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## The CAST-256 Encryption Algorithm

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### Abstract

There is always a desire in the Internet community for unencumbered encryption algorithms with a range of key sizes that can provide security for a variety of cryptographic applications and protocols.

This document describes an existing algorithm that can be used to satisfy this requirement. Included are a description of the cipher and the key scheduling algorithm, the s-boxes, and a set of test vectors (Appendix A).

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## 1. Introduction

This document describes the CAST-256 encryption algorithm, a DES-like Substitution-Permutation Network (SPN) cryptosystem built upon the CAST-128 encryption algorithm [1] which appears to have good resistance to differential cryptanalysis, linear cryptanalysis, and related-key cryptanalysis. This cipher also possesses a number of other desirable cryptographic properties, including avalanche, Strict Avalanche Criterion (SAC), Bit Independence Criterion (BIC), no complementation property, and an absence of weak and semi-weak keys. It thus appears to be a good candidate for general-purpose use throughout the Internet community wherever a cryptographically-strong, freely-available encryption algorithm is required.

CAST-256 has a block size of 128 bits and a variable key size (128, 160, 192, 224, or 256 bits).

## 2. CAST-256 Algorithm Specification

### 2.1 CAST-128 Notation

The following notation from CAST-128 [1] is relevant to CAST-256.

CAST-128 uses a pair of subkeys per round: a 5-bit quantity  $K_{ri}$  is used as a "rotation" key for round  $i$  and a 32-bit quantity  $K_{mi}$  is used as a "masking" key for round  $i$ .

Three different round functions are used in CAST-128. The rounds are as follows (where  $D$  is the data input to the operation,  $I_a - I_d$  are the most significant byte through least significant byte of  $I$ , respectively,  $S_i$  is the  $i$ th s-box (see Section 2.1.1 for s-box contents), and  $O$  is the output of the operation). Note that "+" and "-" are addition and subtraction modulo  $2^{*}32$ , "^" is bitwise eXclusive-OR, and "<<<" is the circular left-shift operation.

Type 1:  $I = ((K_{mi} + D) \lll K_{ri})$   
 $O = ((S1[I_a] \wedge S2[I_b]) - S3[I_c]) + S4[I_d]$

Type 2:  $I = ((K_{mi} \wedge D) \lll K_{ri})$   
 $O = ((S1[I_a] - S2[I_b]) + S3[I_c]) \wedge S4[I_d]$

Type 3:  $I = ((K_{mi} - D) \lll K_{ri})$   
 $O = ((S1[I_a] + S2[I_b]) \wedge S3[I_c]) - S4[I_d]$

Let  $f_1$ ,  $f_2$ ,  $f_3$  be keyed round function operations of Types 1, 2, and 3 (respectively) above.

CAST-128 uses four round function substitution boxes (s-boxes), S1 - S4. These are defined as follows (entries -- written in hexadecimal notation -- are to be read left-to-right, top-to-bottom).

### 2.1.1.1 S-Boxes

#### S-Box S1

30fb40d4	9fa0ff0b	6beccd2f	3f258c7a	1e213f2f	9c004dd3	6003e540	cf9fc949
bfd4af27	88bbdb5	e2034090	98d09675	6e63a0e0	15c361d2	c2e7661d	22d4ff8e
28683b6f	c07fd059	ff2379c8	775f50e2	43c340d3	df2f8656	887ca41a	a2d2bd2d
alc9e0d6	346c4819	61b76d87	22540f2f	2abe32e1	aa54166b	22568e3a	a2d341d0
66db40c8	a784392f	004dff2f	2db9d2de	97943fac	4a97c1d8	527644b7	b5f437a7
b82cbaef	d751d159	6ff7f0ed	5a097a1f	827b68d0	90ecf52e	22b0c054	bc8e5935
4b6d2f7f	50bb64a2	d2664910	bee5812d	b7332290	e93b159f	b48ee411	4bff345d
fd45c240	ad31973f	c4f6d02e	55fc8165	d5b1caad	alac2dae	a2d4b76d	c19b0c50
882240f2	0c6e4f38	a4e4bfd7	4f5ba272	564c1d2f	c59c5319	b949e354	b04669fe
b1b6ab8a	c71358dd	6385c545	110f935d	57538ad5	6a390493	e63d37e0	2a54f6b3
3a787d5f	6276a0b5	19a6fcdf	7a42206a	29f9d4d5	f61b1891	bb72275e	aa508167
38901091	c6b505eb	84c7cb8c	2ad75a0f	874a1427	a2d1936b	2ad286af	aa56d291
d7894360	425c750d	93b39e26	187184c9	6c00b32d	73e2bb14	a0bebc3c	54623779
64459eab	3f328b82	7718cf82	59a2cea6	04ee002e	89fe78e6	3fab0950	325ff6c2
81383f05	6963c5c8	76cb5ad6	d49974c9	ca180dcf	380782d5	c7fa5cf6	8ac31511
35e79e13	47da91d0	f40f9086	a7e2419e	31366241	051ef495	aa573b04	4a805d8d
548300d0	00322a3c	bf64cddf	ba57a68e	75c6372b	50afd341	a7c13275	915a0bf5
6b54bfab	2b0b1426	ab4cc9d7	449ccd82	f7fbf265	ab85c5f3	1b55db94	aad4e324
cfa4bd3f	2deaa3e2	9e204d02	c8bd25ac	eadf55b3	d5bd9e98	e31231b2	2ad5ad6c
954329de	adbe4528	d8710f69	aa51c90f	aa786bf6	22513f1e	aa51a79b	2ad344cc
7b5a41f0	d37cfbad	1b069505	41ece491	b4c332e6	032268d4	c9600acc	ce387e6d
bf6bb16c	6a70fb78	0d03d9c9	d4df39de	e01063da	4736f464	5ad328d8	b347cc96
75bb0fc3	98511bfb	4ffbcc35	b58bcf6a	e11f0abc	bfc5fe4a	a70aec10	ac39570a
3f04442f	6188b153	e0397a2e	5727cb79	9ceb418f	1cacd68d	2ad37c96	0175cb9d
c69dff09	c75b65f0	d9db40d8	ec0e7779	4744ead4	b11c3274	dd24cb9e	7e1c54bd
f01144f9	d2240eb1	9675b3fd	a3ac3755	d47c27af	51c85f4d	56907596	a5bb15e6
580304f0	ca042cf1	011a37ea	8dbfaadb	35ba3e4a	3526ffa0	c37b4d09	bc306ed9
98a52666	5648f725	ff5e569d	0ced63d0	7c63b2cf	700b45e1	d5ea50f1	85a92872
af1fbd7	d4234870	a7870bf3	2d3b4d79	42e04198	0cd0ede7	26470db8	f881814c
474d6ad7	7c0c5e5c	d1231959	381b7298	f5d2f4db	ab838653	6e2f1e23	83719c9e
bd91e046	9a56456e	dc39200c	20c8c571	962bdalc	e1e696ff	b141ab08	7cca89b9
1a69e783	02cc4843	a2f7c579	429ef47d	427b169c	5ac9f049	dd8f0f00	5c8165bf

