從平面導體導電之研究
談 靜電學

主講：吳原旭

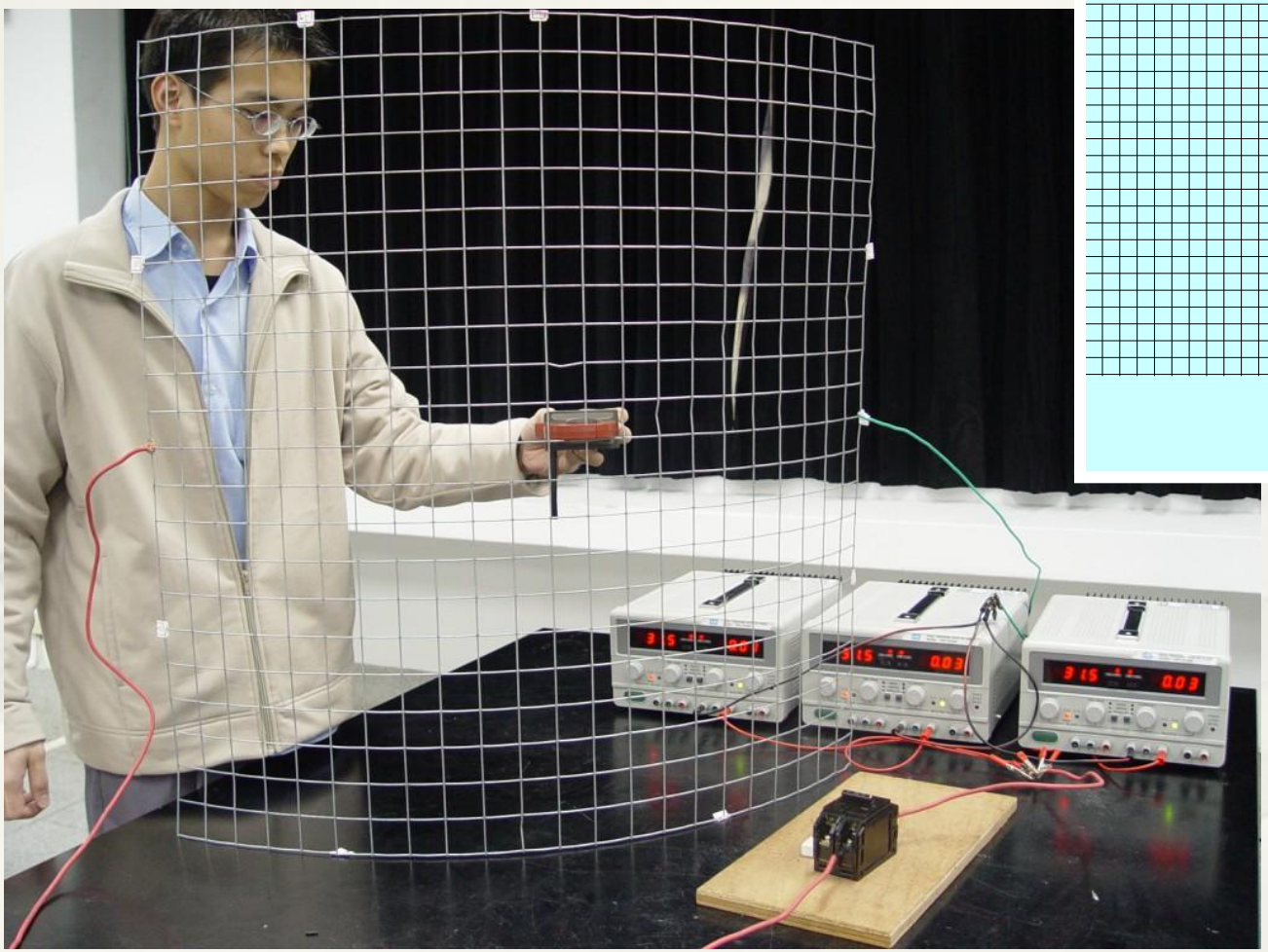
從平面導體導電之研究
談 靜電學

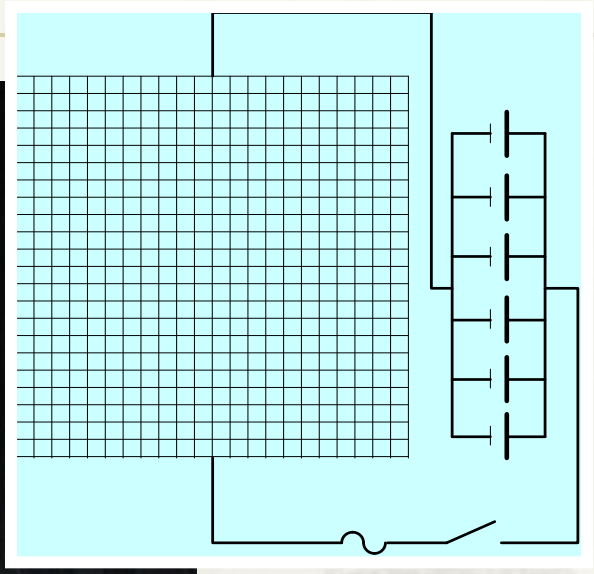
* 研究如何進行？
* 電流的強度
* 克西荷夫結點定則
* 克西荷夫迴路定則
* 平方反比定律V.S反比定律
* 邊界問題
* 等電位線
* 等電位線與電(流)場方向關係

網格電路之研究

- 如何研究平面導體之導電問題？
  如何測電流大小與方向
  如何測電位(差)

