sup> , 52 <sup>6</sup>
448	65		1+64	1, 64

Order	Index	Description	Permutation Character	Orbit Lengths
$U(3, 4) (62,400 = 2^6 \cdot 3 \cdot 5^2 \cdot 13)$				
39	1600	$N(13)$	$1+39_1+39_2+2.52_1$ $+2.52_2+2.52_3+2.52_4$ $+2.64+65_1+65_2+65_3$ $+65_4+65_5+13_1+13_2$ $+13_3+13_4+2.75_1$ $+2.75_2+2.75_3+2.75_4$	
150	416	$(5^2) \cdot \Sigma_3$	$1+39_1+39_2+52_1+52_2$ $+52_3+52_4+64+65_1$	
300	208	$5 \times A_5$	$1+39_1+39_2+64+65_1$	
960	65		$1+64$	1, 64
$M_{1,2} (95,040 = 2^6 \cdot 3^3 \cdot 5 \cdot 11)$				
72	1320	$A_4 \times \Sigma_3 = N(2^2)$	$1+16_1+16_2+2.45 + 2.54$ $+55_3+2.66+2.99$ $+2.120+2.144+176$	
192	495	$2^2 \cdot 2^3 \cdot \Sigma_3 = N(2^2)$	$1+16_1+16_2+45+2.54$ $+66+99+144$	1, 6, 16, 24, $32^2, 48^2, 96^3$
192	495	$M_8 \cdot \Sigma_4 = C(2B)$	$1+11_1+11_2+55_3$ $+2.54+66+99+144$	1, 6, 16, 24, $32^2, 48^2, 96^3$
240	396	$2 \times \Sigma_5 = C(2A)$	$1+16_1+16_2+45$ $+2.54+66+144$	
432	220	$M_9 \cdot \Sigma_3 = \text{Hessian } .2$	$1+11_1+54+55_3+99$	1, 9, 18, 48, 144
432	220	$M_9 \cdot \Sigma_3 = \text{Hessian } .2$	$1+11_2+54+55_3+99$	1, 9, 18, 48, 144
660	144	$L(2, 11)$	$1+11_1+11_2+55_3+66$	1, $11^2$ , 55, 66
1440	66	$M_{10} \cdot 2$	$1+11_1+54$	1, 45, 20
1440	66	$M_{10} \cdot 2$	$1+11_2+54$	1, 45, 20
7920	12	$M_{11}$	$1+11_1$	1, 11
7920	12	$M_{11}$	$1+11_2$	1, 11
$U(3, 5) (126,000 = 2^4 \cdot 3^2 \cdot 5^3 \cdot 7)$				
240	525	$C_6(2A)$	$1+28_1+28_2+28_3+84$ $+105+125+126_1$	
720	175	$M_{10}$	$1+21+28_1+125$	1, 12, 72, 90
1000	126	$N(5A)$	$1+125$	1, 125
2520	50	$A_7$	$1+21+28_1$	1, 7, 42
2520	50	$A_7$	$1+21+28_2$	1, 7, 42
2520	50	$A_7$	$1+21+28_3$	1, 7, 42

Order	Index	Description	Permutation Character	Orbit Lengths
		$J_1$ (175,560 = $2^3 \cdot 3 \cdot 5 \cdot 7 \cdot 11 \cdot 19$ )		
42	4180	$N(7)$ , Frobenius group	$1+3.120_1+3.120_2$ $+3.120_3+2.56_1$ $+2.56_2+5.209$ $+6.133_1+4.77_1$ $+4.76_1+77_2+77_3$ $+133_2+133_3$	
60	2926	$15.2^2$	$1+4.209+2.120_1$ $+2.120_2+2.120_3+77_1$ $+2.76_1+76_2+2.133_1$ $+56_1+56_2+2.133_2$ $+2.133_3+77_2+77_3$	
110	1596	$N(11)$ , Frobenius group	$1+120_1+120_2+120_3$ $+2.209+2.77_1+76_2$ $+76_3+133_1+133_2$ $+133_3+56_1+56_2$	
114	1540	$N(19)$ , Frobenius group	$1+2.209+2.133_1+77_1$ $+77_2+77_3+2.76_1+56_1$ $+56_2+120_1+120_2$ $+120_3$	
120	1463	$2 \times A_5 = C(2A)$	$1+56_1+56_2+2.76_1$ $+2.77_1+120_1+120_2$ $+120_3+2.133_1+2.209$	
168	1045	$2^3 \cdot 7 \cdot 3$	$1+120_1+120_2+120_3$ $+209+133_1+76_1+56_1$ $+56_2+77_2+77_3$	
660	266	$L(2, 11)$	$1+56_1+56_2+76_1$ $+77_1$	1, 11, 12 110, 132
		$A_9$ (181,440 = $2^6 \cdot 3^4 \cdot 5 \cdot 7$ )		
216	840	Hessian, primitive	$1+21_1+21_2+48+56$ $+2.84+120+189+216$	
648	280	imprimitive	$1+27+48+84+120$	1, 27, 36, 54, 162
1440	126	$(5, 4)^+$ , intransitive	$1+8+27+42+48$	1, 5, 20, 40, 60
1512	120	$L(2, 8).3$ , primitive	$1+35_1+84$	1, 56, 63
1512	120	$L(2, 8).3$ , primitive	$1+35_2+84$	1, 56, 63
2160	84	$(6, 3)^+$ , intransitive	$1+8+27+48$	1, 18, 20, 45
5040	36	$\Sigma_7 = (7, 2)^+$ , intransitive	$1+8+27$	1, 14, 21
20160	9	$A_8 = (8, 1)^+$ , intransitive	$1+8$	1, 8