#### S-Box S2

1f201094	ef0ba75b	69e3cf7e	393f4380	fe61cf7a	eec5207a	55889c94	72fc0651
ada7ef79	4e1d7235	d55a63ce	de0436ba	99c430ef	5f0c0794	18dcd7b	a1d6eff3
a0b52f7b	59e83605	ee15b094	e9ffd909	dc440086	ef944459	ba83ccb3	e0c3cdfb
d1da4181	3b092ab1	f997f1c1	a5e6cf7b	01420ddb	e4e7ef5b	25a1ff41	e180f806
1fc41080	179bee7a	d37ac6a9	fe5830a4	98de8b7f	77e83f4e	79929269	24fa9f7b
e113c85b	acc40083	d7503525	f7ea615f	62143154	0d554b63	5d681121	c866c359

```

3d63cf73 cee234c0 d4d87e87 5c672b21 071f6181 39f7627f 361e3084 e4eb573b
602f64a4 d63acd9c 1bbc4635 9e81032d 2701f50c 99847ab4 a0e3df79 ba6cf38c
10843094 2537a95e f46f6ffe a1ff3b1f 208cfb6a 8f458c74 d9e0a227 4ec73a34
fc884f69 3e4de8df ef0e0088 3559648d 8a45388c 1d804366 721d9bfd a58684bb
e8256333 844e8212 128d8098 fed33fb4 ce280ae1 27e19ba5 d5a6c252 e49754bd
c5d655dd eb667064 77840b4d a1b6a801 84db26a9 e0b56714 21f043b7 e5d05860
54f03084 066ff472 a31aa153 dadc4755 b5625dbf 68561be6 83ca6b94 2d6ed23b
eccf01db a6d3d0ba b6803d5c af77a709 33b4a34c 397bc8d6 5ee22b95 5f0e5304
81ed6f61 20e74364 b45e1378 de18639b 881ca122 b96726d1 8049a7e8 22b7da7b
5e552d25 5272d237 79d2951c c60d894c 488cb402 1ba4fe5b a4b09f6b 1ca815cf
a20c3005 8871df63 b9de2fcb 0cc6c9e9 0beeff53 e3214517 b4542835 9f63293c
ee41e729 6e1d2d7c 50045286 1e6685f3 f33401c6 30a22c95 31a70850 60930f13
73f98417 a1269859 ec645c44 52c877a9 cdff33a6 a02b1741 7cbad9a2 2180036f
50d99c08 cb3f4861 c26bd765 64a3f6ab 80342676 25a75e7b e4e6d1fc 20c710e6
cdf0b680 17844d3b 31eef84d 7e0824e4 2ccb49eb 846a3bae 8ff77888 ee5d60f6
7af75673 2fdd5cdb a11631c1 30f66f43 b3faec54 157fd7fa ef8579cc d152de58
db2fffd5e 8f32ce19 306af97a 02f03ef8 99319ad5 c242fa0f a7e3ebb0 c68e4906
b8da230c 80823028 dcdef3c8 d35fb171 088a1bc8 bec0c560 61a3c9e8 bca8f54d
c72feffa 22822e99 82c570b4 d8d94e89 8b1c34bc 301e16e6 273be979 b0ffea6
61d9b8c6 00b24869 b7ffce3f 08dc283b 43daf65a f7e19798 7619b72f 8f1c9ba4
dc8637a0 16a7d3b1 9fc393b7 a7136eeb c6bcc63e 1a513742 ef6828bc 520365d6
2d6a77ab 3527ed4b 821fd216 095c6e2e db92f2fb 5eea29cb 145892f5 91584f7f
5483697b 2667a8cc 85196048 8c4bacea 833860d4 0d23e0f9 6c387e8a 0ae6d249
b284600c d835731d dcb1c647 ac4c56ea 3ebd81b3 230eabb0 6438bc87 f0b5b1fa
8f5ea2b3 fc184642 0a036b7a 4fb089bd 649da589 a345415e 5c038323 3e5d3bb9
43d79572 7e6dd07c 06dfdf1e 6c6cc4ef 7160a539 73bfbe70 83877605 4523ecf1