以鉤表測電流





測量範圍及安全評估

* 測量儀器的解析度？ 0.01A
* 通入多大電流才能測出明顯差異？ 37A
* 人體通過多少安培電流會致死？ 0.1A
* 安全嗎？

安全嗎？

爆火花的強電流

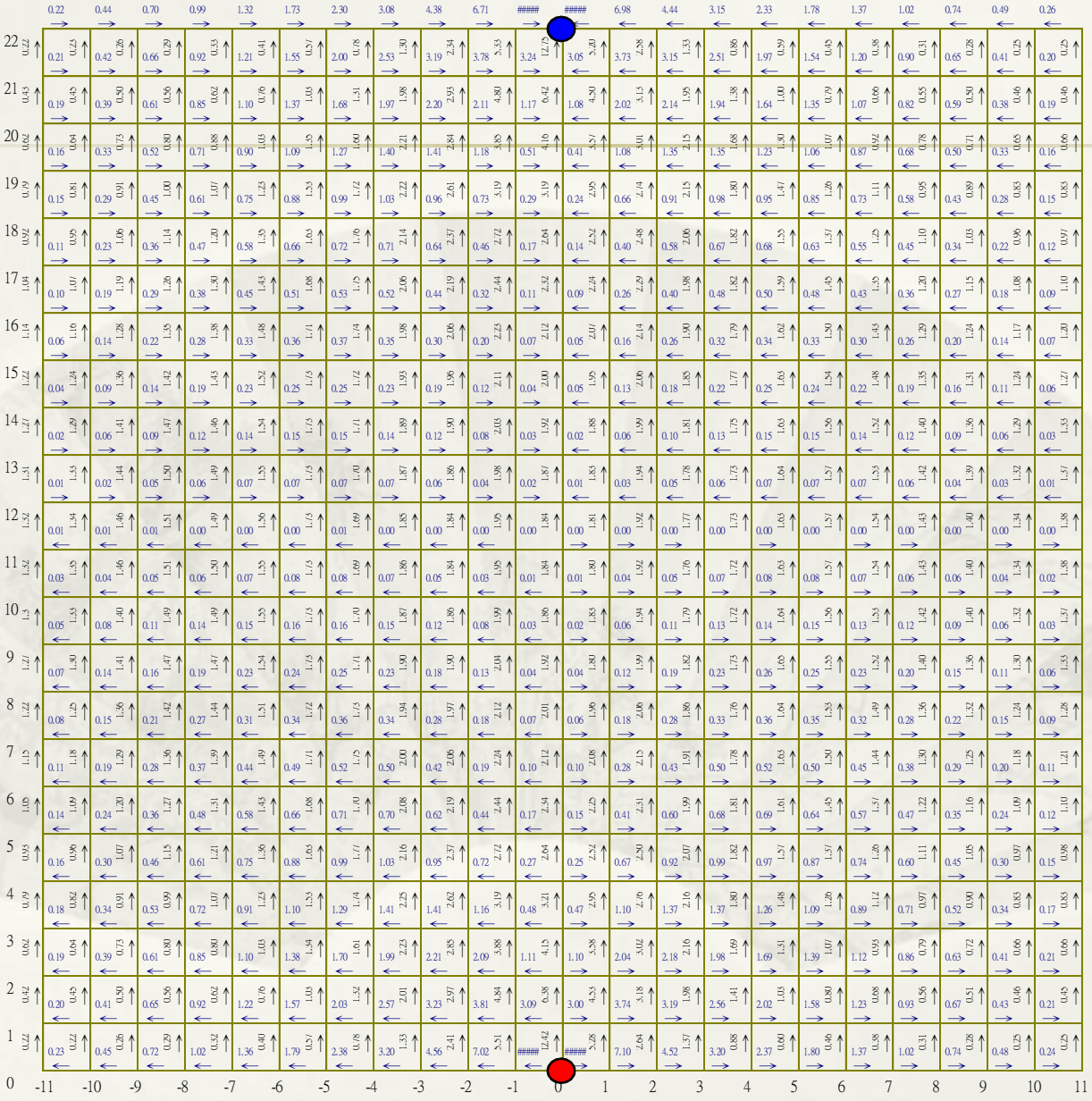
* 簡單的原理

  V=IR

  V固定時 **I**與**R**成反比

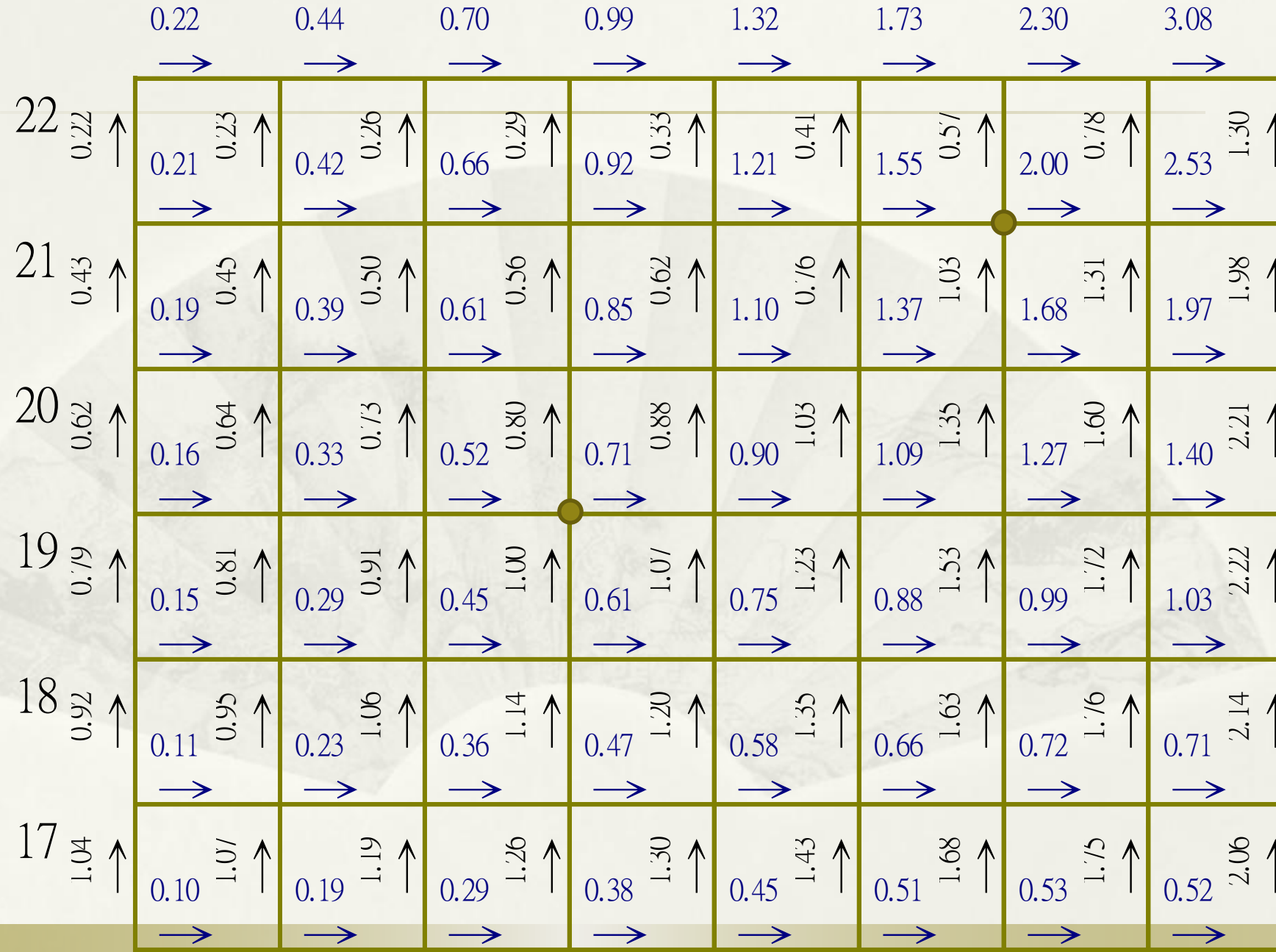
鐵絲網電阻很小，只需 2V 電壓就能通過37A 電流。

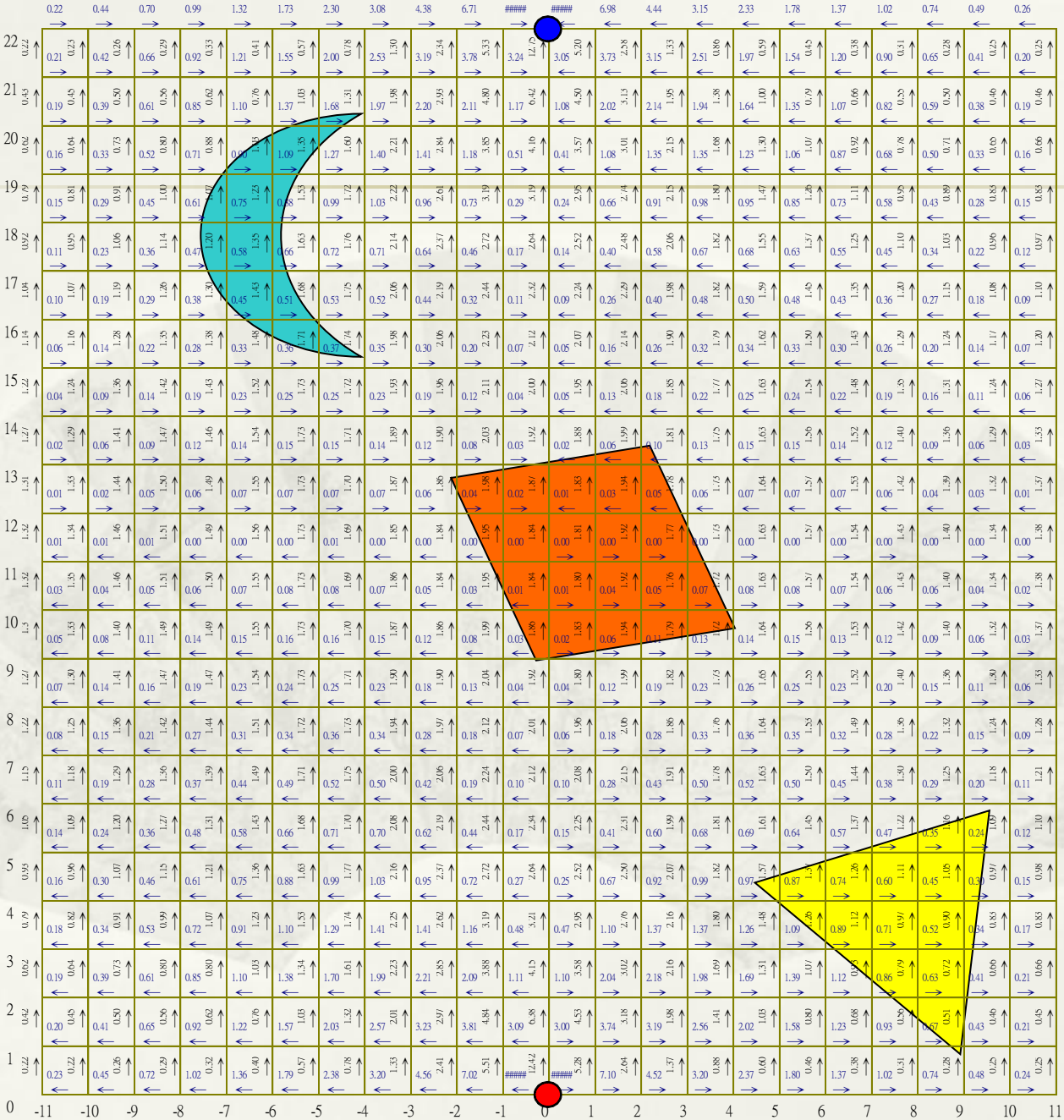
人體的電阻至少數萬歐姆，通過的電流極小。



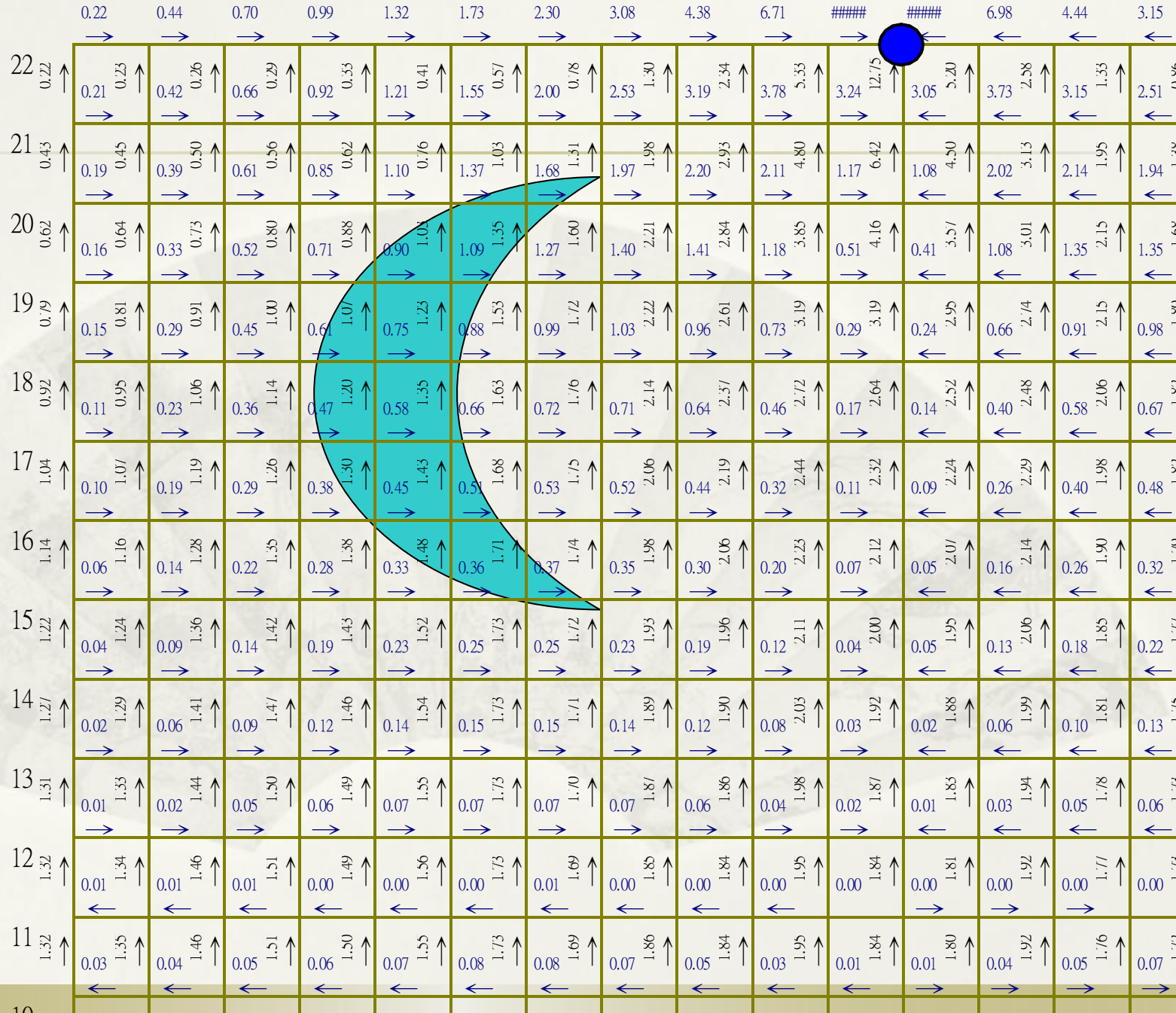
	0.22 →	0.44 →	0.70 →	0.99 →	1.32 →	1.73 →	2.30 →	3.08 →	4.38 →	6.71 →	##### →	##### ←	6.98 ←	4.44 ←	3.15 ←
22	0.22 ↑	0.21 0.23 ↑	0.42 0.26 ↑	0.66 0.29 ↑	0.92 0.33 ↑	1.21 0.41 ↑	1.55 0.57 ↑	2.00 0.78 ↑	2.53 1.30 ↑	3.19 2.34 ↑	3.78 5.33 ↑	3.24 12.75 ↑	3.05 5.20 ↑	3.73 2.58 ↑	3.15 1.33 ↑	2.51 ←
21	0.43 ↑	0.19 0.45 ↑	0.39 0.50 ↑	0.61 0.56 ↑	0.85 0.62 ↑	1.10 0.76 ↑	1.37 1.03 ↑	1.68 1.31 ↑	1.97 1.98 ↑	2.20 2.93 ↑	2.11 4.80 ↑	1.17 6.42 ↑	1.08 4.50 ↑	2.02 3.13 ↑	2.14 1.95 ↑	1.94 ←
20	0.62 ↑	0.16 0.64 ↑	0.33 0.73 ↑	0.52 0.80 ↑	0.71 0.88 ↑	0.90 1.03 ↑	1.09 1.35 ↑	1.27 1.60 ↑	1.40 2.21 ↑	1.41 2.84 ↑	1.18 3.85 ↑	0.51 4.16 ↑	0.41 3.57 ↑	1.08 3.01 ↑	1.35 2.15 ↑	1.35 ←
19	0.79 ↑	0.15 0.81 ↑	0.29 0.91 ↑	0.45 1.00 ↑	0.61 1.07 ↑	0.75 1.23 ↑	0.88 1.53 ↑	0.99 1.72 ↑	1.03 2.22 ↑	0.96 2.61 ↑	0.73 3.19 ↑	0.29 3.19 ↑	0.24 2.95 ↑	0.66 2.74 ↑	0.91 2.15 ↑	0.98 ←
18	0.92 ↑	0.11 0.95 ↑	0.23 1.06 ↑	0.36 1.14 ↑	0.47 1.20 ↑	0.58 1.35 ↑	0.66 1.63 ↑	0.72 1.76 ↑	0.71 2.14 ↑	0.64 2.57 ↑	0.46 2.72 ↑	0.17 2.64 ↑	0.14 2.52 ↑	0.40 2.48 ↑	0.58 2.06 ↑	0.67 ←
17	1.04 ↑	0.10 1.07 ↑	0.19 1.19 ↑	0.29 1.26 ↑	0.38 1.30 ↑	0.45 1.43 ↑	0.51 1.68 ↑	0.53 1.75 ↑	0.52 2.06 ↑	0.44 2.19 ↑	0.32 2.44 ↑	0.11 2.32 ↑	0.09 2.24 ↑	0.26 2.29 ↑	0.40 1.98 ↑	0.48 ←
16	1.14 ↑	0.06 1.16 ↑	0.14 1.28 ↑	0.22 1.35 ↑	0.28 1.38 ↑	0.33 1.48 ↑	0.36 1.71 ↑	0.37 1.74 ↑	0.35 1.98 ↑	0.30 2.06 ↑	0.20 2.23 ↑	0.07 2.12 ↑	0.05 2.07 ↑	0.16 2.14 ↑	0.26 1.90 ↑	0.32 ←
15	1.22 ↑	0.04 1.24 ↑	0.09 1.36 ↑	0.14 1.42 ↑	0.19 1.43 ↑	0.23 1.52 ↑	0.25 1.73 ↑	0.25 1.72 ↑	0.23 1.93 ↑	0.19 1.96 ↑	0.12 2.11 ↑	0.04 2.00 ↑	0.05 1.95 ↑	0.13 2.06 ↑	0.18 1.85 ↑	0.22 ←
14	1.27 ↑	0.02 1.29 ↑	0.06 1.41 ↑	0.09 1.47 ↑	0.12 1.46 ↑	0.14 1.54 ↑	0.15 1.73 ↑	0.15 1.71 ↑	0.14 1.89 ↑	0.12 1.90 ↑	0.08 2.03 ↑	0.03 1.92 ↑	0.02 1.88 ↑	0.06 1.99 ↑	0.10 1.81 ↑	0.13 ←
