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proof that a finite collection of sets will not suffice

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Owner	rspuzio (6075)
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Suppose that you cut $[0, 1]$ into A_0, \dots, A_n . Displacing the parts is simply translating them; you can suppose that you leave A_0 in place and translate all the others to the right. Let ϵ be the smallest translation length : if after translation the union contains $[0, 1]$, necessarily $[0, \epsilon] \subset A_0$. A contradiction ensues.