```

## S-Box S3

```

8defc240 25fa5d9f eb903dbf e810c907 47607fff 369fe44b 8c1fc644 aececa90
beb1f9bf eefbcaea e8cf1950 51df07ae 920e8806 f0ad0548 e13c8d83 927010d5
11107d9f 07647db9 b2e3e4d4 3d4f285e b9afa820 fade82e0 a067268b 8272792e
553fb2c0 489ae22b d4ef9794 125e3fbc 21fffcee 825b1bfd 9255c5ed 1257a240
4e1a8302 bae07fff 528246e7 8e57140e 3373f7bf 8c9f8188 a6fc4ee8 c982b5a5
a8c01db7 579fc264 67094f31 f2bd3f5f 40fff7c1 1fb78dfc 8e6bd2c1 437be59b
99b03dbf b5dbc64b 638dc0e6 55819d99 a197c81c 4a012d6e c5884a28 ccc36f71
b843c213 6c0743f1 8309893c 0feddd5f 2f7fe850 d7c07f7e 02507fbf 5afb9a04
a747d2d0 1651192e af70bf3e 58c31380 5f98302e 727cc3c4 0a0fb402 0f7fef82
8c96fdad 5d2c2aae 8ee99a49 50da88b8 8427f4a0 1eac5790 796fb449 8252dc15
efbd7d9b a672597d ada840d8 45f54504 fa5d7403 e83ec305 4f91751a 925669c2
23efe941 a903f12e 60270df2 0276e4b6 94fd6574 927985b2 8276dbcb 02778176
f8af918d 4e48f79e 8f616ddf e29d840e 842f7d83 340ce5c8 96bbb682 93b4b148
ef303cab 984faf28 779faf9b 92dc560d 224d1e20 8437aa88 7d29dc96 2756d3dc
8b907cee b51fd240 e7c07ce3 e566b4a1 c3e9615e 3cf8209d 6094d1e3 cd9ca341
5c76460e 00ea983b d4d67881 fd47572c f76cedd9 bda8229c 127dadaa 438a074e
1f97c090 081bdb8a 93a07ebe b938ca15 97b03cff 3dc2c0f8 8d1ab2ec 64380e51
68cc7bfb d90f2788 12490181 5de5ffd4 dd7ef86a 76a2e214 b9a40368 925d958f
4b39fffa ba39aee9 a4ffd30b faf7933b 6d498623 193cbcf8 27627545 825cf47a
61bd8ba0 d11e42d1 cead04f4 127ea392 10428db7 8272a972 9270c4a8 127de50b

```

285balc8	3c62f44f	35c0eaa5	e805d231	428929fb	b4fcdcf82	4fb66a53	0e7dc15b
1f081fab	108618ae	fcfd086d	f9ff2889	694bcc11	236a5cae	12deca4d	2c3f8cc5
d2d02dfe	f8ef5896	e4cf52da	95155b67	494a488c	b9b6a80c	5c8f82bc	89d36b45
3a609437	ec00c9a9	44715253	0a874b49	d773bc40	7c34671c	02717ef6	4feb5536
a2d02fff	d2bf60c4	d43f03c0	50b4ef6d	07478cd1	006e1888	a2e53f55	b9e6d4bc
a2048016	97573833	d7207d67	de0f8f3d	72f87b33	abcc4f33	7688c55d	7b00a6b0
947b0001	570075d2	f9bb88f8	8942019e	4264a5ff	856302e0	72dbd92b	ee971b69
6ea22fde	5f08ae2b	af7a616d	e5c98767	cf1febd2	61efc8c2	f1ac2571	cc8239c2
67214cb8	b1e583d1	b7dc3e62	7f10bdce	f90a5c38	0ff0443d	606e6dc6	60543a49
5727c148	2be98a1d	8ab41738	20e1be24	af96da0f	68458425	99833be5	600d457d
282f9350	8334b362	d91d1120	2b6d8da0	642b1e31	9c305a00	52bce688	1b03588a
f7baefd5	4142ed9c	a4315c11	83323ec5	dfef4636	a133c501	e9d3531c	ee353783

## S-Box S4

9db30420	1fb6e9de	a7be7bef	d273a298	4a4f7bdb	64ad8c57	85510443	fa020ed1
7e287aff	e60fb663	095f35a1	79ebf120	fd059d43	6497b7b1	f3641f63	241e4adf
28147f5f	4fa2b8cd	c9430040	0cc32220	fdd30b30	c0a5374f	1d2d00d9	24147b15
ee4d111a	0fca5167	71ff904c	2d195ffe	1a05645f	0c13fefe	081b08ca	05170121
80530100	e83e5efe	ac9af4f8	7fe72701	d2b8ee5f	06df4261	bb9e9b8a	7293ea25
ce84ffdf	f5718801	3dd64b04	a26f263b	7ed48400	547eebe6	446d4ca0	6cf3d6f5
2649abdf	aea0c7f5	36338cc1	503f7e93	d3772061	11b638e1	72500e03	f80eb2bb
abe0502e	ec8d77de	57971e81	e14f6746	c9335400	6920318f	081dbb99	ffc304a5
4d351805	7f3d5ce3	a6c866c6	5d5bcc9	daec6fea	9f926f91	9f46222f	3991467d
a5bf6d8e	1143c44f	43958302	d0214eeb	022083b8	3fb6180c	18f8931e	281658e6
26486e3e	8bd78a70	7477e4c1	b506e07c	f32d0a25	79098b02	e4eabb81	28123b23
69dead38	1574ca16	df871b62	211c40b7	a51a9ef9	0014377b	041e8ac8	09114003
bd59e4d2	e3d156d5	4fe876d5	2f91a340	557be8de	00eae4a7	0ce5c2ec	4db4bba6
e756bdf	dd3369ac	ec17b035	06572327	99afc8b0	56c8c391	6b65811c	5e146119
6e85cb75	be07c002	c2325577	893ff4ec	5bbfc92d	d0ec3b25	b7801ab7	8d6d3b24
20c763ef	c366a5fc	9c382880	0ace3205	aac9548a	ecal7c7	041afa32	1d16625a
6701902c	9b757a54	31d477f7	9126b031	36cc6fdb	c70b8b46	d9e66a48	56e55a79
026a4ceb	52437eff	2f8f76b4	0df980a5	8674cde3	edda04eb	17a9be04	2c18f4df
b7747f9d	ab2af7b4	efc34d20	2e096b7c	1741a254	e5b6a035	213d42f6	2c1c7c26
61c2f50f	6552daf9	d2c231f8	25130f69	d8167fa2	0418f2c8	001a96a6	0d1526ab
63315c21	5e0a72ec	49bafefd	187908d9	8d0dbd86	311170a7	3e9b640c	cc3e10d7
d5cad3b6	0caec388	f73001e1	6c728aff	71eae2a1	1f9af36e	cfcbd12f	c1de8417
ac07be6b	cb44a1d8	8b9b0f56	013988c3	b1c52fca	b4be31cd	d8782806	12a3a4e2
6f7de532	58fd7eb6	d01ee900	24adffc2	f4990fc5	9711aac5	001d7b95	82e5e7d2
109873f6	00613096	c32d9521	ada121ff	29908415	7fbb977f	af9eb3db	29c9ed2a
5ce2a465	a730f32c	d0aa3fe8	8a5cc091	d49e2ce7	0ce454a9	d60acd86	015f1919
77079103	dea03af6	78a8565e	dee356df	21f05cbe	8b75e387	b3c50651	b8a5c3ef
d8eeb6d2	e523be77	c2154529	2f69efdf	afe67afb	f470c4b2	f3e0eb5b	d6cc9876
39e4460c	1fda8538	1987832f	ca007367	a99144f8	296b299e	492fc295	9266beab
b5676e69	9bd3ddda	df7e052f	db25701c	1b5e51ee	f65324e6	6afce36c	0316cc04
8644213e	b7dc59d0	7965291f	ccd6fd43	41823979	932bcdff	b657c34d	4edfd282
7ae5290c	3cb9536b	851e20fe	9833557e	13ecf0b0	d3fffb372	3f85c5c1	0aef7ed2