13	1.31 ↑	0.01 1.33 ↑	0.02 1.44 ↑	0.05 1.50 ↑	0.06 1.49 ↑	0.07 1.55 ↑	0.07 1.73 ↑	0.07 1.70 ↑	0.07 1.87 ↑	0.06 1.86 ↑	0.04 1.98 ↑	0.02 1.87 ↑	0.01 1.83 ↑	0.03 1.94 ↑	0.05 1.78 ↑	0.06 ←
12	1.32 ↑	0.01 1.34 ↑	0.01 1.46 ↑	0.01 1.51 ↑	0.00 1.49 ↑	0.00 1.56 ↑	0.00 1.73 ↑	0.01 1.69 ↑	0.00 1.85 ↑	0.00 1.84 ↑	0.00 1.95 ↑	0.00 1.84 ↑	0.00 1.81 ↑	0.00 1.92 ↑	0.00 1.77 ↑	0.00 ←
11	1.32 ↑	0.03 1.35 ↑	0.04 1.46 ↑	0.05 1.51 ↑	0.06 1.50 ↑	0.07 1.55 ↑	0.08 1.73 ↑	0.08 1.69 ↑	0.07 1.86 ↑	0.05 1.84 ↑	0.03 1.95 ↑	0.01 1.84 ↑	0.01 1.80 ↑	0.04 1.92 ↑	0.05 1.76 ↑	0.07 →

同一結點的總進出電流淨值爲零





同一區塊的總進出電流淨值爲零



克西荷夫結點定則

同一區塊的總進出電流淨值爲零

$$\sum_{i} I_i = 0$$

克西荷夫迴路定則

任一迴路，沿途電位的總變化量等於0

$$\sum_{i} \Delta V_i = 0$$

每一段導線兩端電位差 $\Delta V_i = I_i \times R_i$

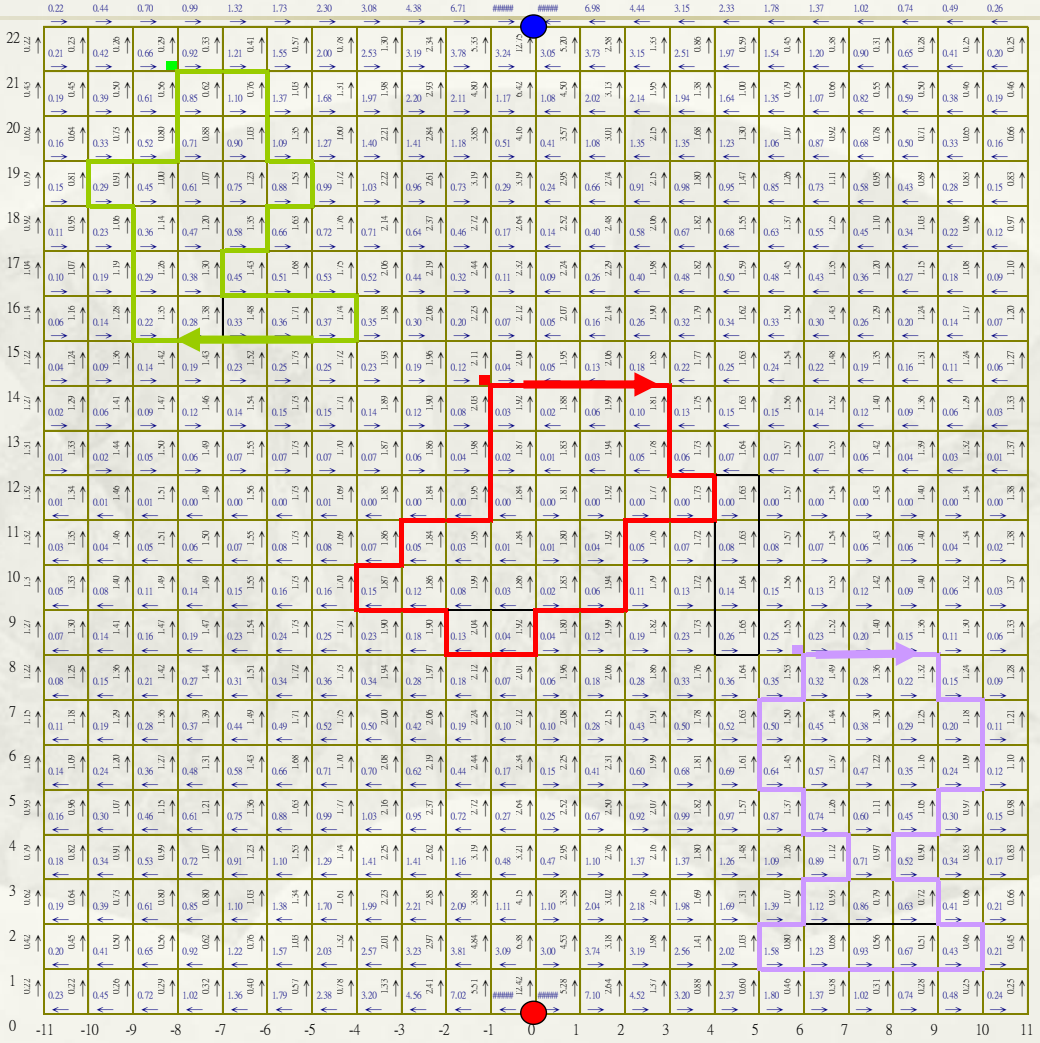
假設每一小段鐵絲長度、粗細、材質均相同且焊接點之電阻可忽略，因此設每一小段電阻均爲R。

$$\sum_{i} (I_i \times R_i) = 0$$

$$\Rightarrow \sum_{i} (I_i \times R) = 0 \quad \Rightarrow R \times \sum_{i} I_i = 0$$

$$\therefore \sum_{i} I_i = 0$$

任一迴路，電流的總變化量等於0




0.22 0.44 0.70 0.99 1.32 1.73 2.30 3.08 4.38 6.71 ##### #####
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21 0.43 0.19 0.45 0.39 0.50 0.61 0.56 0.85 0.62 1.10 0.76 1.37 1.03 1.68 1.31 1.97 1.98 2.20 2.93 2.11 4.80 1.17 6.42 1.08 4.50
20 0.62 0.16 0.64 0.33 0.73 0.52 0.80 0.71 0.88 0.90 1.03 1.09 1.35 1.27 1.60 1.40 2.21 1.41 2.84 1.18 3.85 0.51 4.16 0.41 3.57
19 0.79 0.15 0.81 0.29 0.91 0.45 1.00 0.61 1.07 0.75 1.23 0.88 1.53 0.99 1.72 1.03 2.22 0.96 2.61 0.73 3.19 0.29 3.19 0.24 2.95
18 0.92 0.11 0.95 0.23 1.06 0.36 1.14 0.47 1.20 0.58 1.35 0.66 1.63 0.72 1.76 0.71 2.14 0.64 2.37 0.46 2.72 0.17 2.64 0.14 2.52
17 1.04 0.10 1.07 0.19 1.19 0.29 1.26 0.38 1.30 0.45 1.43 0.51 1.68 0.53 1.75 0.52 2.06 0.44 2.19 0.32 2.44 0.11 2.32 0.09 2.24
16 1.14 0.06 1.16 0.14 1.28 0.22 1.35 0.28 1.38 0.33 1.48 0.36 1.71 0.37 1.74 0.35 1.98 0.30 2.06 0.20 2.23 0.07 2.12 0.05 2.07
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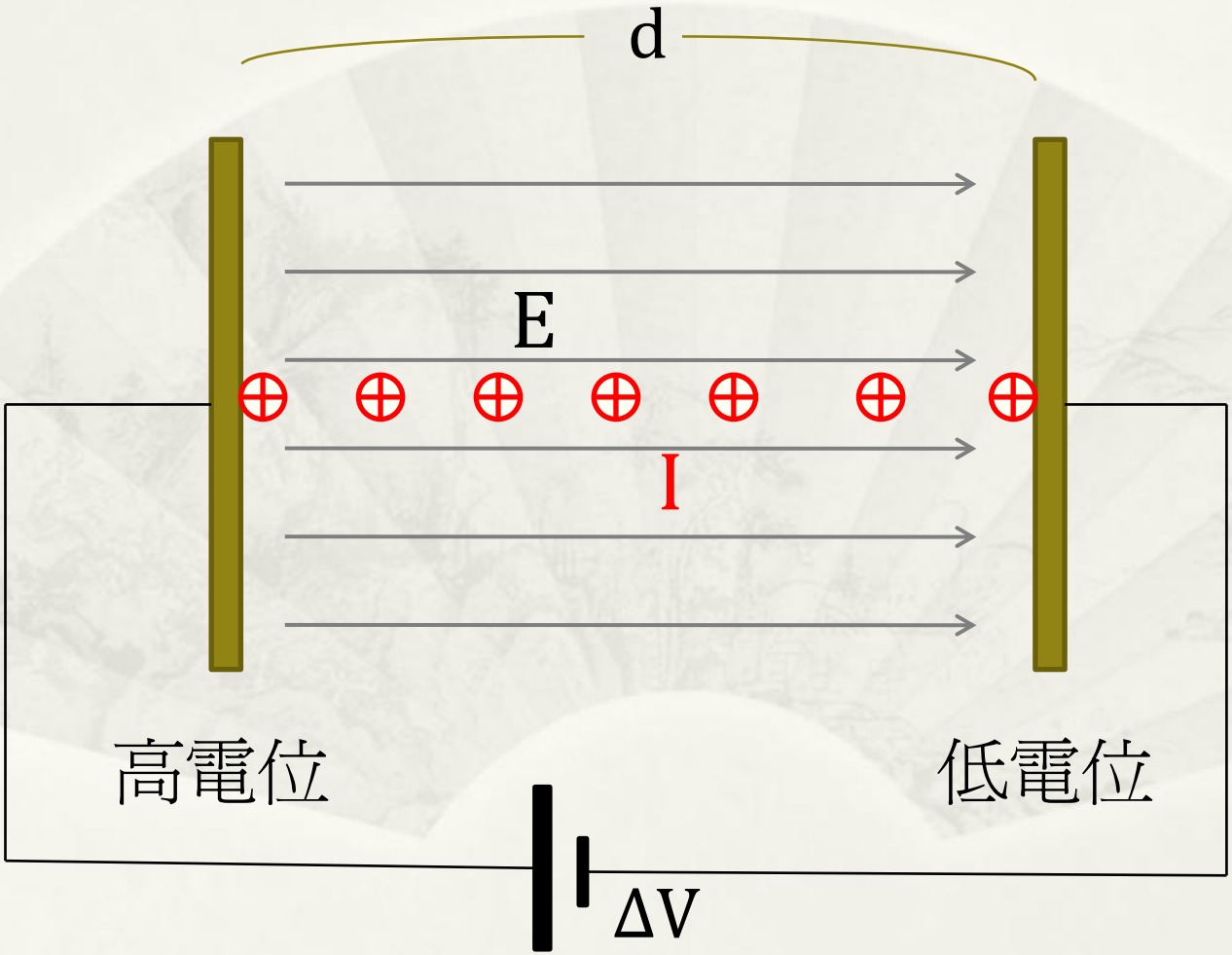
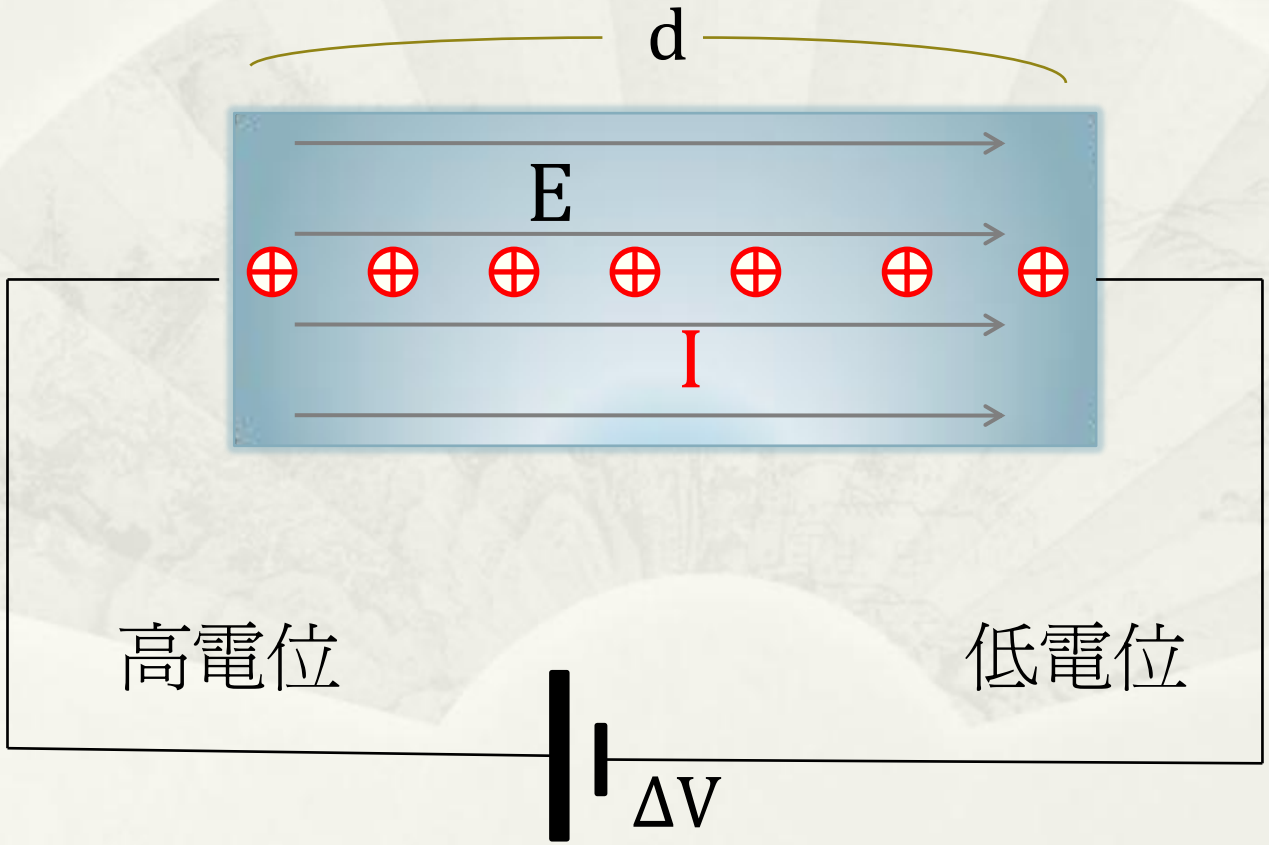
$$E \cdot d = \Delta V = I \cdot R$$