Order	Index	Description	Permutation Character	Orbit Lengths
			$L(3, 5) (372,000 = 2^5 \cdot 3 \cdot 5^3 \cdot 31)$	
93	4000	$N(31)$	$1+31_1+31_2+31_3$ $+ \Sigma_1^{10} 96_i + 125$ $+155_1+155_2$ $+155_3+2.186$ $+2.124_1+2.124_2$ $+2\Sigma_5^{10} 124_i$	$1, 31^{15}, 93^{38}$
96	3875	Monomial group	$1+\Sigma_1^{10} 96_i+2.30+31_1$ $+2.124_1+3.124_2$ $+2.124_5+2.124_6$ $+124_7+124_8$ $+124_9+124_{10}$ $+2.125+3.155_1$ $+155_2+155_3+186$	
120	3100	$N(2^2) = \text{SL}(2, 5)$	$1+2.30+2.31_1+2.31_2$ $+2.31_3+\Sigma_1^{10} 124_i+125$ $+2.155_1+2.155_2$ $+2.155_3+3.186$	
12000	31	$5^2 \cdot \text{GL}(2, 5)$	$1+30$	$1, 30$
12000	31	$5^2 \cdot \text{GL}(2, 5)$	$1+30$	$1, 30$
			$M_{22} (443,520 = 2^7 \cdot 3^2 \cdot 5 \cdot 7 \cdot 11)$	
660	672	$L(2, 11)$	$1+21+55+154+210$ $+231$	$1, 55^2, 66$ $165, 330$
720	616	$M_{10}$	$1+21+55+154+385$	$1, 30, 45, 180, 360$
1344	330	$2^3 \cdot L(3, 2) = N(2^3)$	$1+21+55+99+154$	$1, 21, 84, 112^2$
1920	231	$2^4 \cdot \Sigma_5 = N(2^4)$	$1+21+55+154$	$1, 30, 40, 160$
2520	176	$A_7$	$1+21+154$	$1, 70, 105$
2520	176	$A_7$	$1+21+154$	$1, 70, 105$
5760	77	$2^4 \cdot A_6$	$1+21+55$	$1, 16, 60$
20160	22	$M_{21}$	$1+21$	$1, 21$
			$J_2 (604,800 = 2^7 \cdot 3^3 \cdot 5^2 \cdot 7)$	
60	10080	$A_5$	$1+14_1+14_2+36+63$ $+70_1+70_2+3.90$ $+4.126+4.160+2.175$ $+3.189_1+3.189_2$ $+2.224_1+2.224_2$ $+6.225+4.288+5.300$ $+6.336$	



Order	Index	Description	Permutation Character	Orbit Lengths
300	2016	$5^2.(2 \times \Sigma_3)$	1+63+2.90+2.126 +160+175+225+288 +2.336	
336	1800	$N(L(2, 7))$	1+36+2.63+90+2.126 +160+175+288+2.336	
600	1008	$A_5 \times D_{10}$	1+14 <sub>1</sub> +14 <sub>2</sub> +2.90+126 +160+225+288	
720	840	$A_4 \times A_5$	1+63+90+126+160 +175+225	
1152	525	$(2^6.3)\Sigma_3$	1+36+90+160+63 +175	
1920	315	$2^5.A_5$	1+36+90+160+14 <sub>1</sub> +14 <sub>2</sub>	1, 10, 32 <sup>2</sup> , 80, 160
2160	280	$3.PGL(2, 9)$	1+63+90+126	1, 36, 108, 135
6048	100	$U(3, 3)$	1+36+63	1, 36, 63
$Sp(4, 4) (979,200 = 2^8.3^2.5^2.17)$				
720	1360	$Sp(4, 2) \cong \Sigma_6$	1+2.50+85 <sub>1</sub> +85 <sub>2</sub> +153+256+340 <sub>1</sub> +340 <sub>2</sub>	
7200	136		1+50+85 <sub>1</sub>	1, 60, 75
7200	136		1+50+85 <sub>2</sub>	1, 60, 75
8160	120	$L(2, 16).2$	1+34 <sub>1</sub> +85 <sub>1</sub>	1, 51, 68
8160	120	$L(2, 16).2$	1+34 <sub>2</sub> +85 <sub>2</sub>	1, 51, 68
11520	85		1+34 <sub>1</sub> +50	1, 20, 64
11520	85		1+34 <sub>2</sub> +50	1, 20, 64

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