## 2.2 CAST-256 Notation

The following notation is employed in the specification of CAST-256.

Let  $f_1, f_2, f_3$  be as defined for CAST-128.

Let  $BETA = (ABCD)$  be a 128-bit block where  $A, B, C$  and  $D$  are each 32 bits in length.

Let " $BETA \leftarrow Qi(BETA)$ " be short-hand notation for the following:

$$\begin{aligned} C &= C \wedge f_1(D, Kr0_{(i)}, Km0_{(i)}) \\ B &= B \wedge f_2(C, Kr1_{(i)}, Km1_{(i)}) \\ A &= A \wedge f_3(B, Kr2_{(i)}, Km2_{(i)}) \\ D &= D \wedge f_1(A, Kr3_{(i)}, Km3_{(i)}) \end{aligned}$$

Let " $BETA \leftarrow QBARi(BETA)$ " be short-hand notation for the following:

$$\begin{aligned} D &= D \wedge f_1(A, Kr3_{(i)}, Km3_{(i)}) \\ A &= A \wedge f_3(B, Kr2_{(i)}, Km2_{(i)}) \\ B &= B \wedge f_2(C, Kr1_{(i)}, Km1_{(i)}) \\ C &= C \wedge f_1(D, Kr0_{(i)}, Km0_{(i)}) \end{aligned}$$

( $Q(*)$  is called a "forward quad-round" and  $QBAR(*)$  is called a "reverse quad-round".)

Let  $Kr_{(i)} = \{Kr0_{(i)}, Kr1_{(i)}, Kr2_{(i)}, Kr3_{(i)}\}$  be the set of rotation keys for the  $i$ th quad-round, where  $Krj_{(i)}$  is a 5-bit rotation key for  $f_1, f_2$ , or  $f_3$  (as specified above).

Let  $Km_{(i)} = \{Km0_{(i)}, Km1_{(i)}, Km2_{(i)}, Km3_{(i)}\}$  be the set of masking keys for the  $i$ th quad-round, where  $Kmj_{(i)}$  is a 32-bit masking key for  $f_1, f_2$ , or  $f_3$  (as specified above).

Let  $KAPPA = (ABCDEFGH)$  be a 256-bit block where  $A, B, \dots, H$  are each 32 bits in length.

Let " $KAPPA \leftarrow Wi(KAPPA)$ " be short-hand notation for the following:

$$\begin{aligned} G &= G \wedge f_1(H, Tr0_{(i)}, Tm0_{(i)}) \\ F &= F \wedge f_2(G, Tr1_{(i)}, Tm1_{(i)}) \\ E &= E \wedge f_3(F, Tr2_{(i)}, Tm2_{(i)}) \\ D &= D \wedge f_1(E, Tr3_{(i)}, Tm3_{(i)}) \\ C &= C \wedge f_2(D, Tr4_{(i)}, Tm4_{(i)}) \\ B &= B \wedge f_3(C, Tr5_{(i)}, Tm5_{(i)}) \\ A &= A \wedge f_1(B, Tr6_{(i)}, Tm6_{(i)}) \\ H &= H \wedge f_2(A, Tr7_{(i)}, Tm7_{(i)}) \end{aligned}$$

( $W(*)$  is called a "forward octave".)

Let "Kr\_(i) <- KAPPA" be short-hand notation for the following: Kr0\_(i) = 5LSB(A), Kr1\_(i) = 5LSB(C), Kr2\_(i) = 5LSB(E), Kr3\_(i) = 5LSB(G)  
where 5LSB(x) denotes "the five least significant bits of x".