$$E \cdot d = \Delta V = I \cdot R$$

以金屬爲介質，情形都一樣



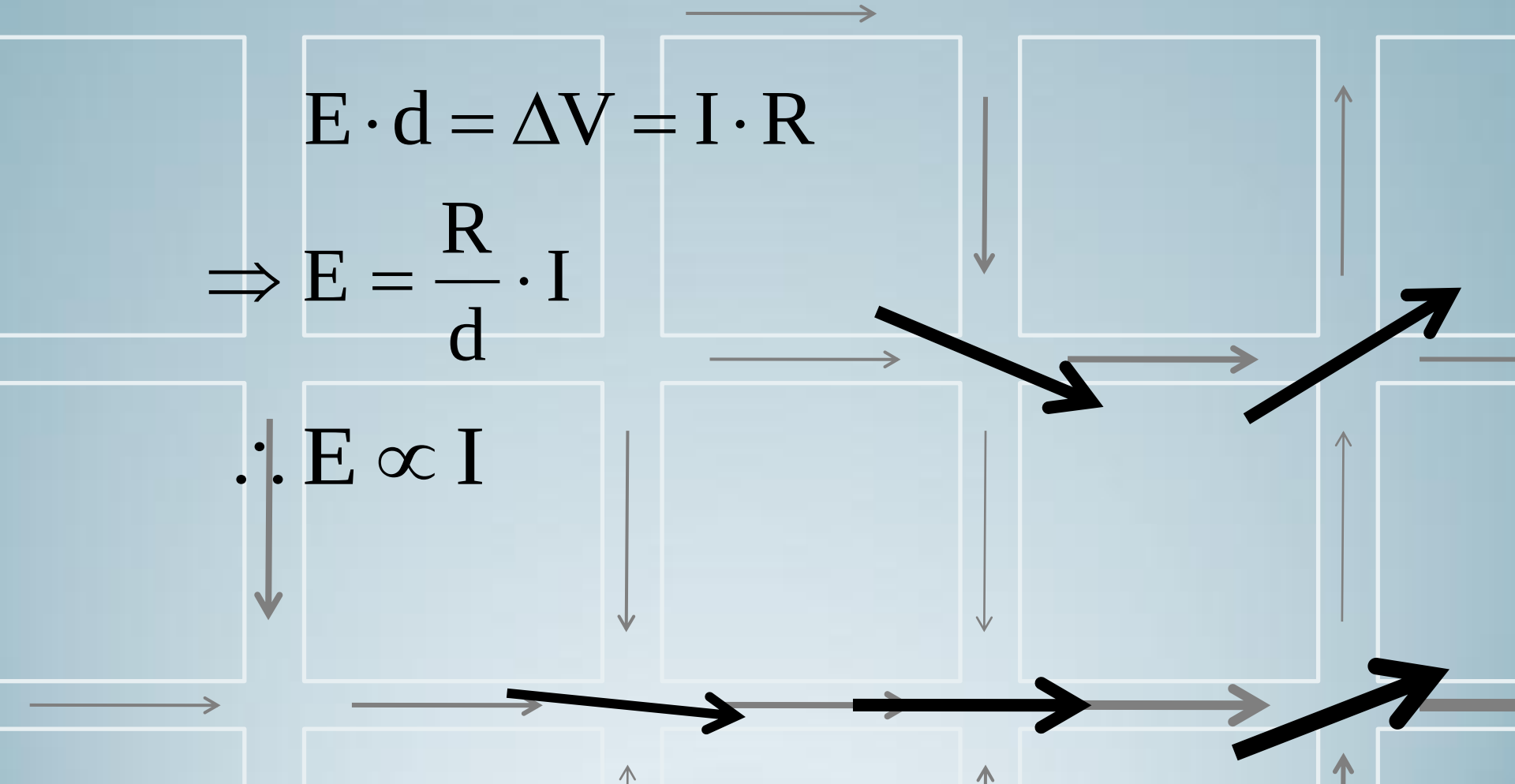
探討網格電路上的電流向量場

將每一小段鐵絲視爲均勻導體

$$E \cdot d = \Delta V = I \cdot R$$

$$\Rightarrow E = \frac{R}{d} \cdot I$$

$$\therefore E \propto I$$

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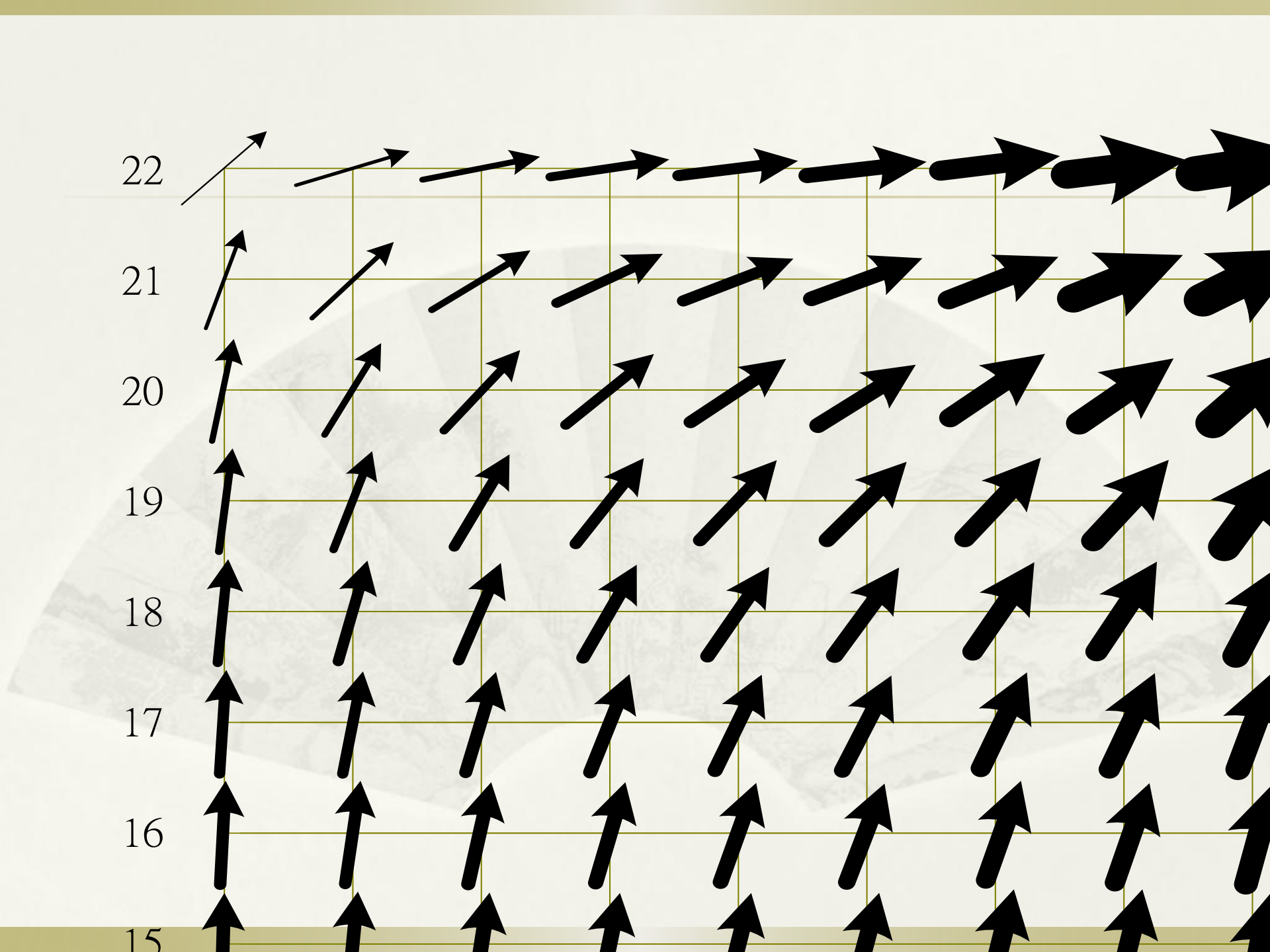
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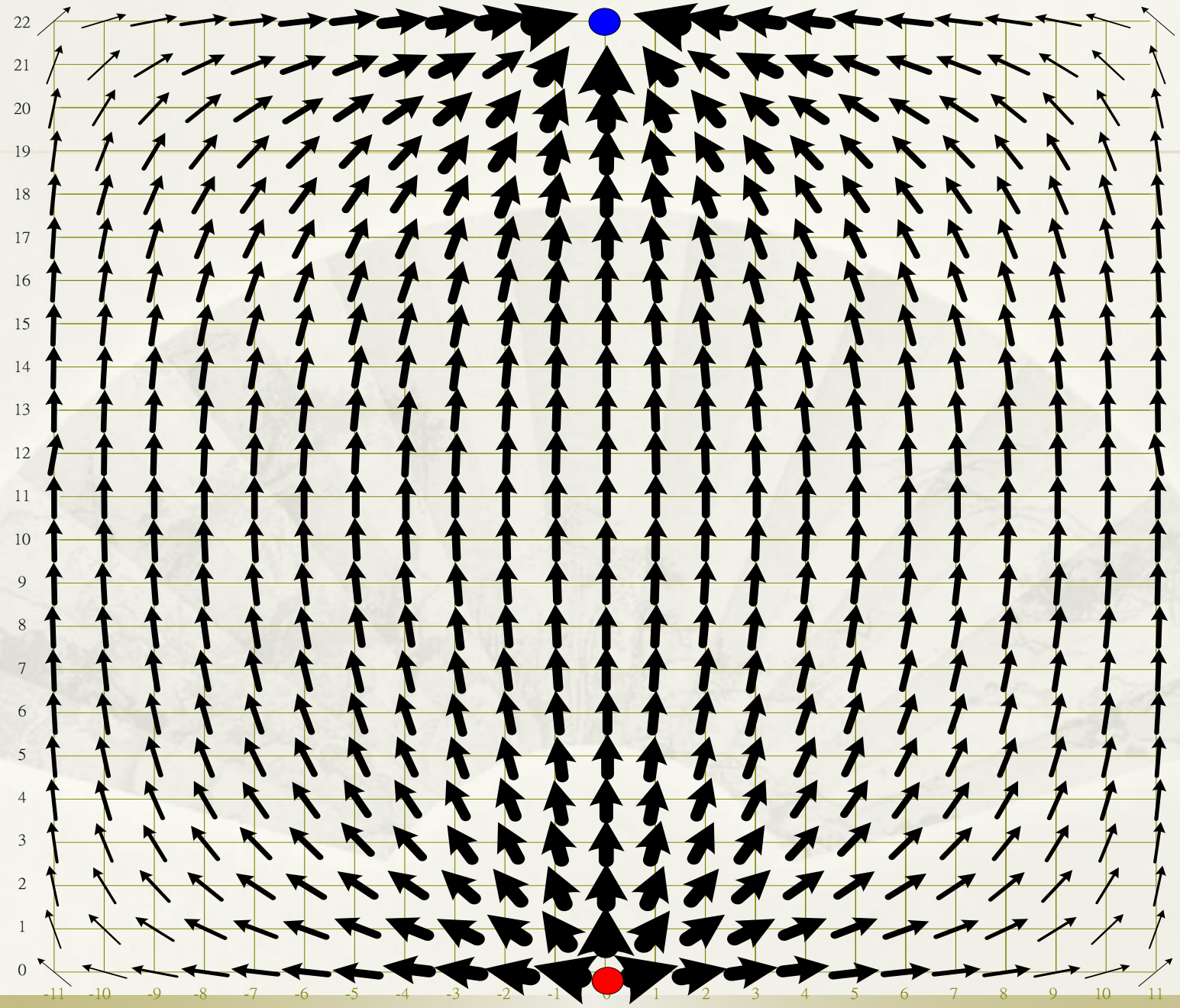
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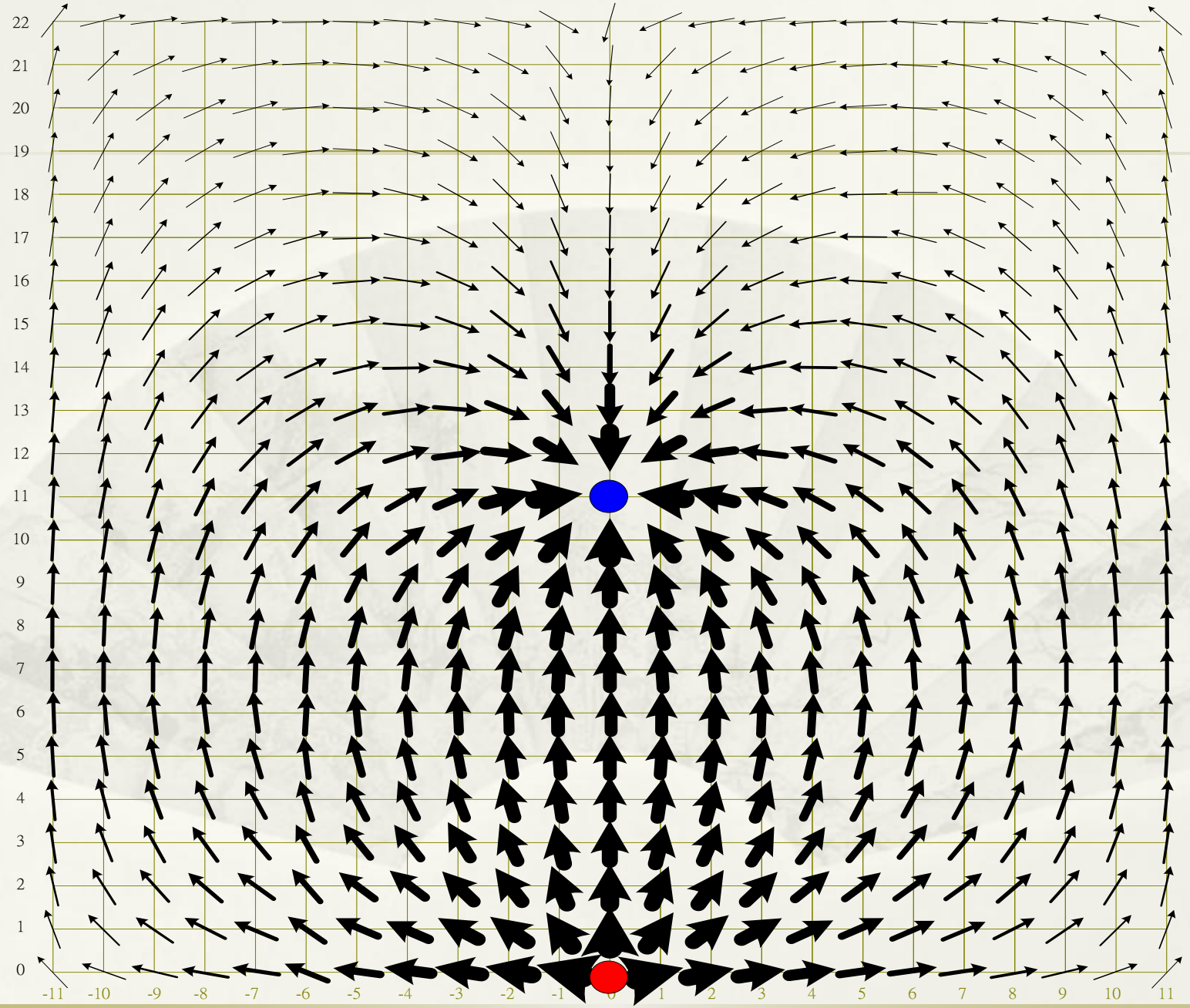
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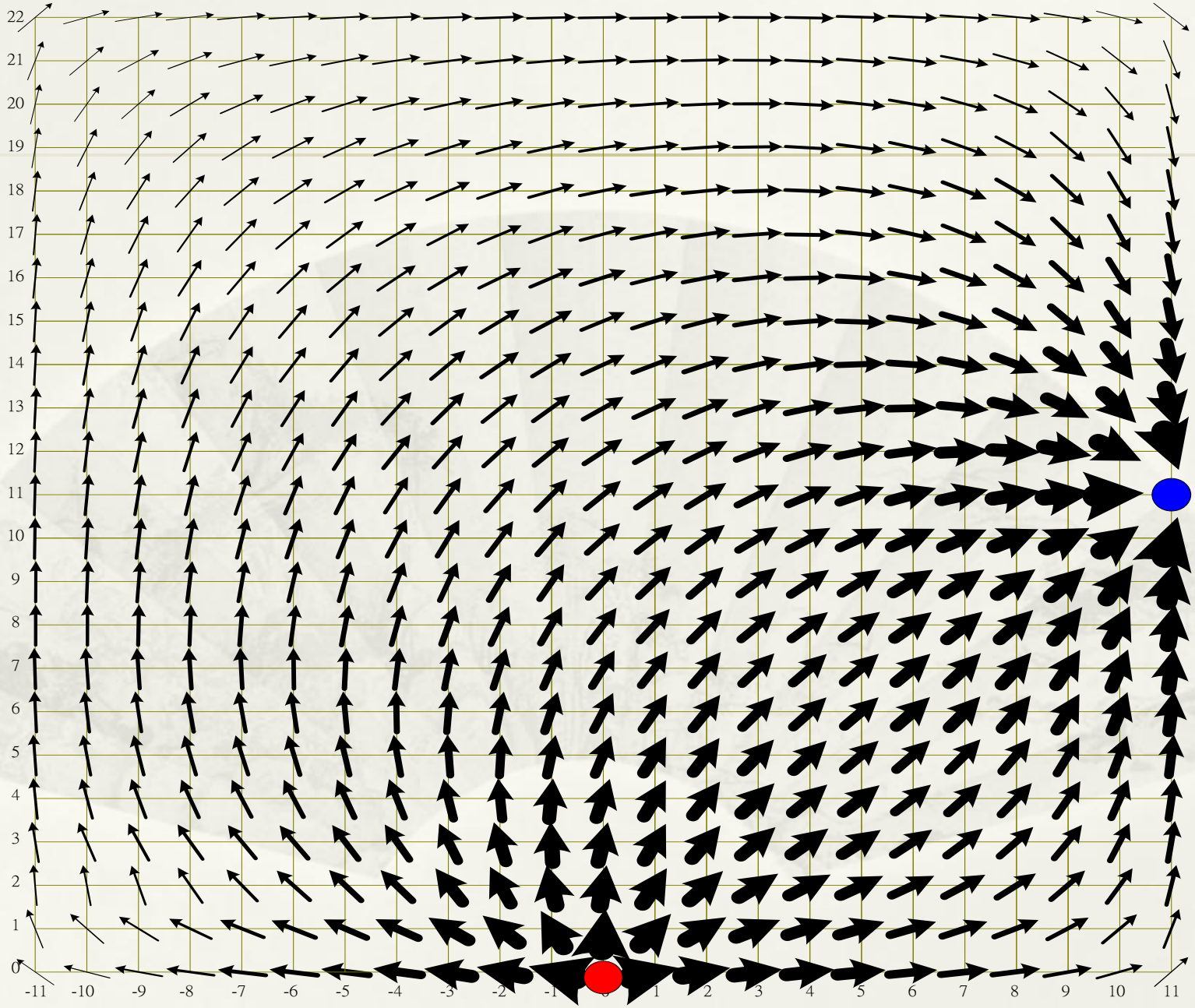
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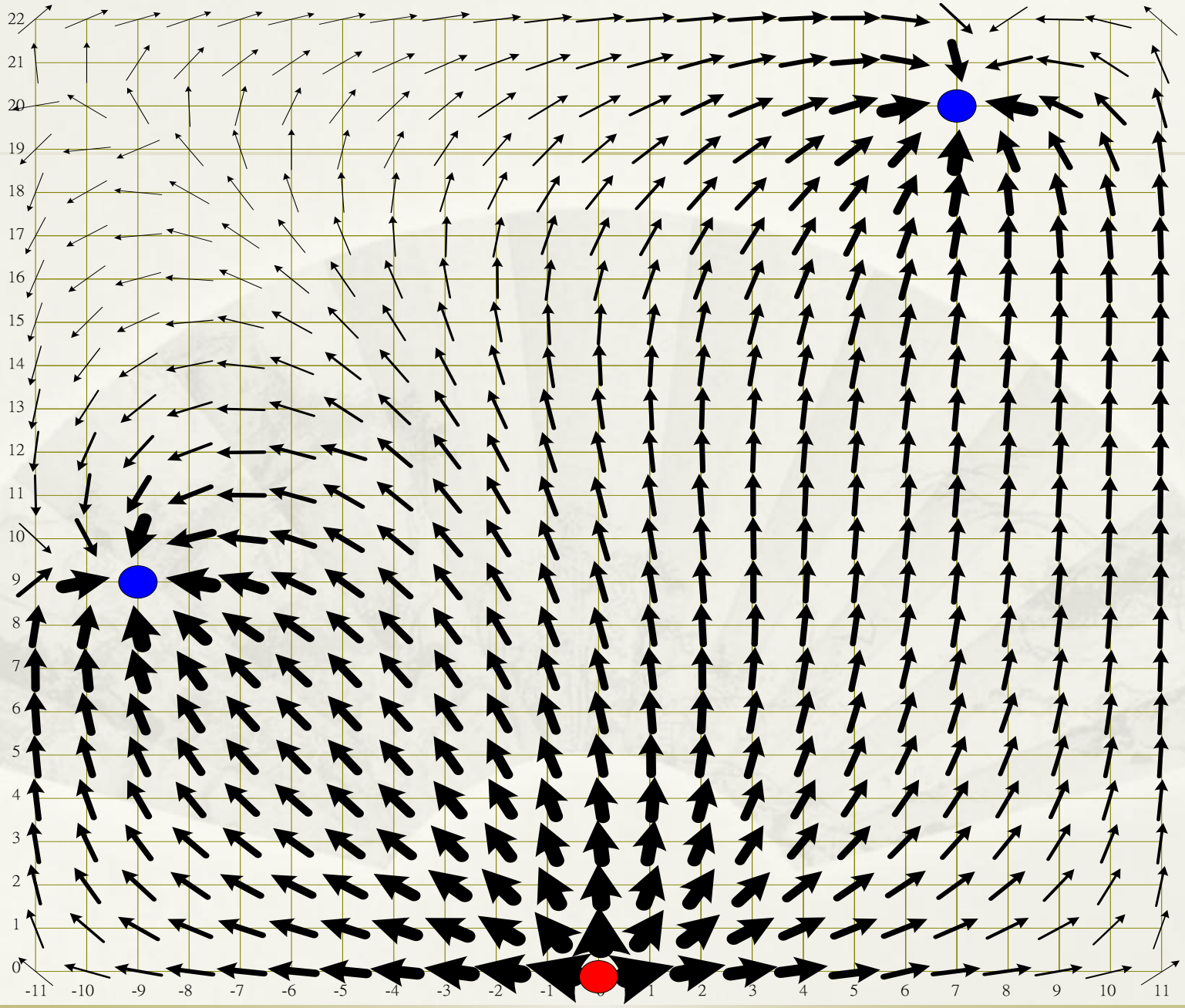
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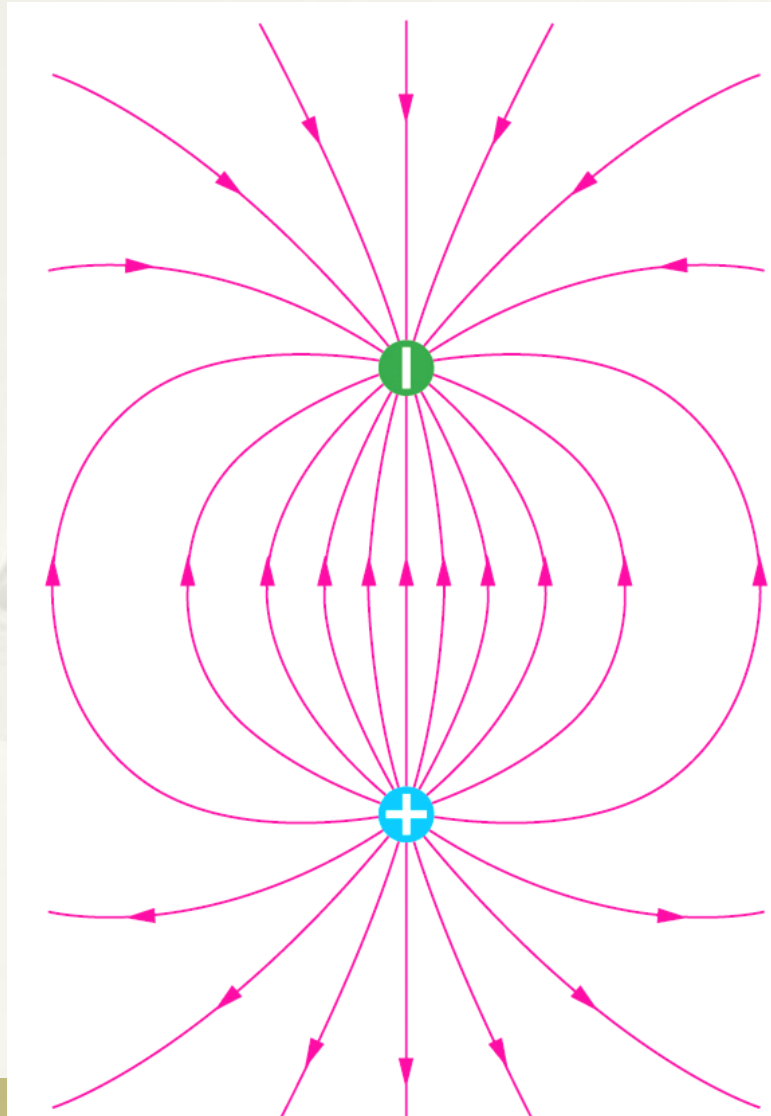
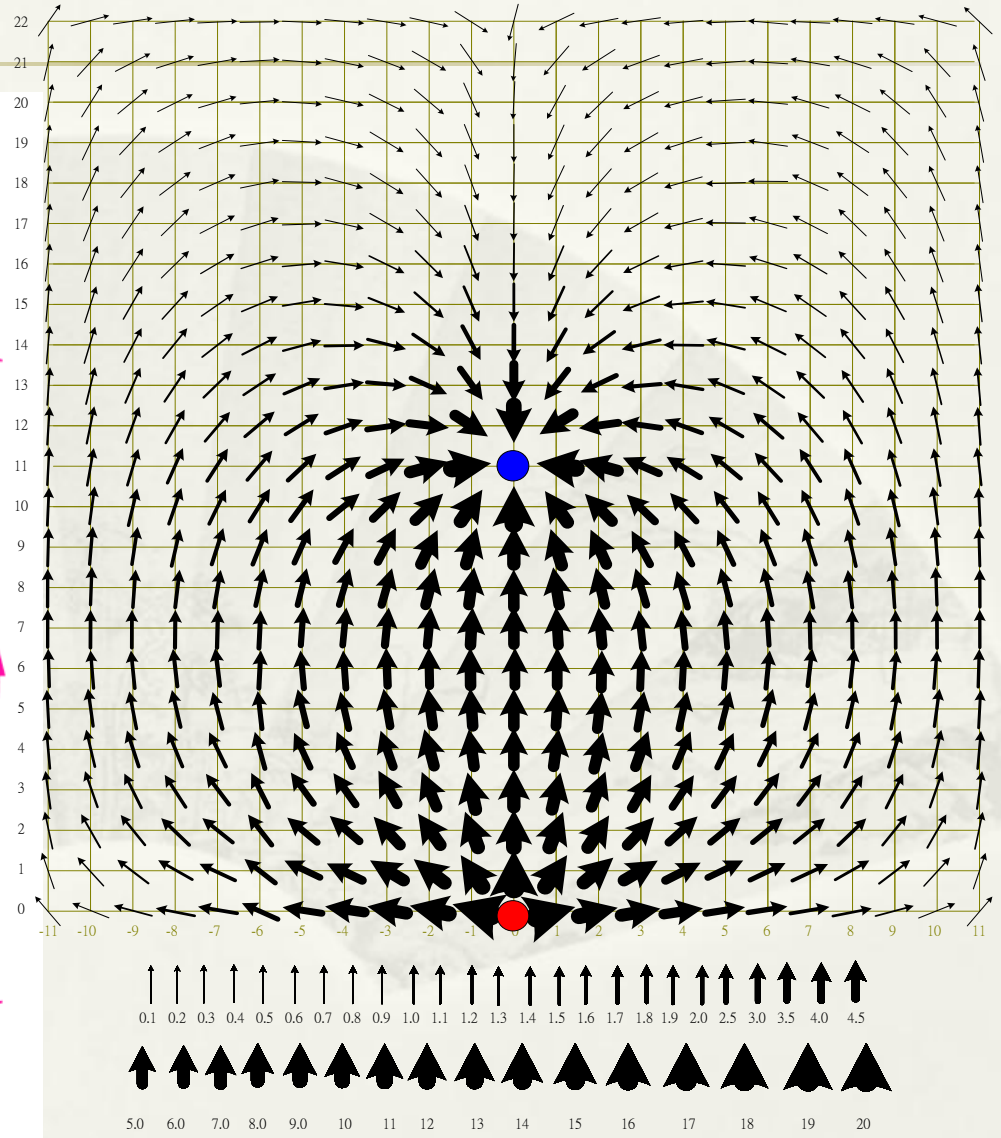
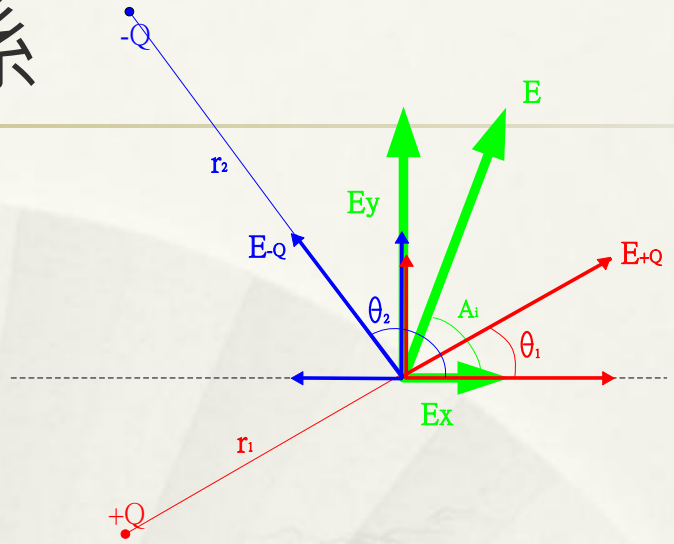
正、負兩點電荷所建立的靜電場





以距離平方反比關係分析



$E = Ex + Ey$

其中$Ex = E_{+Q}\cos\theta_1 + E_{-Q}\cos\theta_2$

$Ey = E_{+Q}\sin\theta_1 + E_{-Q}\sin\theta_2$

設+Q點電荷在空間中建立的電場爲$E_{+Q} = +\frac{kQ}{r^2} = +\frac{C}{r^2}$ (C爲一常數)

-Q點電荷在空間中建立的電場爲$E_{-Q} = -\frac{kQ}{r^2} = -\frac{C}{r^2}$

而電場E與X軸之水平夾角$A_i = \tan^{-1}\frac{Ey}{Ex}$

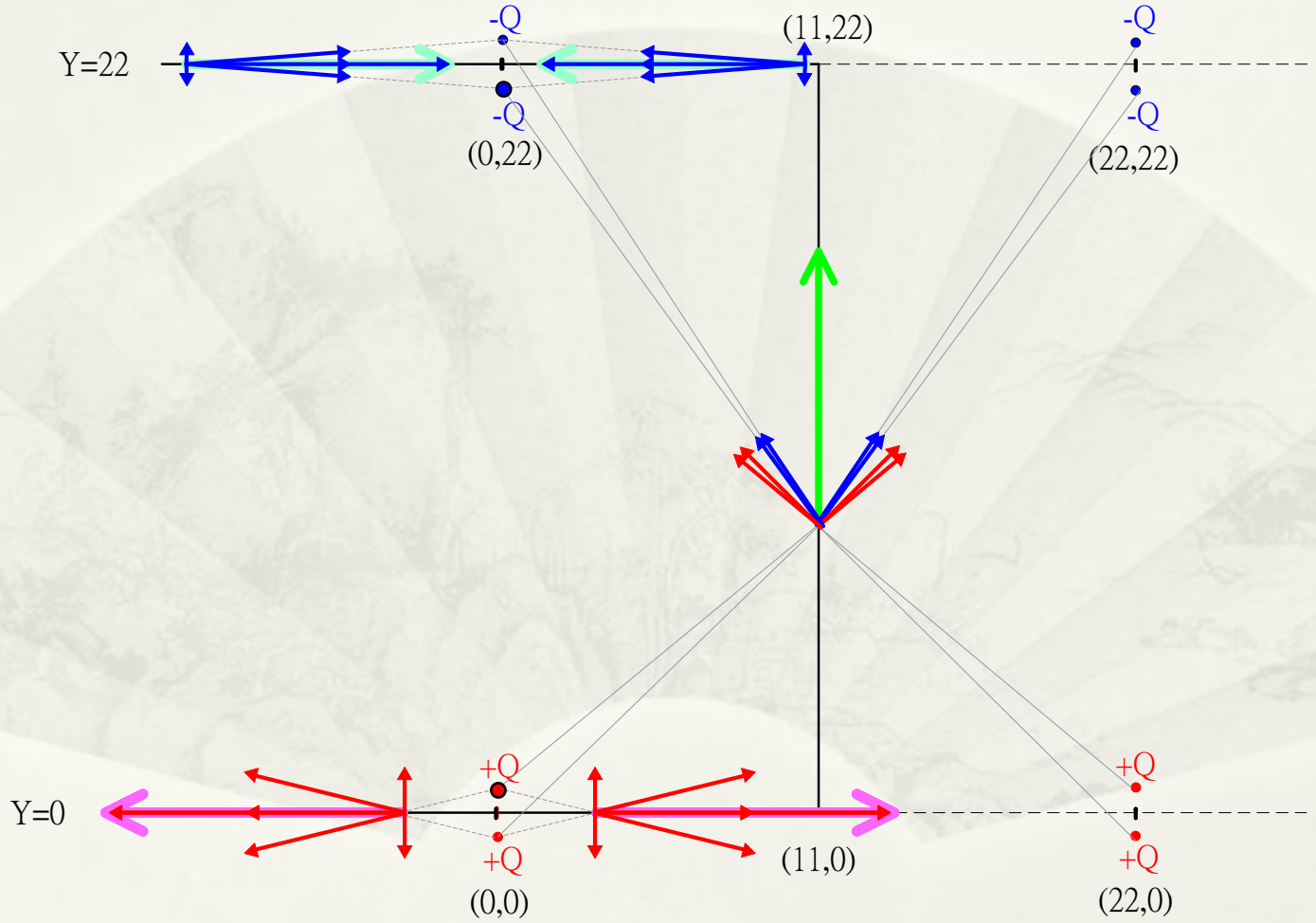
電場方向理論值與電流場方向比對

Xi	Yi	電場 Ei	夾角 Ai	電流 向量和	夾角 (度)	電流 電場	角度差	
-11	0	1.23	168.9	0.32	136.3	0.26	-32.6	***
-11	1	1.23	162.5	0.67	107.4	0.54	-55.1	****
-11	2	1.22	155.9	1.06	100.4	0.87	-55.5	****
-11	3	1.19	149.1	1.42	97.3	1.19	-51.8	****
-11	4	1.15	142.2	1.73	95.3	1.50	-46.9	****
-11	5	1.11	135.2	1.98	94.0	1.79	-41.1	****
-11	6	1.06	128.0	2.20	92.9	2.07	-35.1	***
-11	7	1.02	120.7	2.37	91.9	2.32	-28.7	**
-11	8	0.99	113.2	2.49	91.6	2.53	-21.6	**
-11	9	0.96	105.5	2.57	91.1	2.68	-14.4	*
-11	10	0.94	97.8	2.62	90.7	2.79	-7.1	
-11	11	0.94	90.0	2.64	90.3	2.82	0.3	
-11	12	0.94	82.2	2.63	89.8	2.80	7.6	
-11	13	0.96	74.5	2.58	89.6	2.69	15.1	*
-11	14	0.99	66.8	2.49	89.1	2.53	22.3	**
-11	15	1.02	59.3	2.36	88.5	2.31	29.2	**
-11	16	1.06	52.0	2.18	87.4	2.05	35.4	***
-11	17	1.11	44.8	1.96	86.8	1.77	42.0	****
-11	18	1.15	37.8	1.72	85.0	1.49	47.2	****
-11	19	1.19	30.9	1.42	83.5	1.19	52.6	****
-11	20	1.22	24.1	1.07	79.7	0.88	55.6	****
-11	21	1.23	17.5	0.68	72.1	0.55	54.6	****
-11	22	1.23	11.1	0.31	45.0	0.25	33.9	***
-10	0	1.51	170.5	0.71	162.1	0.47	-8.4	
-10	1	1.51	163.7	0.91	132.3	0.60	-31.4	***
-10	2	1.49	156.7	1.23	118.0	0.83	-38.7	***
-10	3	1.44	149.6	1.55	109.6	1.07	-40.0	****
-10	4	1.38	142.5	1.84	104.5	1.33	-38.0	***
-10	5	1.32	135.3	2.08	100.5	1.58	-34.8	***
-10	6	1.25	128.0	2.29	97.5	1.83	-30.5	***
-10	7	1.19	120.6	2.44	95.4	2.05	-25.2	**
-10	8	1.14	113.1	2.56	94.7	2.24	-18.4	*
-10	9	1.10	105.5	2.63	92.8	2.39	-12.7	*
-10	10	1.08	97.8	2.68	91.5	2.48	-6.3	
-10	11	1.07	90.0	2.69	90.5	2.51	0.5	
-10	12	1.08	82.2	2.67	89.4	2.47	7.1	
-10	13	1.10	74.5	2.62	88.3	2.38	13.7	*
-10	14	1.14	66.9	2.53	87.1	2.22	20.2	**
-10	15	1.19	59.4	2.41	85.2	2.02	25.8	**
-10	16	1.25	52.0	2.25	82.6	1.80	30.6	***
-10	17	1.32	44.7	2.05	80.4	1.55	35.7	***
-10	18	1.38	37.5	1.81	76.0	1.31	38.5	***
-10	19	1.44	30.4	1.53	71.3	1.06	41.0	****
-10	20	1.49	23.3	1.23	62.0	0.83	38.7	***
-10	21	1.51	16.3	0.93	47.2	0.61	30.9	***
-10	22	1.51	9.5	0.70	19.2	0.46	9.7	

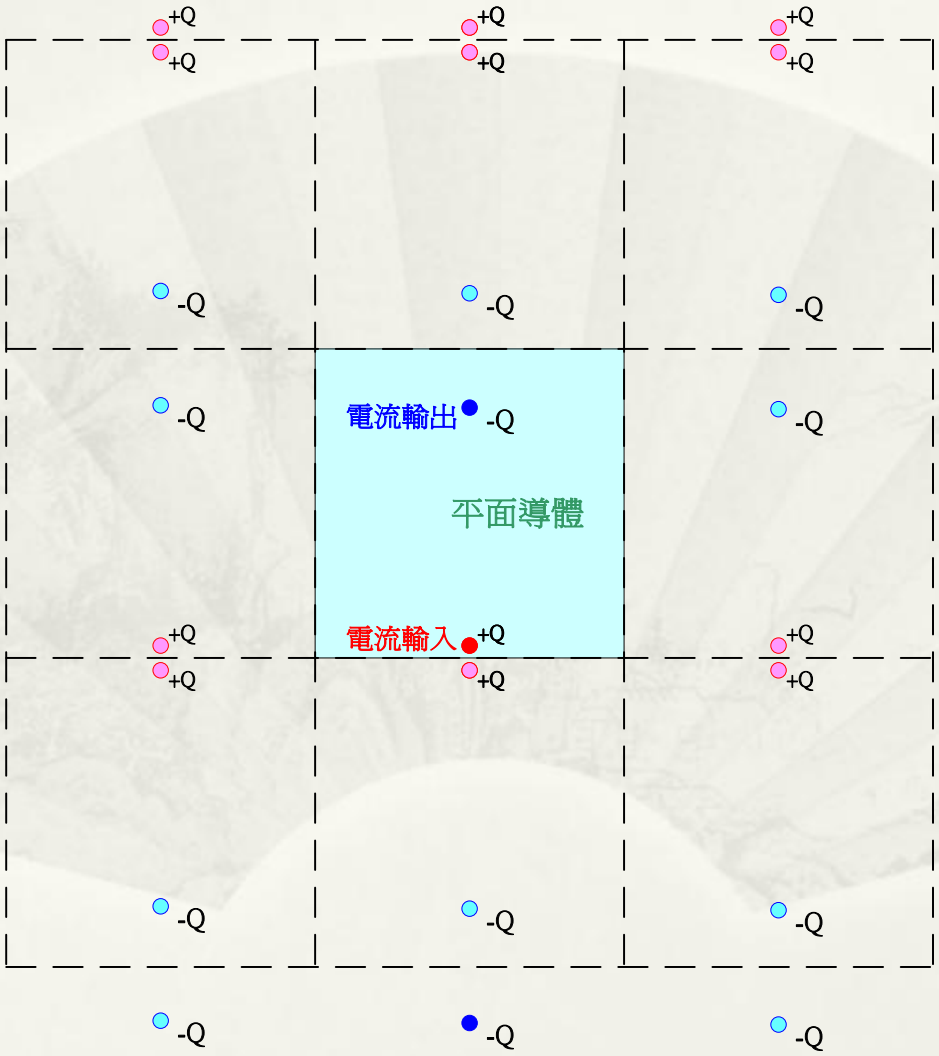
Xi	Yi	電場 Ei	夾角 Ai	電流 向量和	夾角 (度)	電流 電場	角度差	
-9	0	0.13	172.0	1.20	167.5	9.50	-4.5	
-9	1	0.13	164.7	1.30	144.4	10.35	-20.3	**
-9	2	0.12	157.3	1.59	129.1	12.86	-28.2	**
-9	3	0.12	149.9	1.86	117.9	15.67	-31.9	***
-9	4	0.11	142.4	2.12	111.0	18.89	-31.4	***
-9	5	0.11	135.0	2.35	104.8	22.24	-30.2	***
-9	6	0.10	127.7	2.53	100.7	25.58	-27.0	**
-9	7	0.09	120.3	2.67	97.7	28.69	-22.5	**
-9	8	0.09	112.8	2.79	96.2	31.51	-16.6	*
-9	9	0.08	105.3	2.82	93.9	33.18	-11.4	*
-9	10	0.08	97.7	2.86	91.8	34.59	-5.8	
-9	11	0.08	90.0	2.92	90.3	35.61	0.3	
-9	12	0.08	82.3	2.90	88.6	35.07	6.3	
-9	13	0.08	74.7	2.85	87.0	33.62	12.2	*
-9	14	0.09	67.2	2.78	85.3	31.43	18.1	*
-9	15	0.09	59.7	2.66	82.2	28.58	22.5	**
-9	16	0.10	52.3	2.52	79.0	25.40	26.7	**
-9	17	0.11	45.0	2.33	75.3	22.03	30.4	***
-9	18	0.11	37.6	2.10	69.4	18.75	31.9	***
-9	19	0.12	30.1	1.85	62.6	15.60	32.5	***
-9	20	0.12	22.7	1.59	50.9	12.86	28.2	**
-9	21	0.13	15.3	1.32	35.1	10.47	19.8	*
-9	22	0.13	8.0	1.17	12.8	9.27	4.9	
-8	0	0.16	173.5	1.76	170.5	10.92	-2.9	
-8	1	0.16	165.5	1.79	151.6	11.10	-14.0	*
-8	2	0.16	157.5	2.00	137.0	12.80	-20.5	**
-8	3	0.15	149.6	2.18	124.9	14.78	-24.7	**
-8	4	0.14	141.9	2.39	116.6	17.36	-25.3	**
-8	5	0.13	134.3	2.56	109.1	20.10	-25.2	**
-8	6	0.12	126.9	2.71	103.9	23.02	-23.0	**
-8	7	0.11	119.5	2.82	99.8	25.83	-19.7	*
-8	8	0.10	112.2	2.91	96.9	28.42	-15.3	*
-8	9	0.10	104.8	2.97	94.8	30.46	-10.0	*
-8	10	0.09	97.4	3.00	92.1	31.75	-5.3	
-8	11	0.09	90.0	3.02	90.2	32.28	0.2	
-8	12	0.09	82.6	3.01	87.9	31.86	5.3	
-8	13	0.10	75.2	2.98	86.0	30.53	10.8	*
-8	14	0.10	67.8	2.91	83.5	28.40	15.7	*
-8	15	0.11	60.5	2.81	79.8	25.77	19.3	*
-8	16	0.12	53.1	2.69	75.6	22.90	22.5	**
-8	17	0.13	45.7	2.54	70.9	19.93	25.3	**
-8	18	0.14	38.1	2.39	63.6	17.33	25.6	**
-8	19	0.15	30.4	2.18	55.7	14.76	25.3	**
-8	20	0.16	22.5	2.00	43.0	12.80	20.5	**
-8	21	0.16	14.5	1.79	28.3	11.15	13.8	*
-8	22	0.16	6.5	1.71	9.7	10.61	3.2	