Let "Km\_(i) <- KAPPA" be short-hand notation for the following:  
Km0\_(i) = H, Km1\_(i) = F, Km2\_(i) = D, Km3\_(i) = B

### 2.3 The CAST-256 Cipher

BETA = 128bits of plaintext.

```
for (i=0; i<6; i++)  
  BETA <- Qi(BETA)  
for (i=6; i<12; i++)  
  BETA <- QBARI(BETA)
```

128bits of ciphertext = BETA

Round Key Re-Ordering for Decryption

The cipher employs a 256-bit primary key K. Decryption is identical to encryption except that the sets of quad-round keys Kr\_(i), Km\_(i) derived from K are used in reverse order as follows.

```
for (i=0; i<12; i++)  
{  
  KrNEW_(i) = Kr_(11-i)  
  KmNEW_(i) = Km_(11-i)  
}
```

### 2.4 The CAST-256 Key Schedule

Initialization:

```
Cm = 2**30 * SQRT(2) = 5A827999 (base 16)  
Mm = 2**30 * SQRT(3) = 6ED9EBA1 (base 16)  
Cr = 19  
Mr = 17
```

```

for (i=0; i<24; i++)
{
    for (j=0; j<8; j++)
    {
        Tmj_(i) = Cm
        Cm = (Cm + Mm) mod 2**32
        Trj_(i) = Cr
        Cr = (Cr + Mr) mod 32
    }
}

```

#### Key Schedule:

KAPPA = ABCDEFGH = 256 bit of primary key, K.

```

for (i=0; i<12; i++)
{
    KAPPA <- W2i(KAPPA)
    KAPPA <- W2i+1(KAPPA)
    Kr_(i) <- KAPPA
    Km_(i) <- KAPPA
}

```

Note: (|K| = 128) => (E = F = G = H = 0)  
(|K| = 160) => (F = G = H = 0)  
(|K| = 192) => (G = H = 0)  
(|K| = 224) => (H = 0)

### 3. Cipher Naming

In order to avoid confusion when variable keysize operation is used, the name CAST-256 is to be considered synonymous with the name CAST6; this allows a keysize to be appended without ambiguity. Thus, for example, CAST-256 with a 192-bit key is to be referred to as CAST6-192; where a 256-bit key is explicitly intended, the name CAST6-256 should be used.

### 4. Cipher Usage

The CAST-256 cipher described in this document is available worldwide on a royalty-free and licence-free basis for commercial and non-commercial uses.

### 5. Security Considerations

This entire memo is about security since it describes an algorithm which is specifically intended for cryptographic purposes.



## 6. References

- [1] Adams, C., "The CAST-128 Encryption Algorithm", RFC 2144, May 1997.

## 7. Authors' Addresses

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## Appendix A: Test Vectors

Intermediate Values Known Answer Test. The data listed is:

KEYSIZE=the current key length in bits  
KEY=the key in hexadecimal format  
PT=the plaintext to be encrypted  
R=the quad-round number (1 to 12)  
ROTK1,ROTK2,ROTK3,ROTK4=the rotation keys for the current quad-round  
MASK1,MASK2,MASK3,MASK4=the masking keys for the current quad-round  
OUT=the output of the quad-round  
CT=the ciphertext corresponding to the given plaintext.

For each key size, an encryption and the corresponding decryption are shown.

KEYSIZE=128

KEY=2342bb9efa38542c0af75647f29f615d

PT=00000000000000000000000000000000

R=1

ROTK1=1c

ROTK2=1d

ROTK3=18

ROTK4=06

MASK1=f364d7f9

MASK2=233500c0

MASK3=83cee501

MASK4=01f857c6

OUT=e2c604af966715811b377f12de19e459

R=2

ROTK1=1e

ROTK2=18

ROTK3=13

ROTK4=02

MASK1=ae877786

MASK2=ef78852e

MASK3=0aa1c41f

MASK4=a28ec9c4

OUT=5375c3be208f38eed0419d98f50dd9b3

R=3

ROTK1=02

ROTK2=1d

ROTK3=01

ROTK4=0b

MASK1=a3eedefb

MASK2=ac426ecf

MASK3=2e8220ec

MASK4=cd92c34a

OUT=732e4ec0f205e39afaf407c956d83728

R=4

ROTK1=0d

ROTK2=1d

ROTK3=04

ROTK4=12

MASK1=3046827f

MASK2=568ab6b9

MASK3=b86e7c10

MASK4=ef290a58

OUT=af23fd837033dc81a60be8a69865c543

R=5

ROTK1=01

ROTK2=14

ROTK3=0c

ROTK4=06

MASK1=302e76c3

MASK2=cf429964

MASK3=e9ecad47

MASK4=8850a515

OUT=8b5e011401e1124f731135fa780c59ef

R=6

ROTK1=17

ROTK2=1d

ROTK3=0e

ROTK4=09

MASK1=bb903fdc      MASK2=a9915d2f      MASK3=0974e50a      MASK4=0c1708f1  
OUT=bdea3985cd08c7902096561b76f20944

R=7  
ROTK1=03              ROTK2=13              ROTK3=07              ROTK4=0e  
MASK1=13330f06      MASK2=5e1906f5      MASK3=fb2bce75      MASK4=8331aed4  
OUT=438053fe465c299bcb35f273b10ea71a

R=8  
ROTK1=07              ROTK2=02              ROTK3=14              ROTK4=14  
MASK1=a29189c1      MASK2=d1aeff98      MASK3=c9b55ba7      MASK4=c149f70c  
OUT=172c3a9a2791509d5939f58b703f2533

R=9  
ROTK1=1c              ROTK2=08              ROTK3=1f              ROTK4=1f  
MASK1=5687e118      MASK2=bc4f5d80      MASK3=cca4c042      MASK4=bab3fb68  
OUT=79178d5f90187732f8007fd3884cc309

R=10  
ROTK1=15              ROTK2=12              ROTK3=04              ROTK4=0f  
MASK1=cdb18671      MASK2=f06a3c64      MASK3=0c7031f9      MASK4=7dfbff4e  
OUT=e9e2b1f23e82479baec3b3b35fdf890f

R=11  
ROTK1=1f              ROTK2=1a              ROTK3=01              ROTK4=0e  
MASK1=317654b5      MASK2=a1433222      MASK3=f6d8c69f      MASK4=304dfbeb  
OUT=1f3270101b2b38adc4818ca2aaafc334a