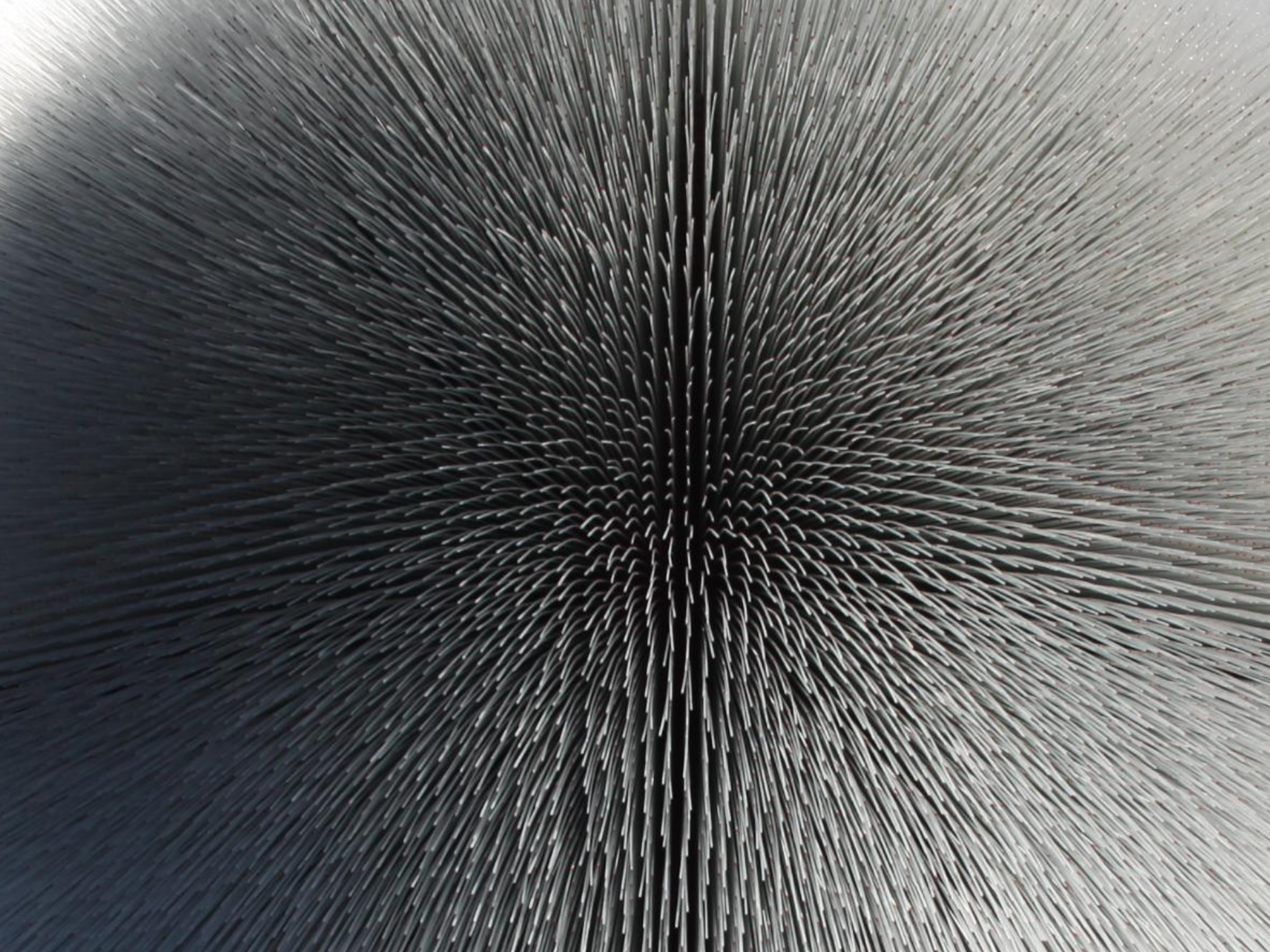
誤差很大，尤其邊界附近角度差很大

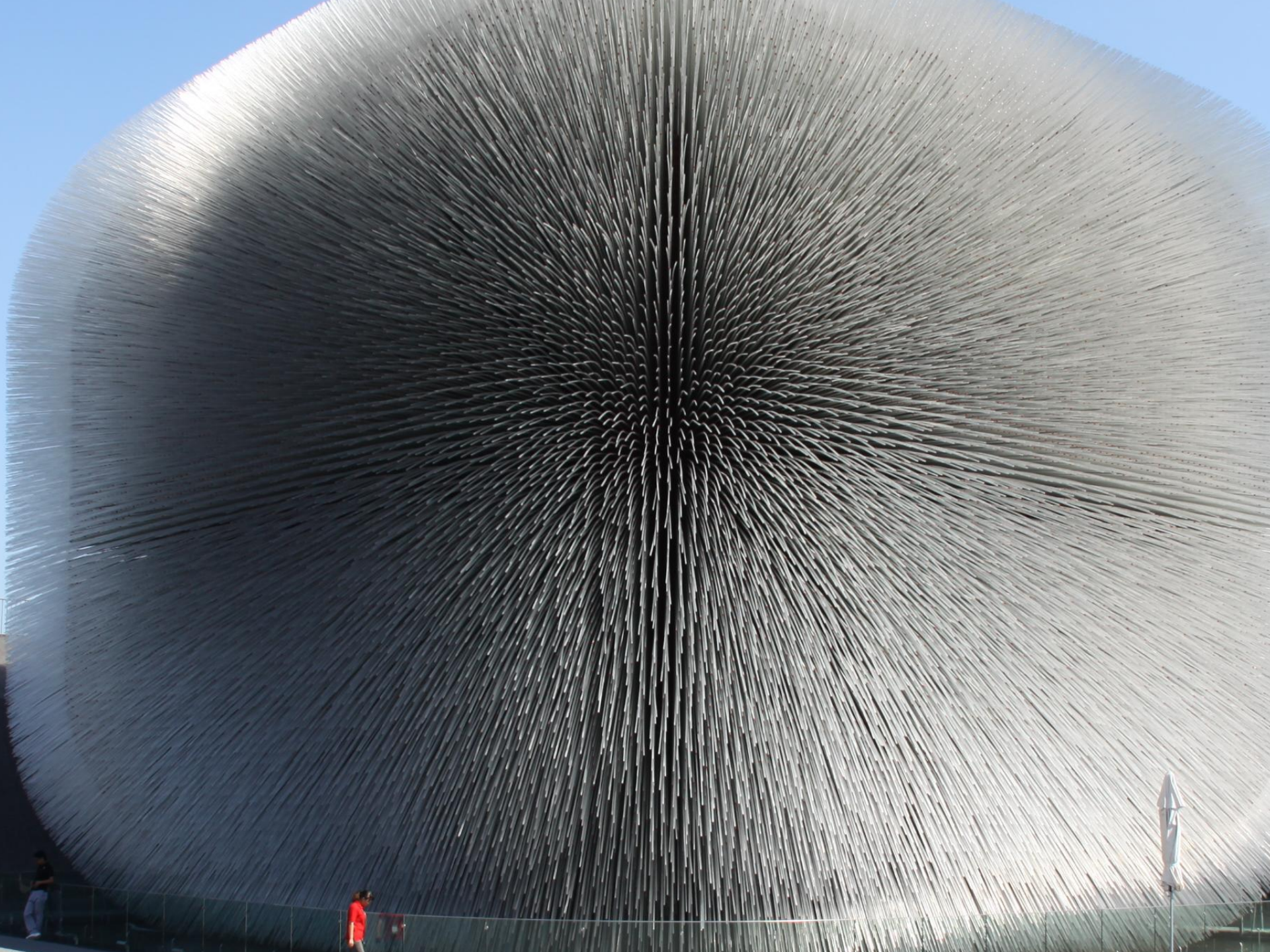
利用類似『鏡面』效果來滿足邊界電流場的方向問題

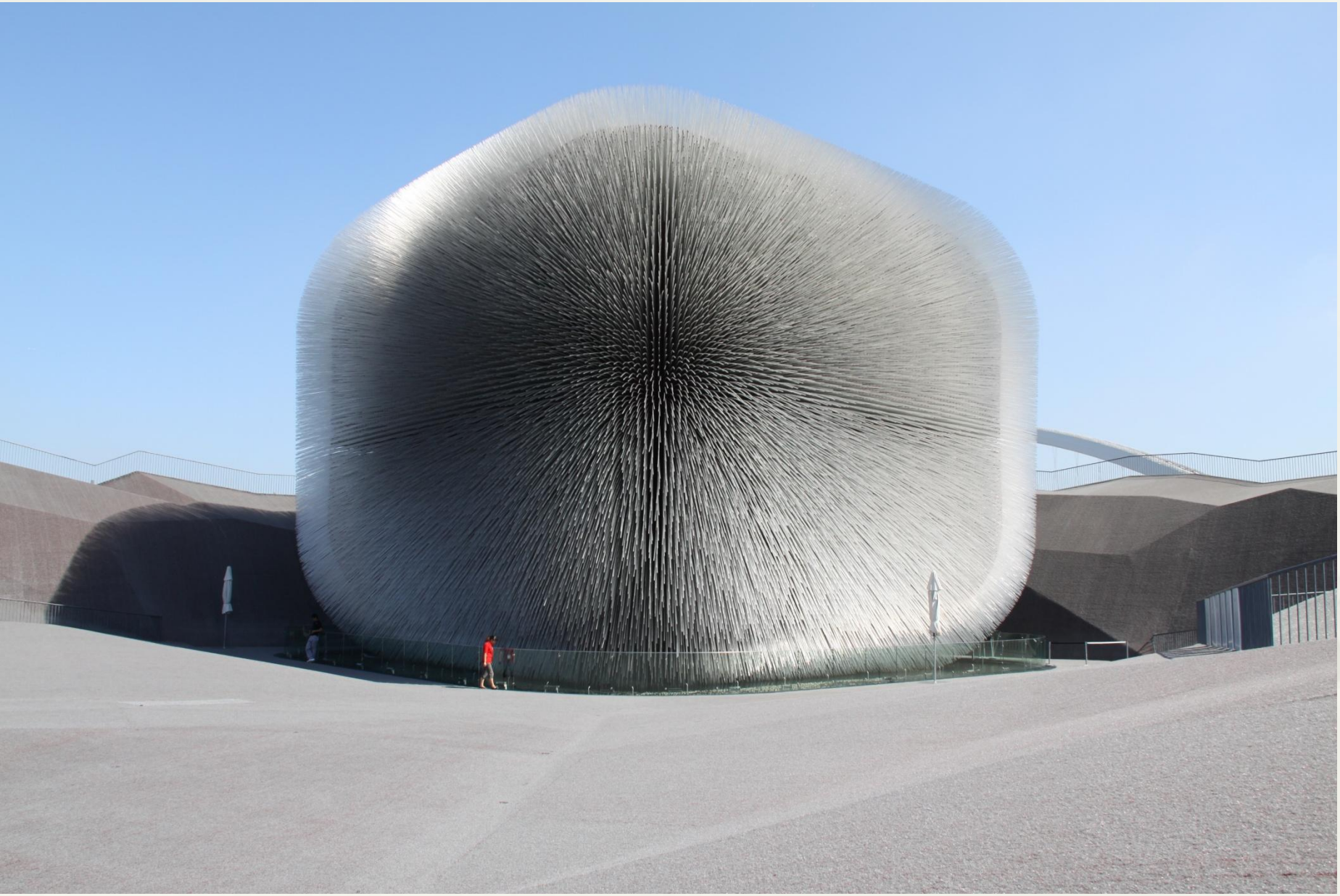


利用類似『鏡面』效果來滿足邊界電流場的方向問題

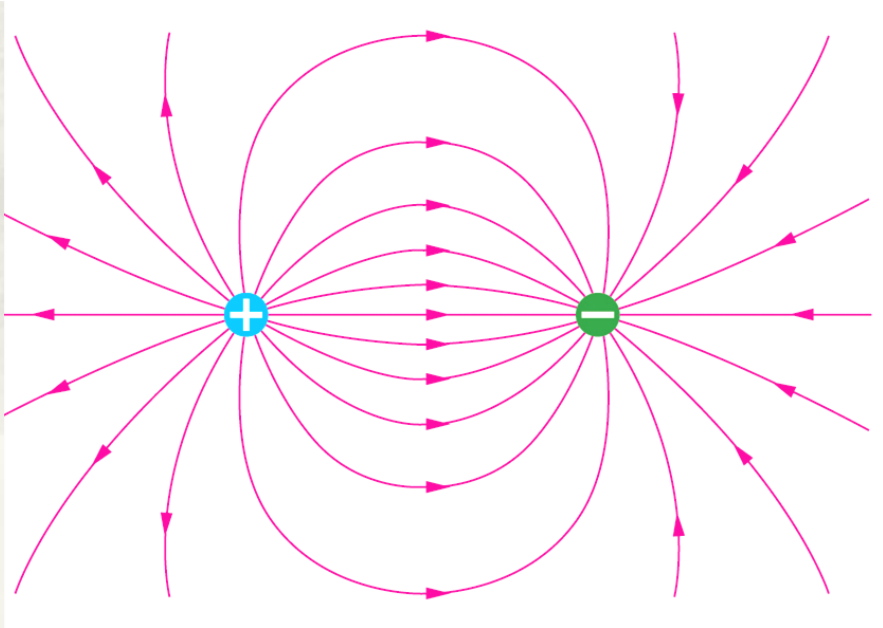






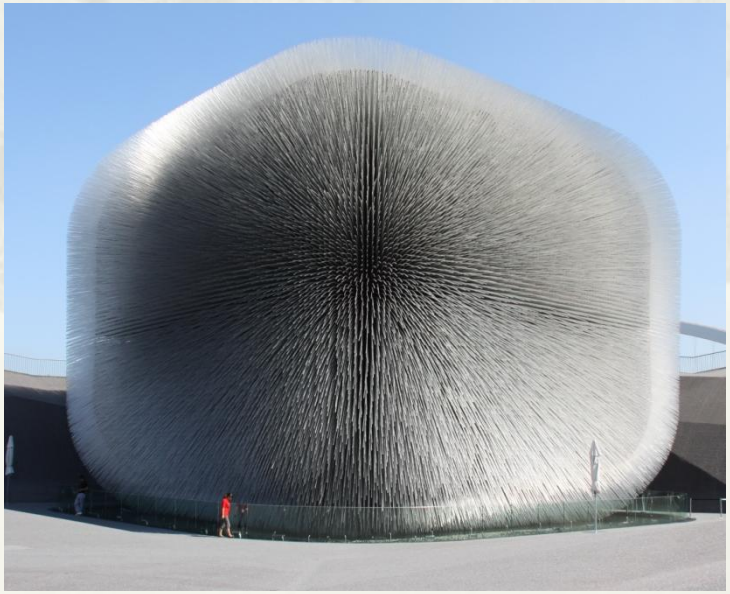


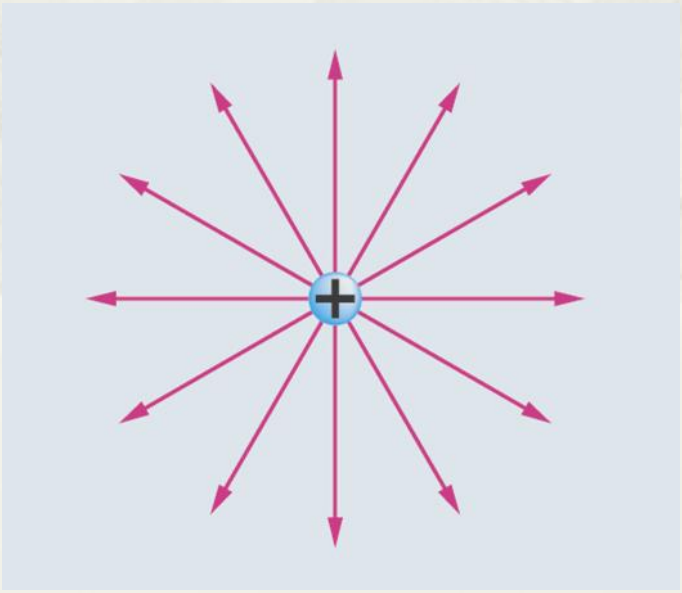
正、負兩點電荷所建立的靜電場



修正平面電場

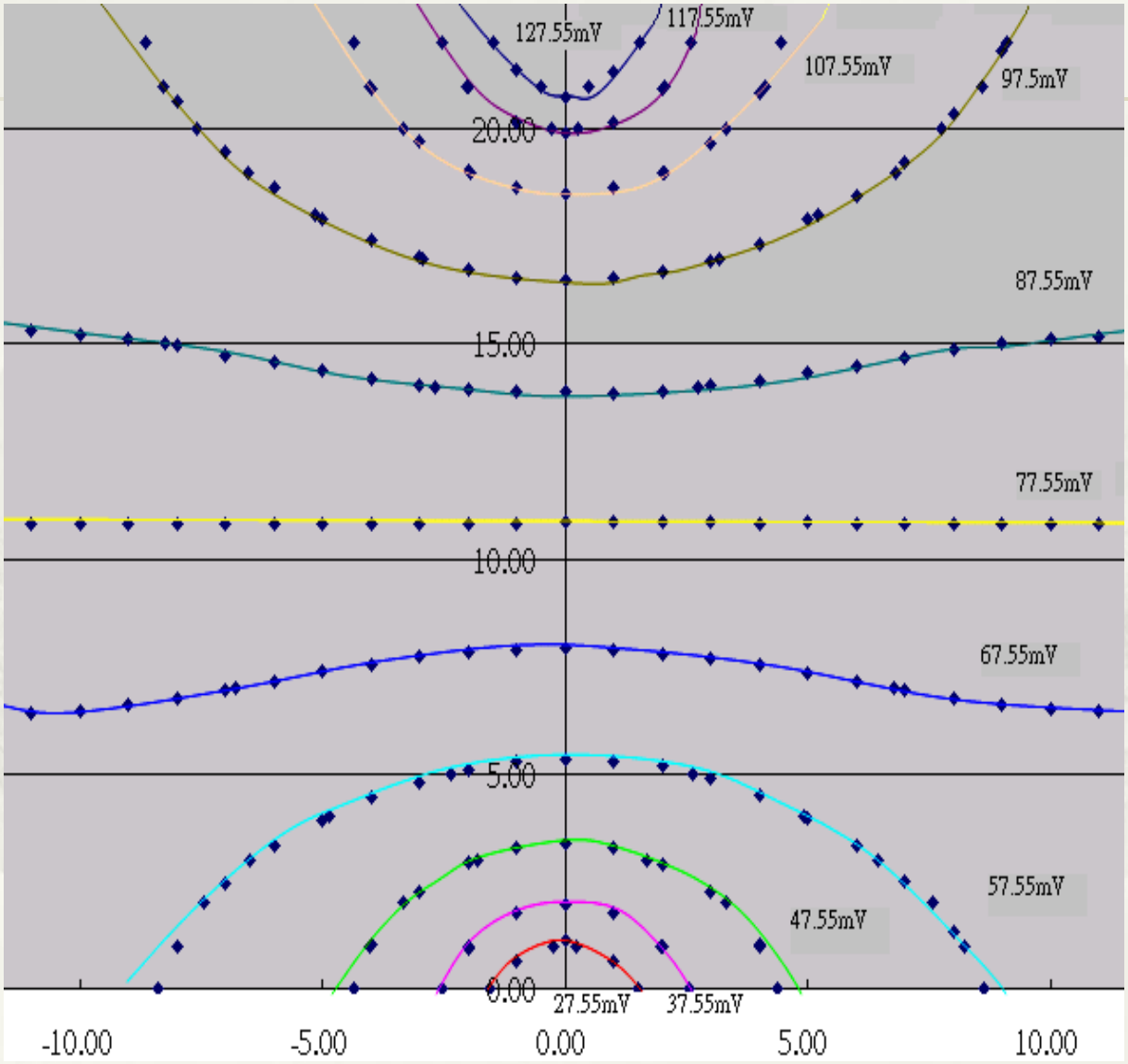
- 將電場修正爲與距離一次方成反比帶入比對。
- 結果，電場方向與電流場方向幾乎一致，且電流強度與電場強度比值幾乎爲一定值。