R=12  
ROTK1=0b              ROTK2=11              ROTK3=0f              ROTK4=18  
MASK1=9339b14f      MASK2=971d14bb      MASK3=f3b7ca97      MASK4=2b8a06f9  
OUT=c842a08972b43d20836c91d1b7530f6b

CT=c842a08972b43d20836c91d1b7530f6b

R=1  
ROTK1=0b              ROTK2=11              ROTK3=0f              ROTK4=18  
MASK1=9339b14f      MASK2=971d14bb      MASK3=f3b7ca97      MASK4=2b8a06f9  
OUT=1f3270101b2b38adc4818ca2aaafc334a

R=2  
ROTK1=1f              ROTK2=1a              ROTK3=01              ROTK4=0e  
MASK1=317654b5      MASK2=a1433222      MASK3=f6d8c69f      MASK4=304dfbeb  
OUT=e9e2b1f23e82479baec3b3b35fdf890f

R=3  
ROTK1=15              ROTK2=12              ROTK3=04              ROTK4=0f  
MASK1=cdb18671      MASK2=f06a3c64      MASK3=0c7031f9      MASK4=7dfbff4e

OUT=79178d5f90187732f8007fd3884cc309

R=4

ROTK1=1c	ROTK2=08	ROTK3=1f	ROTK4=1f
MASK1=5687e118	MASK2=bc4f5d80	MASK3=cca4c042	MASK4=bab3fb68
OUT=172c3a9a2791509d5939f58b703f2533			

R=5

ROTK1=07	ROTK2=02	ROTK3=14	ROTK4=14
MASK1=a29189c1	MASK2=d1aeff98	MASK3=c9b55ba7	MASK4=c149f70c
OUT=438053fe465c299bcb35f273b10ea71a			

R=6

ROTK1=03	ROTK2=13	ROTK3=07	ROTK4=0e
MASK1=13330f06	MASK2=5e1906f5	MASK3=fb2bce75	MASK4=8331aed4
OUT=bdea3985cd08c7902096561b76f20944			

R=7

ROTK1=17	ROTK2=1d	ROTK3=0e	ROTK4=09
MASK1=bb903fdc	MASK2=a9915d2f	MASK3=0974e50a	MASK4=0c1708f1
OUT=8b5e011401e1124f731135fa780c59ef			

R=8

ROTK1=01	ROTK2=14	ROTK3=0c	ROTK4=06
MASK1=302e76c3	MASK2=cf429964	MASK3=e9ecad47	MASK4=8850a515
OUT=af23fd837033dc81a60be8a69865c543			

R=9

ROTK1=0d	ROTK2=1d	ROTK3=04	ROTK4=12
MASK1=3046827f	MASK2=568ab6b9	MASK3=b86e7c10	MASK4=ef290a58
OUT=732e4ec0f205e39afaf407c956d83728			

R=10

ROTK1=02	ROTK2=1d	ROTK3=01	ROTK4=0b
MASK1=a3eedefb	MASK2=ac426ecf	MASK3=2e8220ec	MASK4=cd92c34a
OUT=5375c3be208f38eed0419d98f50dd9b3			

R=11

ROTK1=1e	ROTK2=18	ROTK3=13	ROTK4=02
MASK1=ae877786	MASK2=ef78852e	MASK3=0aa1c41f	MASK4=a28ec9c4
OUT=e2c604af966715811b377f12de19e459			

R=12

ROTK1=1c	ROTK2=1d	ROTK3=18	ROTK4=06
MASK1=f364d7f9	MASK2=233500c0	MASK3=83cee501	MASK4=01f857c6
OUT=00000000000000000000000000000000			

PT=00000000000000000000000000000000

=====

KEYSIZE=192

KEY=2342bb9efa38542cbcd0ac83940ac298bac77a7717942863

PT=00000000000000000000000000000000

R=1

ROTK1=1e	ROTK2=1a	ROTK3=1b	ROTK4=16
MASK1=21daa501	MASK2=fcdfc612	MASK3=62f629b3	MASK4=9ec93bfa
OUT=4d468c8ca43c1ab66eae0bb9062fe876			

R=2

ROTK1=1a	ROTK2=1d	ROTK3=19	ROTK4=1f
MASK1=d7f04aaf	MASK2=76a4b0c2	MASK3=7364327b	MASK4=fe0602c3
OUT=1fd808cfd82ac7354728e719a4cc0ebe			

R=3

ROTK1=13	ROTK2=19	ROTK3=15	ROTK4=18
MASK1=c5b5a24e	MASK2=20577cc0	MASK3=e58b12aa	MASK4=a87da0f1
OUT=d3507d51934db5335cebdbb550b774b6			

R=4

ROTK1=0f	ROTK2=00	ROTK3=15	ROTK4=08
MASK1=5b1b847c	MASK2=3d700297	MASK3=310383e1	MASK4=a1a19785
OUT=fab3a20243c1c67bf1759f40c4b732e8			

R=5

ROTK1=01	ROTK2=0f	ROTK3=0f	ROTK4=11
MASK1=34422fa1	MASK2=745d0d3c	MASK3=0804535e	MASK4=42de73d8
OUT=cf003a27ba91d2346ddfa8ec76bdf029			

R=6

ROTK1=06	ROTK2=10	ROTK3=06	ROTK4=07
MASK1=ae5e85f6	MASK2=d1f789b0	MASK3=e2113794	MASK4=db8768c0
OUT=b4fb78a74bbaccbfa45c36c23ed997e			

R=7

ROTK1=09	ROTK2=1d	ROTK3=08	ROTK4=1f
MASK1=1a000d83	MASK2=dc6d0e51	MASK3=3b65ccaf	MASK4=b0470998
OUT=1cedb6d94abb223765f0fb9364a8f07f			

R=8

ROTK1=09	ROTK2=0a	ROTK3=01	ROTK4=0d
MASK1=d500ec2c	MASK2=77e23f6f	MASK3=3d1422b2	MASK4=0e4c04aa
OUT=b3289009a03b021d54cec6628712c165			

R=9

ROTK1=1b	ROTK2=0d	ROTK3=0b	ROTK4=14
MASK1=f9b1a192	MASK2=aded6200	MASK3=0fc10d02	MASK4=d8bdb797
OUT=a4d8f6d0abd8613d241fff3c2ba02882			

R=10

ROTK1=17	ROTK2=1d	ROTK3=1c	ROTK4=17
MASK1=a81550e2	MASK2=44e56b22	MASK3=ac97284c	MASK4=e1021ad2
OUT=61a3f74a9a5da18d53a25ce8f3302357			

R=11

ROTK1=19	ROTK2=1e	ROTK3=11	ROTK4=02
MASK1=b09d0346	MASK2=15167c69	MASK3=19990bbd	MASK4=a9258551
OUT=ca5ad45111a662f740c9a94b1d43dfb6			

R=12

ROTK1=10	ROTK2=0d	ROTK3=08	ROTK4=01
MASK1=69d0c348	MASK2=c8a3d81d	MASK3=d2714d62	MASK4=8cc3f35a
OUT=1b386c0210dcadcbdd0e41aa08a7a7e8			

CT=1b386c0210dcadcbdd0e41aa08a7a7e8

R=1

ROTK1=10	ROTK2=0d	ROTK3=08	ROTK4=01
MASK1=69d0c348	MASK2=c8a3d81d	MASK3=d2714d62	MASK4=8cc3f35a
OUT=ca5ad45111a662f740c9a94b1d43dfb6			

R=2

ROTK1=19	ROTK2=1e	ROTK3=11	ROTK4=02
MASK1=b09d0346	MASK2=15167c69	MASK3=19990bbd	MASK4=a9258551
OUT=61a3f74a9a5da18d53a25ce8f3302357			

R=3

ROTK1=17	ROTK2=1d	ROTK3=1c	ROTK4=17
MASK1=a81550e2	MASK2=44e56b22	MASK3=ac97284c	MASK4=e1021ad2
OUT=a4d8f6d0abd8613d241fff3c2ba02882			

R=4

ROTK1=1b	ROTK2=0d	ROTK3=0b	ROTK4=14
MASK1=f9b1a192	MASK2=aded6200	MASK3=0fc10d02	MASK4=d8bdb797
OUT=b3289009a03b021d54cec6628712c165			

R=5

ROTK1=09	ROTK2=0a	ROTK3=01	ROTK4=0d
MASK1=d500ec2c	MASK2=77e23f6f	MASK3=3d1422b2	MASK4=0e4c04aa
OUT=1cedb6d94abb223765f0fb9364a8f07f			

R=6

ROTK1=09	ROTK2=1d	ROTK3=08	ROTK4=1f
MASK1=1a000d83	MASK2=dc6d0e51	MASK3=3b65ccaf	MASK4=b0470998
OUT=b4fb78a74bbaccbfa45c36c23ed997e			

R=7

ROTK1=06	ROTK2=10	ROTK3=06	ROTK4=07
MASK1=ae5e85f6	MASK2=d1f789b0	MASK3=e2113794	MASK4=db8768c0
OUT=cf003a27ba91d2346ddfa8ec76bdf029			

R=8

ROTK1=01	ROTK2=0f	ROTK3=0f	ROTK4=11
MASK1=34422fa1	MASK2=745d0d3c	MASK3=0804535e	MASK4=42de73d8
OUT=fab3a20243c1c67bf1759f40c4b732e8			

R=9

ROTK1=0f	ROTK2=00	ROTK3=15	ROTK4=08
MASK1=5b1b847c	MASK2=3d700297	MASK3=310383e1	MASK4=a1a19785
OUT=d3507d51934db5335cebdbb550b774b6			

R=10

ROTK1=13	ROTK2=19	ROTK3=15	ROTK4=18
MASK1=c5b5a24e	MASK2=20577cc0	MASK3=e58b12aa	MASK4=a87da0f1
OUT=1fd808cfd82ac7354728e719a4cc0ebe			

R=11

ROTK1=1a	ROTK2=1d	ROTK3=19	ROTK4=1f
MASK1=d7f04aaf	MASK2=76a4b0c2	MASK3=7364327b	MASK4=fe0602c3
OUT=4d468c8ca43c1ab66eae0bb9062fe876			

R=12

ROTK1=1e	ROTK2=1a	ROTK3=1b	ROTK4=16
MASK1=21daa501	MASK2=fcdfc612	MASK3=62f629b3	MASK4=9ec93bfa
OUT=00000000000000000000000000000000			

PT=00000000000000000000000000000000

=====

KEYSIZE=256

KEY=2342bb9efa38542cbcd0ac83940ac2988d7c47ce264908461cc1b5137ae6b604

PT=00000000000000000000000000000000

R=1  
ROTK1=08                      ROTK2=12                      ROTK3=0e                      ROTK4=17  
MASK1=420b1cef              MASK2=03f07e80              MASK3=cd2ab3ee              MASK4=15371a16  
OUT=f6c3b9a6ffd8a31ce04dbcf7772f1536

R=2  
ROTK1=0a                      ROTK2=04                      ROTK3=01                      ROTK4=13  
MASK1=bc6025e3              MASK2=d54f5aba              MASK3=17fa667a              MASK4=bb8a840e  
OUT=9477ef6fd7d6fce3dcaa27d6132465ee

R=3  
ROTK1=1e                      ROTK2=0d                      ROTK3=10                      ROTK4=01  
MASK1=446c0950              MASK2=b4542da0              MASK3=523baa91              MASK4=4a914503  
OUT=c056ec5748ecd90f992cf07f3529160f

R=4  
ROTK1=15                      ROTK2=0e                      ROTK3=0d                      ROTK4=09  
MASK1=4106d4de              MASK2=9ce441e7              MASK3=2c390c3b              MASK4=52d1b516  
OUT=7bcc57d80603b6c7b9ca75eea5cb1c2d