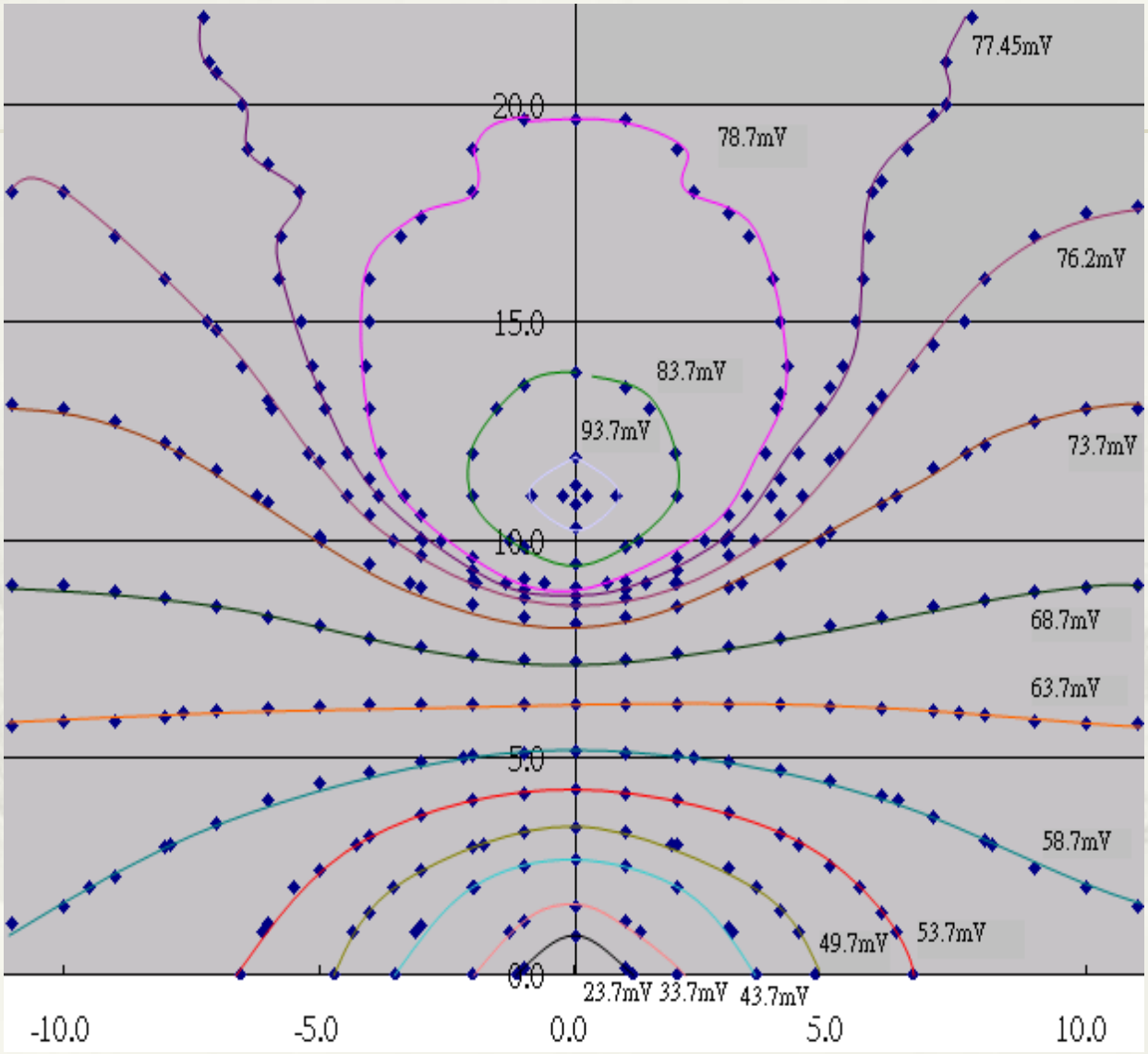




高中物理等電位線實驗

實驗做了嗎？


127.55mV
117.55mV
107.55mV
97.5mV
20.00
87.55mV
15.00
77.55mV
10.00
67.55mV
5.00
57.55mV
47.55mV
0.00
27.55mV
37.55mV
-10.00
-5.00
0.00
5.00
10.00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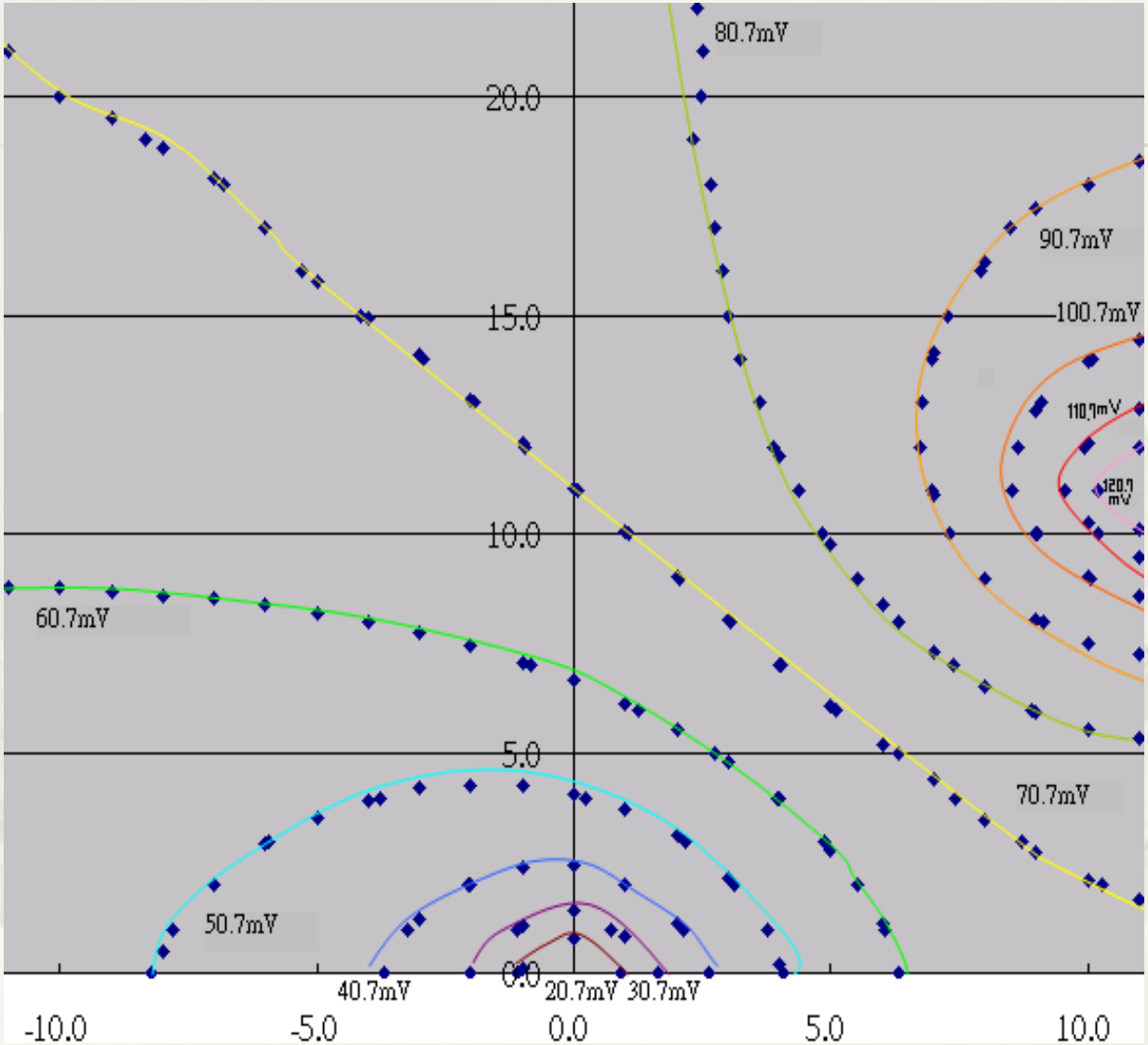
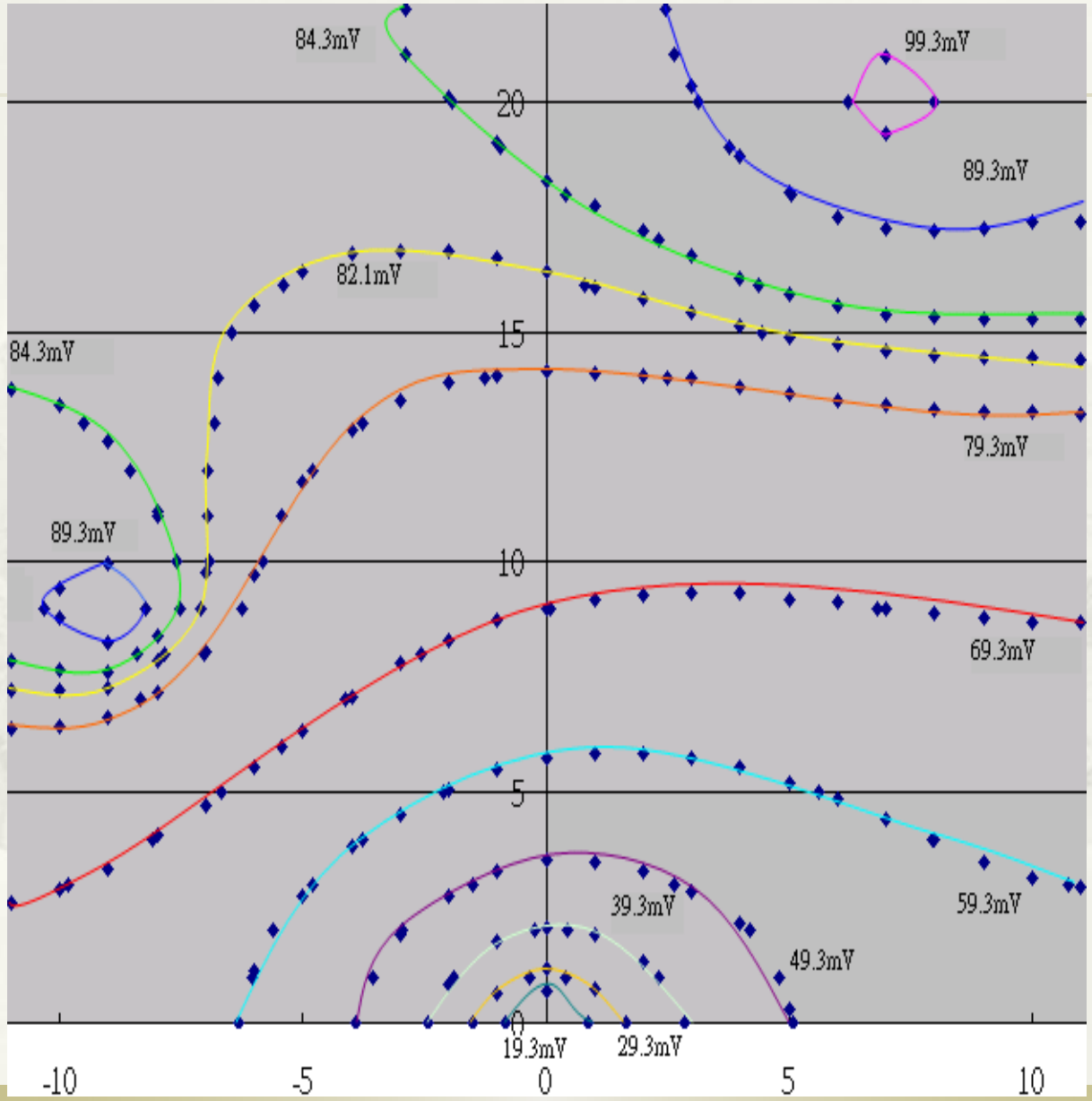
78.7mV
76.2mV
83.7mV
93.7mV
73.7mV
68.7mV
63.7mV
58.7mV
53.7mV
49.7mV
23.7mV
33.7mV
43.7mV
20.0
15.0
10.0
5.0
0.0
-10.0
-5.0
0.0
5.0
10.0


80.7mV
20.0
90.7mV
15.0
100.7mV
10.0
60.7mV
5.0
70.7mV
50.7mV
0.0
40.7mV
20.7mV
30.7mV
-10.0
-5.0
0.0
5.0
10.0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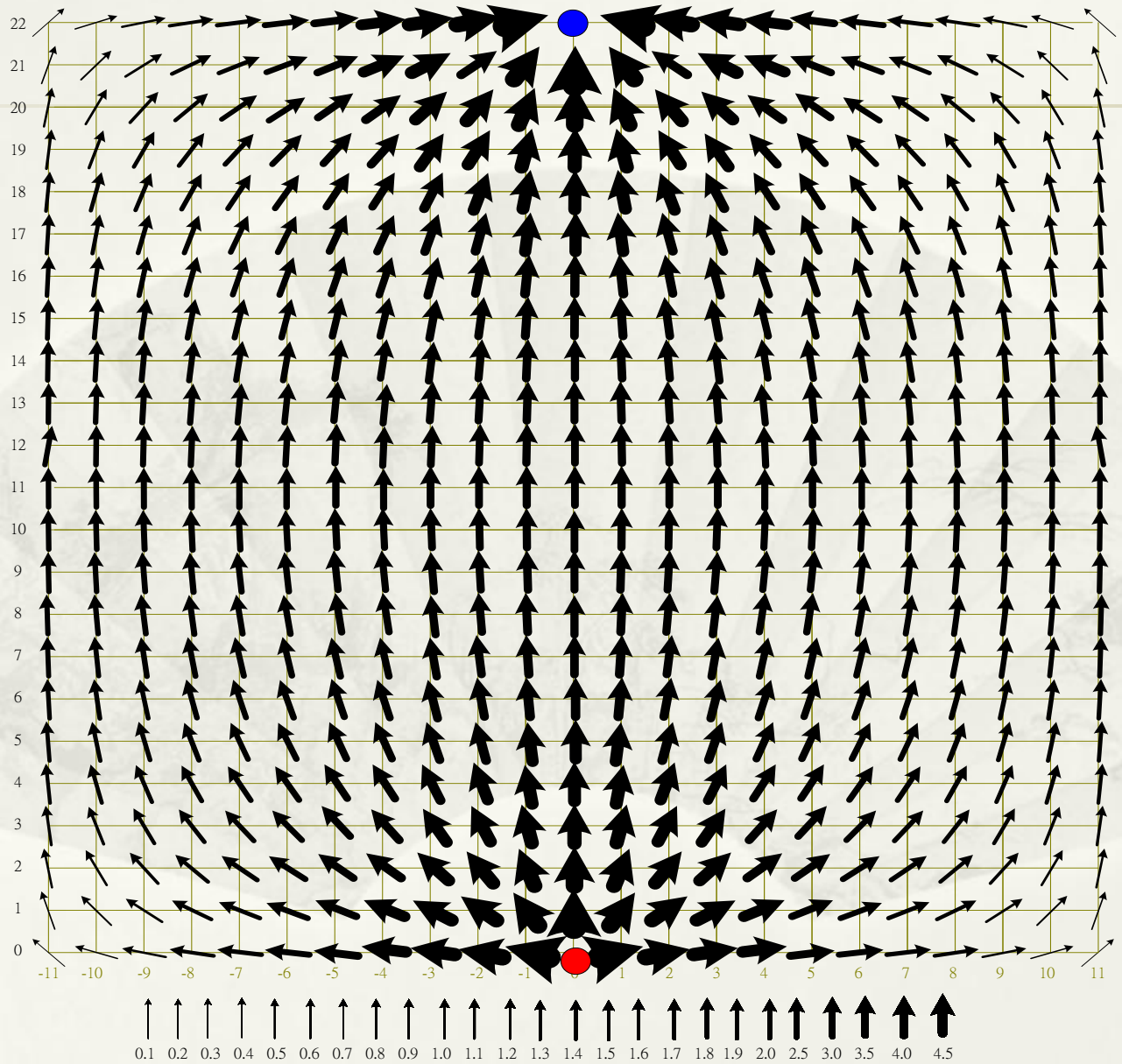
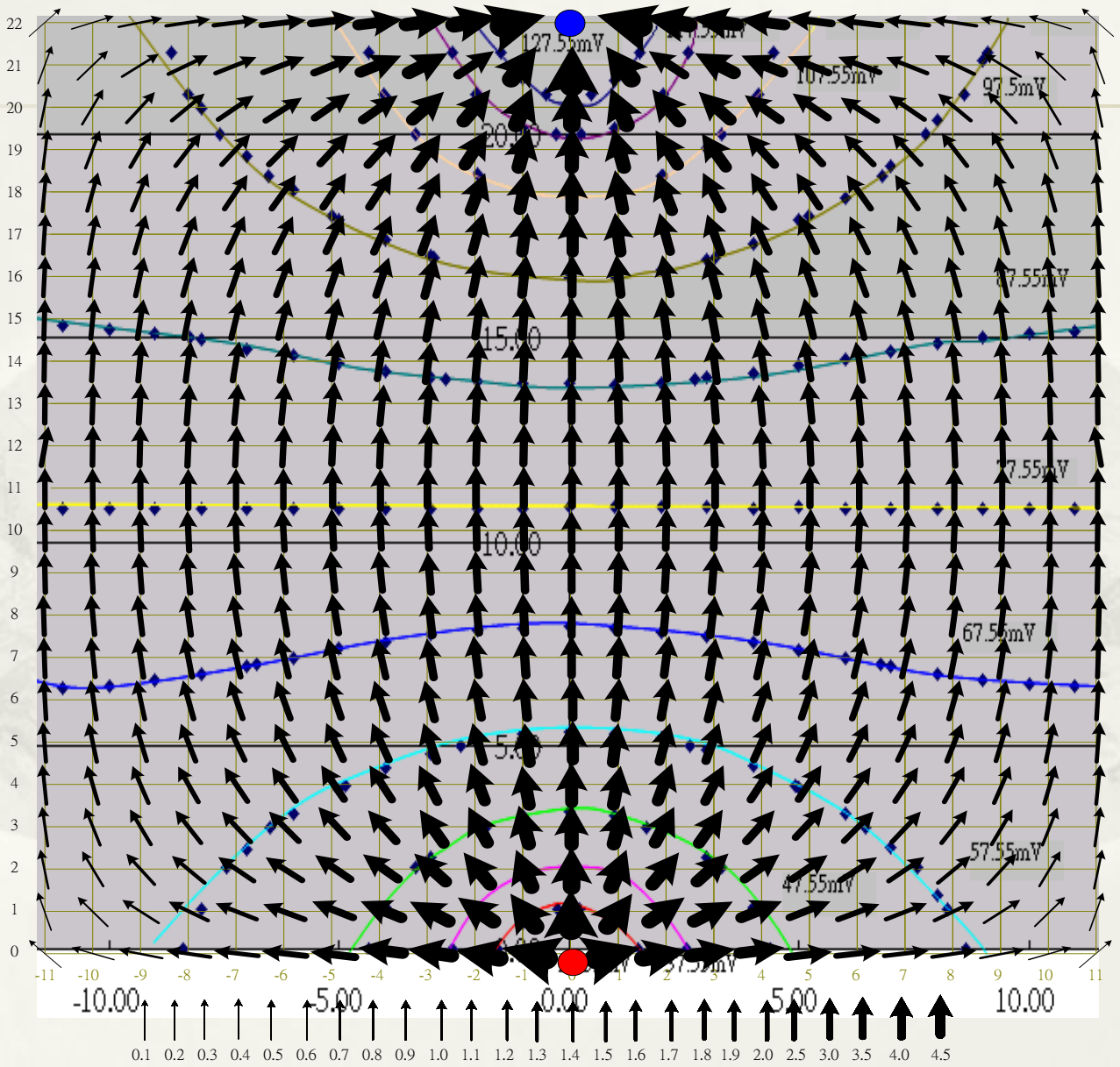
89.3mV
82.1mV
84.3mV
79.3mV
89.3mV
69.3mV
59.3mV
39.3mV
49.3mV
19.3mV
29.3mV
20
15
10
5
0
-10
-5
0
5
10