R=5  
ROTK1=09                      ROTK2=16                      ROTK3=08                      ROTK4=16  
MASK1=2827db72              MASK2=7920623f              MASK3=10948a1a              MASK4=b639f290  
OUT=d62686a2b01d11837fb6a46c79fc1816

R=6  
ROTK1=1f                      ROTK2=11                      ROTK3=17                      ROTK4=0a  
MASK1=85fcd124              MASK2=c567c5fe              MASK3=a4113025              MASK4=ce949239  
OUT=1b03a108d6f1878e03a62e72c9c97662

R=7  
ROTK1=1d                      ROTK2=06                      ROTK3=0b                      ROTK4=1c  
MASK1=c0e98900              MASK2=8832532c              MASK3=d7403525              MASK4=26ed4609  
OUT=b11d972f22ed26d085189ca3b6c79d36

R=8  
ROTK1=0b                      ROTK2=04                      ROTK3=0e                      ROTK4=19  
MASK1=69b1d027              MASK2=e628d930              MASK3=4904b3cd              MASK4=51fad71a  
OUT=4265774a393a8a32ed78c5c1571893e4

R=9  
ROTK1=1a                      ROTK2=0f                      ROTK3=09                      ROTK4=10  
MASK1=4b81b846              MASK2=9f1d941b              MASK3=ebb8fe8a              MASK4=6616847e  
OUT=f4f1322a076d4f5eb2d14dc75815ccf1



R=10  
ROTK1=1b                      ROTK2=00                      ROTK3=01                      ROTK4=01  
MASK1=2cf3fd07              MASK2=75580ec1              MASK3=513614b9              MASK4=478097ef  
OUT=57c3a554eafe71dc6a33fe0bda83f566

R=11  
ROTK1=1c                      ROTK2=0b                      ROTK3=1b                      ROTK4=1f  
MASK1=4fdf26fe              MASK2=a4850785              MASK3=615eadd0              MASK4=9b507d47  
OUT=dd9940f4f2e1786ab6f2bdee519a407e

R=12  
ROTK1=0f                      ROTK2=09                      ROTK3=1d                      ROTK4=02  
MASK1=4bd673d3              MASK2=36399d66              MASK3=63385006              MASK4=0579675f  
OUT=4f6a2038286897b9c9870136553317fa

CT=4f6a2038286897b9c9870136553317fa

R=1  
ROTK1=0f                      ROTK2=09                      ROTK3=1d                      ROTK4=02  
MASK1=4bd673d3              MASK2=36399d66              MASK3=63385006              MASK4=0579675f  
OUT=dd9940f4f2e1786ab6f2bdee519a407e

R=2  
ROTK1=1c                      ROTK2=0b                      ROTK3=1b                      ROTK4=1f  
MASK1=4fdf26fe              MASK2=a4850785              MASK3=615eadd0              MASK4=9b507d47  
OUT=57c3a554eafe71dc6a33fe0bda83f566

R=3  
ROTK1=1b                      ROTK2=00                      ROTK3=01                      ROTK4=01  
MASK1=2cf3fd07              MASK2=75580ec1              MASK3=513614b9              MASK4=478097ef  
OUT=f4f1322a076d4f5eb2d14dc75815ccf1

R=4  
ROTK1=1a                      ROTK2=0f                      ROTK3=09                      ROTK4=10  
MASK1=4b81b846              MASK2=9f1d941b              MASK3=ebb8fe8a              MASK4=6616847e  
OUT=4265774a393a8a32ed78c5c1571893e4

R=5  
ROTK1=0b                      ROTK2=04                      ROTK3=0e                      ROTK4=19  
MASK1=69b1d027              MASK2=e628d930              MASK3=4904b3cd              MASK4=51fad71a  
OUT=b11d972f22ed26d085189ca3b6c79d36

R=6  
ROTK1=1d                      ROTK2=06                      ROTK3=0b                      ROTK4=1c  
MASK1=c0e98900              MASK2=8832532c              MASK3=d7403525              MASK4=26ed4609  
OUT=1b03a108d6f1878e03a62e72c9c97662

R=7  
ROTK1=1f                      ROTK2=11                      ROTK3=17                      ROTK4=0a  
MASK1=85fcd124              MASK2=c567c5fe              MASK3=a4113025              MASK4=ce949239  
OUT=d62686a2b01d11837fb6a46c79fc1816

R=8  
ROTK1=09                      ROTK2=16                      ROTK3=08                      ROTK4=16  
MASK1=2827db72              MASK2=7920623f              MASK3=10948a1a              MASK4=b639f290  
OUT=7bcc57d80603b6c7b9ca75eea5cb1c2d

R=9  
ROTK1=15                      ROTK2=0e                      ROTK3=0d                      ROTK4=09  
MASK1=4106d4de              MASK2=9ce441e7              MASK3=2c390c3b              MASK4=52d1b516  
OUT=c056ec5748ecd90f992cf07f3529160f

R=10  
ROTK1=1e                      ROTK2=0d                      ROTK3=10                      ROTK4=01  
MASK1=446c0950              MASK2=b4542da0              MASK3=523baa91              MASK4=4a914503  
OUT=9477ef6fd7d6f6ce3dcaa27d6132465ee

R=11  
ROTK1=0a                      ROTK2=04                      ROTK3=01                      ROTK4=13  
MASK1=bc6025e3              MASK2=d54f5aba              MASK3=17fa667a              MASK4=bb8a840e  
OUT=f6c3b9a6ffd8a31ce04dbcf7772f1536

R=12  
ROTK1=08                      ROTK2=12                      ROTK3=0e                      ROTK4=17  
MASK1=420b1cef              MASK2=03f07e80              MASK3=cd2ab3ee              MASK4=15371a16  
OUT=00000000000000000000000000000000

PT=00000000000000000000000000000000

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