22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.5 3.0 3.5 4.0 4.5


127.55mV
107.55mV
97.5mV
87.55mV
77.55mV
67.55mV
57.55mV
47.55mV
20.00
15.00
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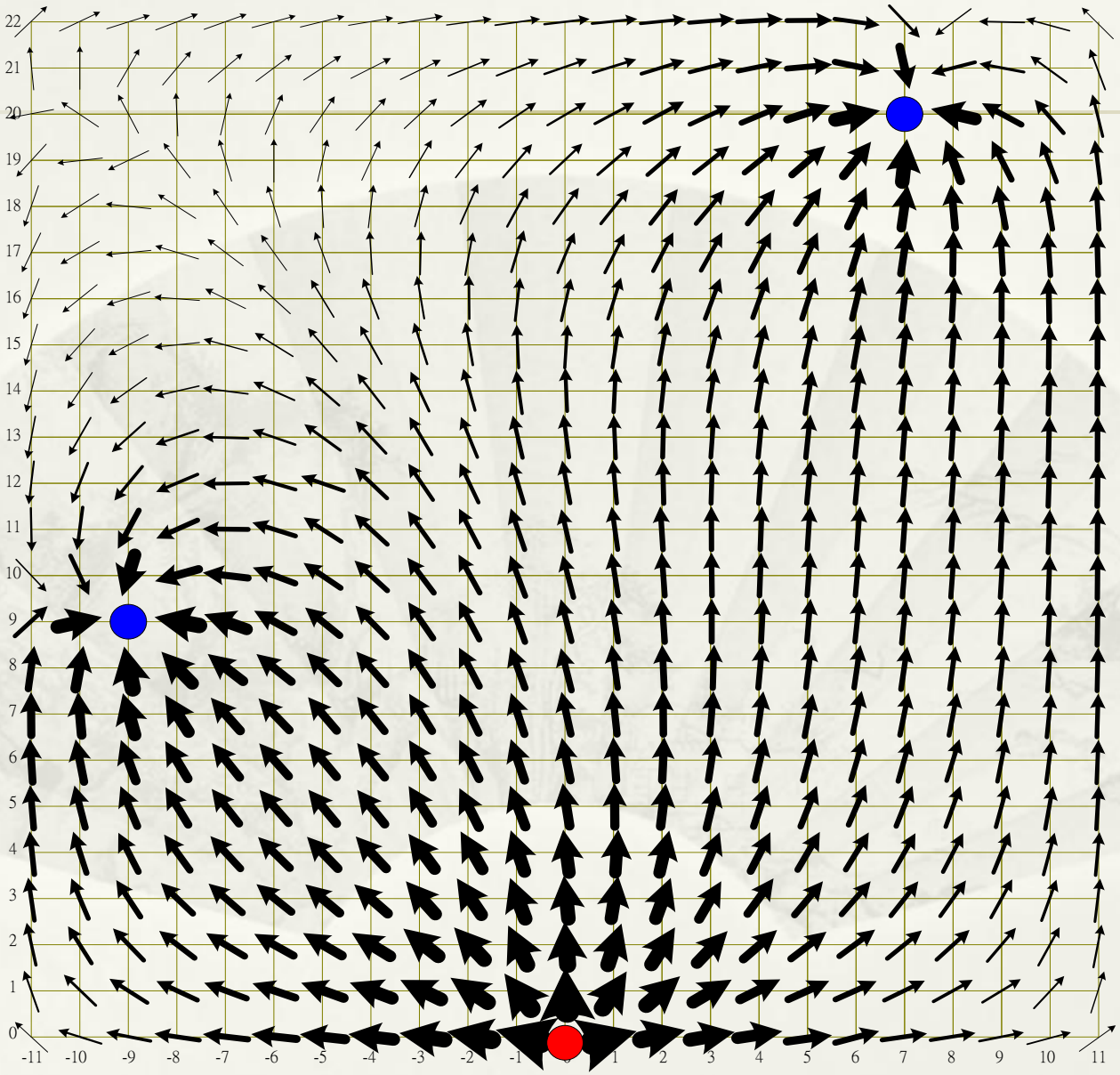
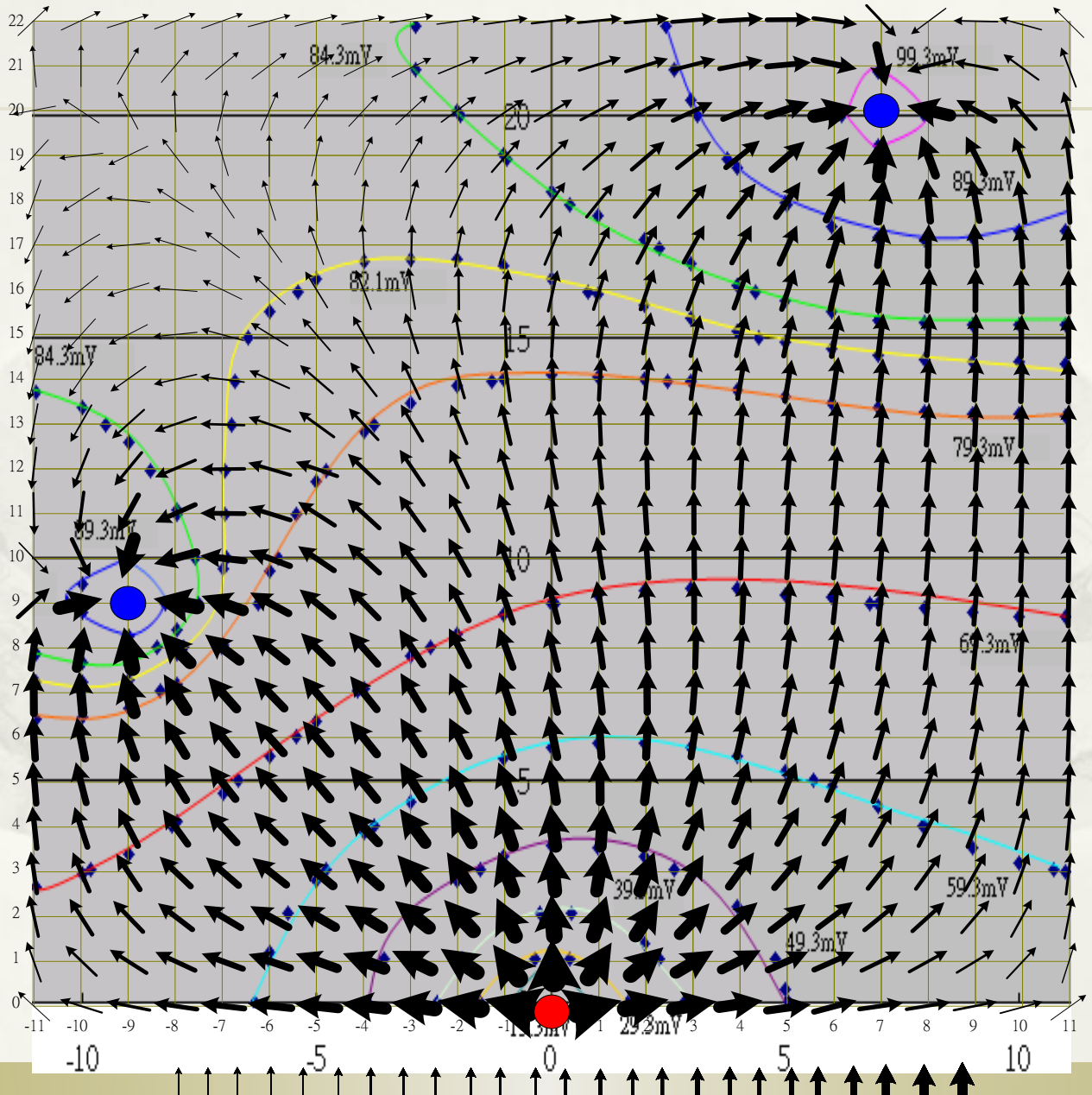
-10.00
-5.00
0.00
5.00
10.00


22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 1 2 3 4 5 6 7 8 9 10 11


84.3mV
99.3mV
89.3mV
82.1mV
84.3mV
79.3mV
89.3mV
69.3mV
59.3mV
49.3mV
20
15
10
5
-10
-5
0
5
10

3-4 爲題組

在「等電位線與電場」實驗中，筱雯使用的電路接法如圖3所示，其中a、b、c爲電極。筱雯以三用電表來測量電位，先將負極探針固定插在a電極上，再以正極探針插入淺水盤中，尋找相同電位差的點，將這些點連成線便可得到一條等電位線，依此方法她繪出數條等電位線，如圖4中之細實線所示。回答3-4題。

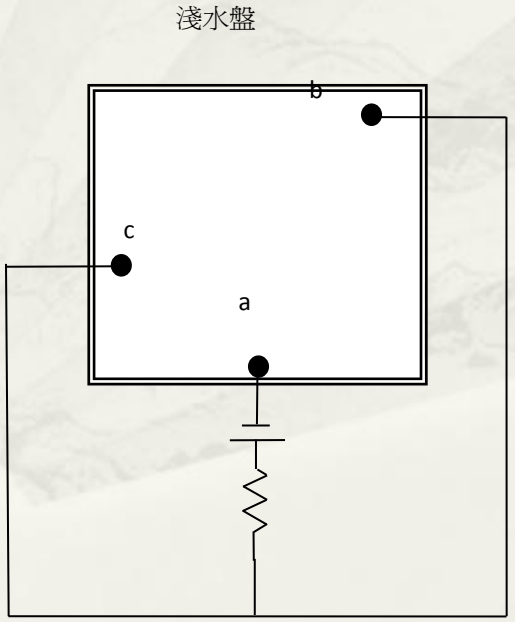


圖3

3. 圖4中，甲~戊五條粗黑實線，哪一條描繪出最接近正確的電力線？(A) 甲　(B) 乙　(C) 丙　(D) 丁　(E) 戊

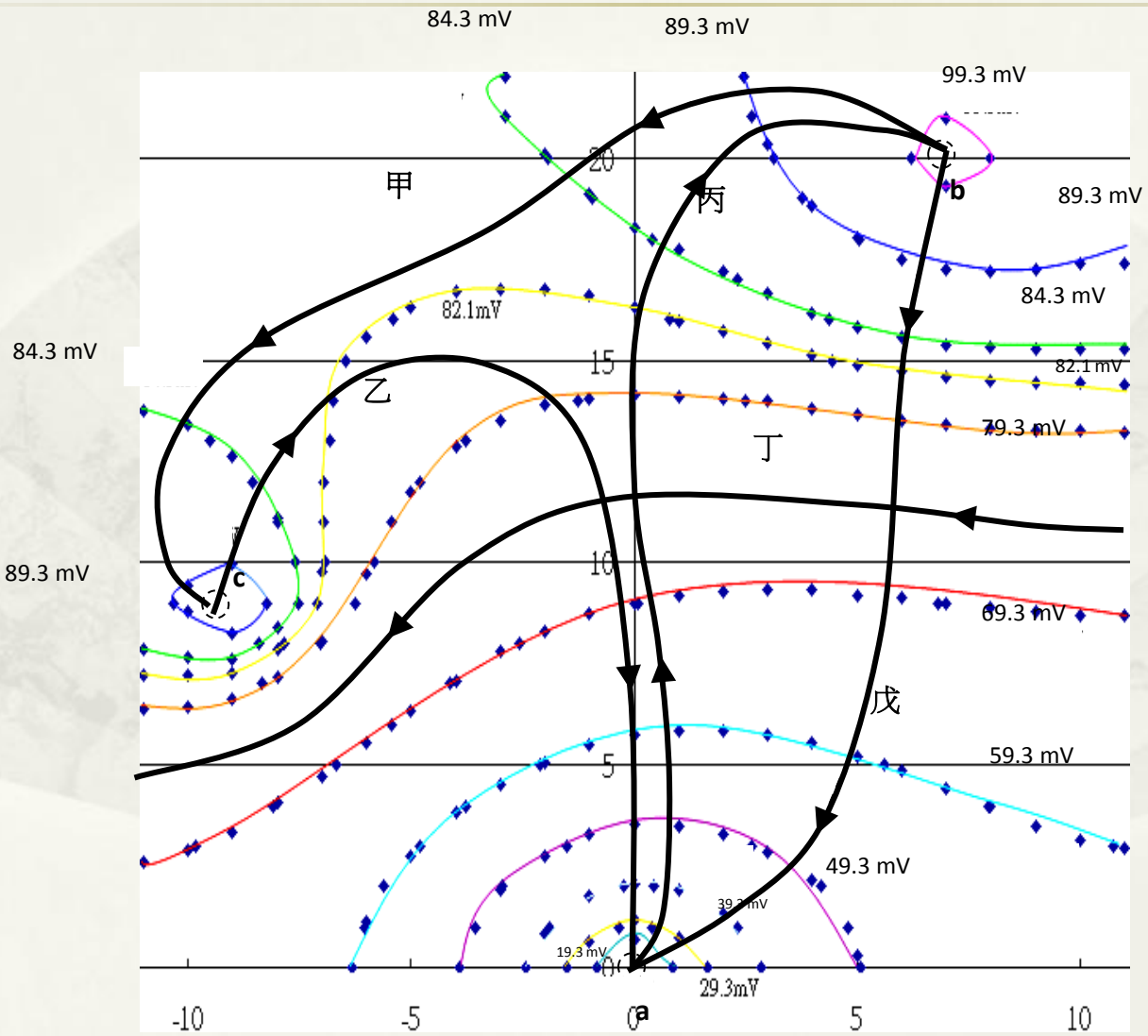
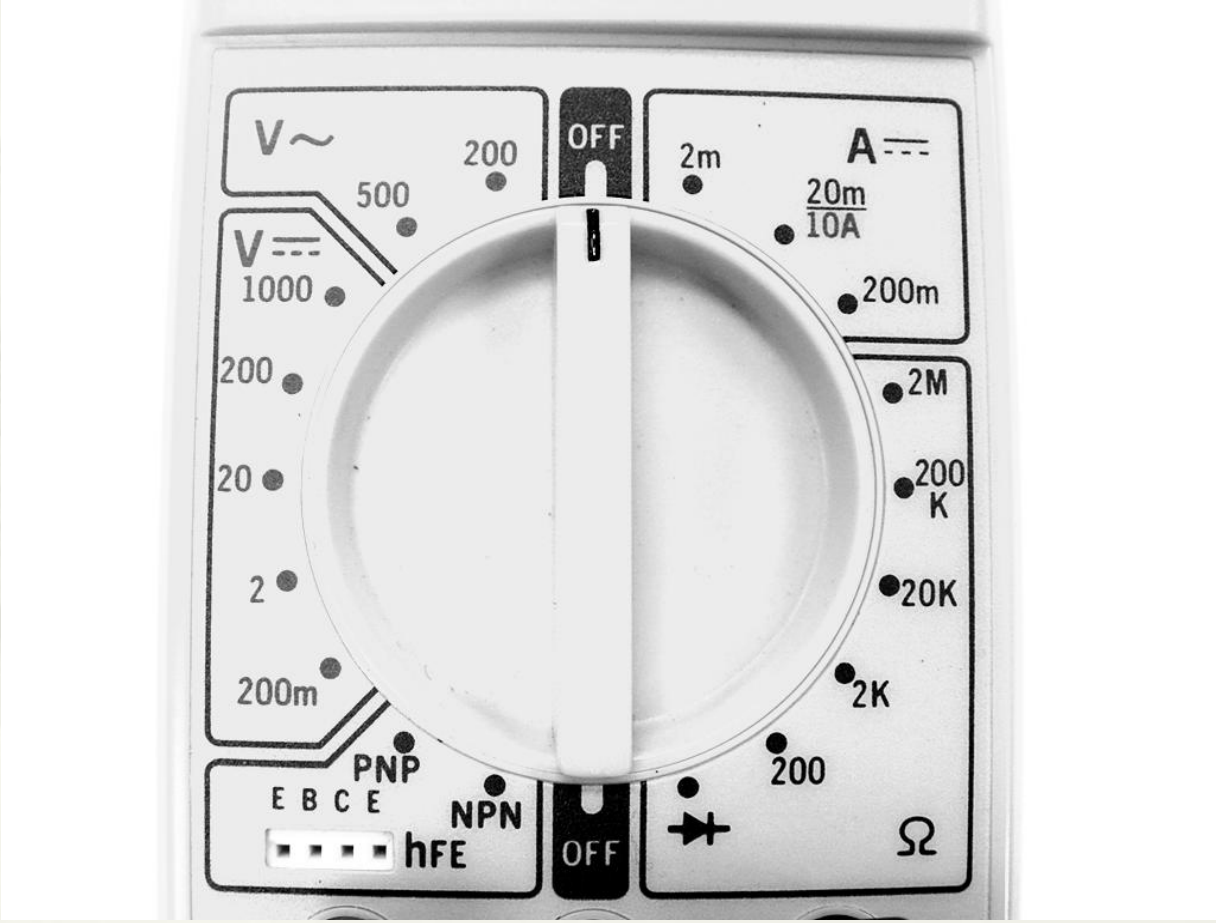
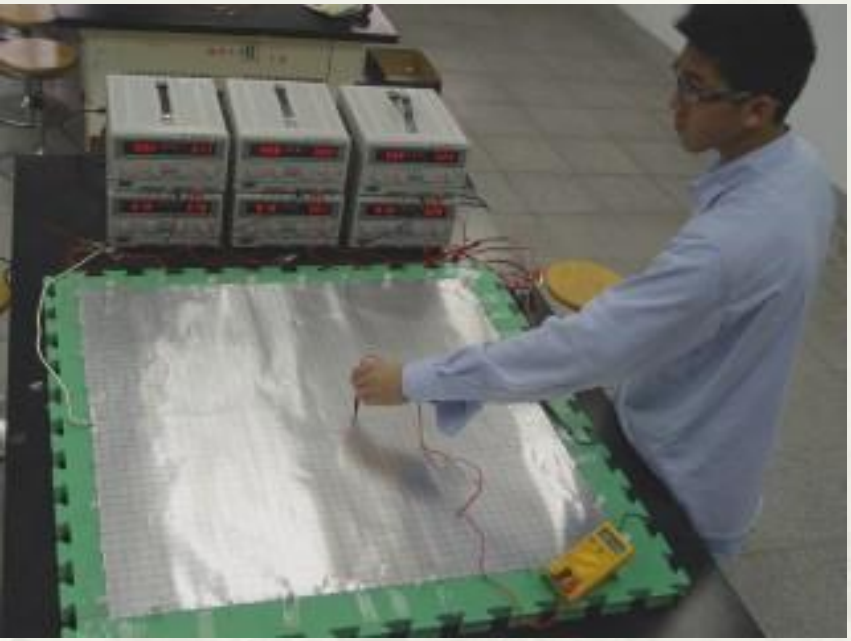


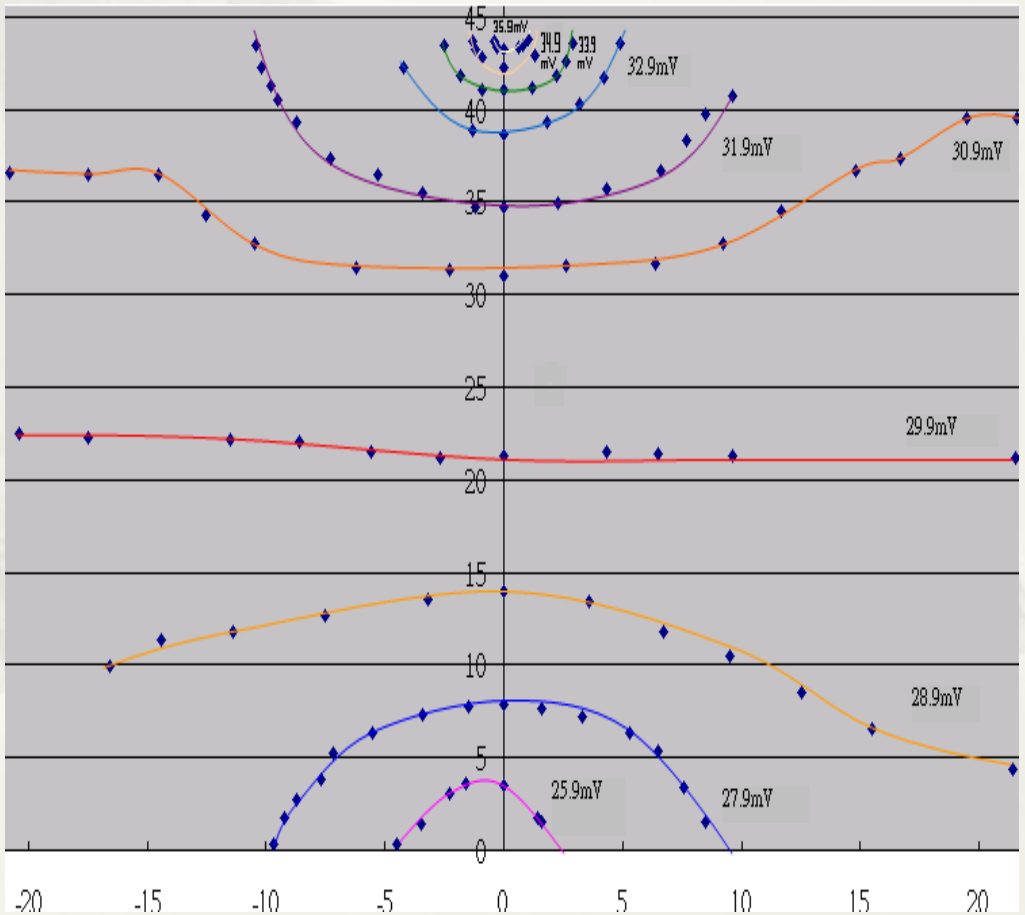
圖4

4. 此實驗中，筱雯應該把三用電表的功能選擇鈕旋轉到哪一位置，能測得較精確的測量結果？



測量鋁片的等電位線




45
40
35
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20
35.9mV
34.9 mV
33.9 mV
32.9mV
31.9mV
30.9mV
29.9mV
28.9mV
27.9mV
25.9mV